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Final Report, Phases 1 and 2
An Interim Structural Design Standard for Solar Energy Applications

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789.

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FINAL REPORT
PHASES 1 AND 2
AN INTERIM STRUCTURAL DESIGN STANDARD FOR SOLAR ENERGY APPLICATIONS

PREPARED FOR

SANDIA LABORATORIES
LIVERMORE, CALIFORNIA 94550

BY

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FOSTER WHEELER DEVELOPMENT CORPORATION
12 Peach Tree Hill Road, Livingston, New Jersey 07039

Sandia Laboratories

Livermore, California 94550

TO: Distribution

RE: An Interim Structural Design Standard for Solar Energy Application

This work was undertaken as a first step toward the evolution of an ASME-type boiler code for solar energy applications. It is being distributed to the Solar Thermal Program Community and to the ASME Solar Energy Standards, Power Subcommittee for their use in the ongoing development of such a design standard.

Further work in the evaluation of materials subjected to the environments of Solar Thermal Central Receivers is continuing in support of this study. In addition, work is being proposed to study the application of design standards to the advanced central receiver systems using other fluids (sodium, salt, or air) in the receiver tubes.

The standards activity at Sandia is being gradually transferred over to the Solar Energy Research Institute, and future work is expected to be conducted through that agency.

J. D. Gilson, Supervisor
Solar Components Division II
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ABSTRACT

ABSTRACT

This is Foster Wheeler Development Corporation's final report covering Phases 1 and 2 of the program "An Interim Structural Design Standard for Solar Energy Applications," which was conducted from June 1977 to December 1978. The report is divided into five sections. Section 1 summarizes the program. Section 2 reviews Central Receiver Solar Thermal Power Systems, relevant ASME Codes, reliability considerations and the criteria used to develop the Interim Design Standard.

A code is needed for solar applications that is consistent with the basic level of reliability required in solar power systems. In order to accomplish this, a basic Design-by-Rule code such as Section VIII-Division 1 of the ASME Boiler and Pressure Vessel Code was chosen and additional requirements gleaned from other Sections of the ASME Code were added and modified if necessary in order to be consistent with the reliability requirements. The salient features of these additions and modifications are:

- A Design-by-Analysis alternative to Section VIII-Division 2.
- Fatigue analysis requirements and exemption rules in the subcreep-temperature regime.
- Creep-fatigue analysis requirements and exemption rules for elevated temperature service. The creep-fatigue criteria are a simplified and less conservative version of the nuclear Code criteria.
- No ratcheting analysis required.
- Additional guidelines for short-time buckling analysis.
- No creep-buckling requirement.

Section 3 is the Interim Design Standard. It is intended to be used in conjunction with Section VIII of the ASME Boiler and Pressure Vessel Code and B31.1 (Power Piping) and B31.3 (Chemical and Petroleum Refinery Piping) of the ANSI Piping Code. No other codes are referenced. All criteria or rules chosen or adapted from the other codes, such as Code Case 1592, are fully stated including all design data. Section 4 provides a detailed paragraph-by-paragraph explanation of the Interim Design Standard. Section 5 identifies the test and development program needed to generate new design data and to update the Interim Design Standard.

SECTION 1

PROGRAM SUMMARY

Section 1

PROGRAM SUMMARY

1.1 INTRODUCTION

A program to develop an "Interim Structural Design Standard for Solar Energy Applications" was authorized by Sandia Laboratories under Contract No. 87-9151, with a period of performance from June 1977 to December 1978.

This program was created to develop a set of interim design rules and standards applicable to the Central Receiver Solar Thermal Power System (CRSTPS) components that generally fall under the scope of the ASME Boiler and Pressure Vessel Code.* Test programs and additional development work required in order to upgrade the Interim Design Standard were also to be identified. This final report describes the results of the study.

1.2 PROGRAM NEED

The conversion of solar energy to usable power involves pressure-containing components such as boiler tubes, pressure vessels, piping, and valves. The pressure requirements, temperatures of operation, fluids used, and environment may vary. In each case there may be a potential hazard associated with the failure of a pressure boundary. To greatly reduce this hazard, a set of requirements may be imposed on material, design, fabrication, and testing of the pressure boundaries. The Code is such a set of requirements.

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*Subsequently called the Code.

The Code may be applied to solar components. From the nature of its use, Section I, Power Boilers, seems to be applicable to the design of a CRSTPS receiver in which steam (or another vapor) is generated. However, there are conditions of loading and service that are unique to solar power systems and very critical in their design. For example, portions of the solar receiver will generally operate at high temperatures. They might be required to have a 20-to-30-year lifetime and withstand a very large number of severe thermal cycles. Section I does not consider thermal cycles explicitly. The fossil-fueled boilers from which the rules of Section I are derived do not sustain as many severe thermal cycles.

There are other aspects of Section I which may be questionable for solar energy applications. For economic reasons it may be important to change these. For example, the determination in Section I of the allowable loading for structural attachments to tubes is very dependent on the experience gained in fossil-fueled boilers. No such experience exists in solar designs.

Other Sections of the Code do have methods which are applicable to many of the special conditions of solar receivers. Included are techniques for the direct evaluation of creep, low-cycle fatigue and the Design by Analysis of structural attachments to tubes. However, before these methods and rules can be used with confidence, they must be examined for their technical validity, consistency, and completeness in the solar design situation. In addition, the use of these methods may be overly conservative for solar requirements and may lead to uneconomical designs.

1.3 STATEMENT OF WORK AND SCHEDULE

According to the contract, the work to be performed was divided into the following two phases:

- Phase 1:
  - Study the range of loading conditions, environment, and different possible failure modes in CRSTPS components that fall under the scope of the Code. Survey the available design rules and criteria dealing with these failure modes in Sections I, III, and VIII of the Code as well as in other standards.
  - Survey the available literature on the failure rates of different components designed under various Sections of the Code. These failure rates will be categorized as loading, material, service conditions, etc. Examine service failure data from Edison Electric Institute (EEI), the American Boiler Manufacturers Association (ABMA), and the National Board of Boiler and Pressure Vessel Inspectors (NBBPVI). Make a comparative evaluation of the reliability achieved by the use of different portions of the Code. Define the level of reliability, availability, and safety desired in CRSTPS.
- Phase 2:
  - Select the existing Code rules that ensure the desired levels of reliability, availability, and safety. Modify the rules that are inconsistent with the above levels. Determine the acceptable design limits and rules for solar design.
  - Identify the development and test program required to generate the design limit data for conditions that are unique to CRSTPS and not covered in present codes and standards.

SECTION 2

PROGRAM BACKGROUND

Section 2

PROGRAM BACKGROUND

2.1 INTRODUCTION

During Phase 1 of this program, CRSTPS system components were reviewed. This review consisted of a study of the range of loading conditions, the environment, and possible failure modes in CRSTPS components that fall under the scope of the Code. In this study, primary attention was given to the receiver subsystem, and the thermal storage subsystem, including the heat exchangers and piping. The electrical power generation subsystem, pumps, and valves were excluded. A detailed description of this study may be found in the Phase 1 Report.[1*] A brief summary of this study relating to the receiver subsystem and the thermal storage subsystem is presented in matrix form in Tables 1 and 2. A detailed review of the various pertinent Sections of the Code was also conducted in order to determine their applicability to solar power system components. The details of this study were reported in the Phase 1 Report and are summarized in Table 3. A reliability study involving a review of the available failure-rate data and other reliability information related to pressure components designed according to the Code, was also undertaken as a part of this program. The purpose of this study was to determine the appropriate level of reliability for solar components in order to aid in choosing the Code rules for solar applications. A comprehensive summary of the reliability study may also be found in Reference 1.

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*Numbers represent references in Section 6.

Table 1 Matrix of Information--Receiver Subsystem

Component	Elements	Loads	Failure Modes*	Failure Consequences	Related Code Rules
Steam drum	Shell Head Feedwater inlet	Internal pressure Thermal (steady-state) Thermal transients Seismic	1 3 5	FM 1 will affect safety FM 3 will lead to shutdown FM 5 will lead to shutdown	Sections I and VIII-Division 1 contain rules for all elements for internal pressure (FM 1). Section VIII-Division 2 has criteria to design all elements for internal pressure, thermal (steady-state), and thermal transients. Section III has criteria for all loads including seismic.
Header (low temperature)	Shell Head	See loads for steam drum	1 3	FM 1 will affect safety FM 3 will lead to shutdown	See Code rules for steam drum.
Header (high temperature)	Shell Head	See loads for steam drum	1 4	FM 1 and 2 will affect safety FM 4 will lead to shutdown	Sections I and VIII-Division 1 have rules to prevent FM 1 and 2 caused by internal pressure. Section VIII-Division 2 is not applicable for high-temperature design. Section III has criteria for all loads and failure modes and includes Code Case 1592.
Tubes (low temperature)	Tubes	Internal pressure Thermal (steady-state) Thermal transients Weight Reactions of lugs, etc. Seismic	1 3 5	FM 1 will affect safety FM 3 will lead to shutdown FM 5 will lead to shutdown	See Code rules for steam drum.
Tubes (high temperature)	Tubes	See loads for tubes (low temperature)	1 2 4 5	FM 1 and 2 will affect safety FM 4 will lead to shutdown FM 5 will lead to shutdown	See Code rules for header (high temperature).
Waterwalls (low temperature)	Tubes Fins	Internal pressure Weight Reactions of lugs, etc. Seismic Thermal (steady-state) Thermal transients	1 3 5	FM 1 will affect safety FM 3 will lead to shutdown FM 5 will lead to shutdown	See Code rules for steam drum.

*FM: 1. Ductile rupture 2. Creep rupture 3. Fatigue failure 4. Creep fatigue 5. Ratcheting.

Table 1 Matrix of Information--Receiver Subsystem (Cont)

Component	Elements	Loads	Failure Modes*	Failure Consequences	Related Code Rules
Waterwalls (high temperature)	Tubes Fins	See loads for waterwalls (low temperature)	1 2 4 5	FM 1 and 2 will affect safety FM 4 will lead to shutdown FM 5 will lead to shutdown	Sections I and VIII-Division 1 have rules to prevent FM 1 and 2 caused by internal pressure. Section VIII-Division 2 is not applicable to high-temperature design. Section III has criteria for all loads and failure modes.
Piping (low temperature)		Internal pressure Thermal (steady-state) Thermal transients Weight Seismic	1 3	FM 1 will affect safety FM 3 will lead to shutdown	Sections I and VIII-Division 1 have rules to prevent FM 1 caused by internal pressure. Section III and Section VIII-Division 2 have criteria for FM 1 and 3 and for all loads.
Piping (high temperature)		See loads for piping (low temperature)	1 2 4	FM 1 and 2 will affect safety FM 4 will lead to shutdown	See Code rules for header (high temperature).

Table 2 Matrix of Information--Thermal Storage Subsystem

Component	Elements	Loads	Failure Modes*	Failure Consequences	Related Code Rules
Storage tank	Shell Head Nozzle	Internal pressure Thermal (steady-state) Thermal transients Seismic Wind Shipping Internal point loads	1 3 5	FM 1 will affect safety FM 3 will lead to shutdown FM 5 will lead to shutdown	Sections I and VIII-Division 1 contain rules for all elements for internal pressure (FM 1). Section VIII-Division 2 has criteria to design all elements for internal pressure, thermal (steady-state), and thermal transients. Section III has criteria for all loads including seismic.
Heat exchanger shell	Shell Head Nozzle	Internal pressure Thermal transients Seismic Shipping	1 3	FM 1 will affect safety FM 3 will lead to shutdown	See Code rules for storage tank.
Heat exchanger tubes (low temperature)	Tubes	Internal pressure Thermal (steady-state) Thermal transients Seismic Vibration Shipping	1 3 5	FM 1 will affect safety FM 3 will lead to shutdown FM 5 will lead to shutdown	See Code rules for storage tank.
Heat exchanger tubes (high temperature)	Tubes	Internal pressure Thermal (steady-state) Thermal transients Seismic Vibration Shipping	1 2 4 5	FM 1 and 2 will affect safety FM 4 and 5 will lead to shutdown	Sections I and VIII-Division 1 have rules to prevent FM 1 and 2 caused by internal pressure. Section VIII-Division 2 is not applicable for high-temperature design. Section III has criteria for all loads and failure modes and includes Code Case 1592.
Tube sheets (low temperature)	Perforated plate	Pressure Thermal (steady-state) Thermal transients Seismic Vibration Shipping	1 3 5	FM 1 will affect safety FM 3 and 5 will lead to shutdown	See Code rules for storage tank.

*FM: 1. Ductile rupture 2. Creep rupture 3. Fatigue failure 4. Creep fatigue 5. Ratcheting

Table 2 Matrix of Information--Thermal Storage Subsystem (Cont)

Component	Elements	Loads	Failure Modes*	Failure Consequences	Related Code Rules
Tube sheets (high temperature)	Perforated plate	Pressure	1	FM 1 and 2 will affect safety	See Code rules for heat exchanger tubes (high-temperature).
		Thermal (steady-state)	2	FM 4 and 5 will lead to shutdown	
		Thermal transients	4		
		Seismic	5		
		Vibration			
		Shipping			
Fluid distribution manifolds	Shell	Internal pressure	1	FM 1 will affect safety	See Code rules for storage tank.
	Head	Thermal transients	3	FM 3 will lead to shutdown	
	Nozzle	Seismic			
		Shipping			
Maintenance tank	Shell	Internal pressure	1	FM 1 will affect safety	See Code rules for storage tank.
	Head	Thermal transients	3	FM 3 will lead to shutdown	
	Nozzle	Seismic			
		Shipping			

Table 3 Comparison of Design Rules of Different Sections of the ASME Code

Code Section	Applicability	Design Approach	Failure Modes Explicitly Considered	Other Salient Features	Suitability and Limitations for Solar Applications
Section I	Power boilers	Design by Rule	Ductile rupture Creep rupture	Developed from power boiler experience where fatigue considerations are not as important as in solar applications Only pressure loads are explicitly considered even though other loads are mentioned	No criteria to evaluate thermal stresses No criteria to evaluate fatigue or creep-fatigue interactions Material choices limited Seismic loads not considered No buckling criteria
Section VIII-Division 1	Pressure vessels	Design by Rule	Ductile rupture Creep rupture Buckling caused by short-term loading	Design philosophy identical to Section I May slightly reduce weight of pressure components	No criteria to evaluate thermal stresses No criteria to evaluate fatigue or creep-fatigue interactions Material choices wide Seismic loads not considered
Section VIII-Division 2	Pressure vessels (alternative rules)	Design by Analysis	Ductile rupture Incremental plastic collapse Fatigue Buckling caused by short-term loading	Design approach similar to Section III More restrictive than Section VIII-Division 1 in choice of materials Permits higher stress values	No criteria to evaluate creep-fatigue at elevated temperatures Criteria provided for evaluation of all failure modes for service at subcreep temperatures May reduce weight of pressure components More analysis required
Section III-Division 1, Subsection NB	Nuclear power system metallic components--Class 1	Design by Analysis	Same as Section VIII-Division 2	High reliability Sophisticated quality control, inspection, testing, material selection, and fabrication requirements A detailed stress report is required	Same as Section VIII-Division 2.
Section III-Division 1, Subsection NC	Nuclear power system metallic components--Class 2	Design by Analysis and Design-by-Rule	Design by Analysis portion is similar to Subsection NB and Design by Rule portion is similar to Section VIII-Division 1. Material choice is limited to those allowed for Class 1 components.		
Section III-Division 1, Subsection ND	Nuclear power system metallic components--Class 3	Design by Rule	Similar to the Design by Rule portion of Subsection NC.		

Table 3 Comparison of Deisgn Rules of Different Sections of the ASME Code (Cont)

Code Section	Applicability	Design Approach	Failure Modes Explicitly Considered	Other Salient Features	Suitability and Limitations for Solar Applications
Code Case 1592	Nuclear metallic components--Class 1 for elevated-temperature service	Design by Analysis	Same as Section III-Division 1, Subsection NB plus creep-rupture, creep-fatigue, and creep-buckling	Same as Section III-Division 1, Subsection NB	Creep-fatigue requirements are very stringent and may result in economic penalties for solar power systems Very sophisticated analysis is necessary Compressive hold times and tensile hold times are treated as equally damaging in determining creep-rupture times Material properties are given only for a very limited number of materials
Code Case 1481	Nuclear metallic components--Class 2 and 3, for elevated-temperature service	Design by Rule and Design by Analysis	Same as Code Case 1592	Various exemption criteria for creep-fatigue and ratcheting are provided. If these criteria are not met, creep-fatigue evaluation as in Code Case 1592 is required Same materials as in Subsections NC and ND	Exemption criteria are difficult to meet Too conservative for solar applications

Some of the general conclusions in the above areas are summarized herein.

2.2 CRSTPS SYSTEM REVIEW

First generation CRSTPS components are subjected to loads similar to those of power boilers which are generally designed to Section I and Section VIII-Division 1 specifications except for the following:

- Control of thermal gradients is made necessary by the possibility of very high flux due to the concentration of solar energy.
- Number of important cycles of load is higher by about an order of magnitude than for power boilers. This is made more important because of possible high thermal stresses.
- Seismic loads may be greater than for power boilers because of great tower height. Special consideration is required. The sloshing effect due to seismic loads on storage may also be important.
- Wind loads may be large and need special evaluation.

2.3 REVIEW OF CODES AND STANDARDS

Section I of the Code is based on power boiler experience and Design by Rule. A power boiler which is designed, built, inspected, and stamped in accordance with the rules of Section I must meet all applicable rules of Section I. The use of other design rules and guides, whether part of the Code or not, may be used to aid the designer, but will have no bearing on the boiler's acceptability under rules of Section I. Thus Section I does not guard against the loads by which solar components differ from the power boiler components on which Section I experience is based.

Other Code Sections were reviewed in the same manner with the following results:

- Section VIII-Division 1, is based on general pressure vessel experience and Design by Rule. Section VIII-Division 1 does indicate specific loads that should be considered in design, and includes earthquake load. However, the large number of cycles is not covered and there is no explicit method of consideration of the thermal, seismic, or wind loads.
- Section VIII-Division 2 is based on Design by Analysis. It considers the nature and magnitude of the stresses for all loads. It also explicitly evaluates fatigue stresses. Thus the cycles of load, thermal loads, seismic loads, and wind loads may all be evaluated. This Section is limited in its use to metal temperatures at which creep is negligible. The cost of the analysis is substantially greater than that for Design by Rule codes.
- Section III-Division 1 is divided into three design subsections. Subsection NB is Design by Analysis which is more inclusive in its load analysis than Section VIII-Division 2. Subsection ND is similar to the Design by Rule of Section VIII-Division 1 and Subsection NC allows the use of Subsections NB or ND. For all cases the design is limited to temperatures below those at which creep would take place.
- Code Case 1592 is similar in concept to Section III-Division 1, Subsection NB. It allows all loads to be considered and is applicable to temperatures in the creep range.
- Code Case 1481 is similar in concept to Section III-Division 1, Subsections NC and ND and is applicable to temperatures in the creep range.

2.4 RELIABILITY CONSIDERATIONS

The study of reliability considerations indicated that there is a "quality" difference between vessels built according to Section III (Nuclear Components) and Section I and VIII-Division 1. This should lead to a failure rate of at least two orders of magnitude smaller for nuclear components than for fossil-fuel components. The requirements of a solar standard in terms of reliability lean more towards that of fossil fuel codes than nuclear codes because the parts are accessible and the usual tube failure would be disruptive but not critical. It may be of value to upgrade the fossil fuel Code rules with applicable elements of the Code developed for nuclear components.

2.5 CRITERIA FOR SELECTING CODE RULES

The following criteria are considered relevant in selecting rules for the Interim Design Standard:

- Simplicity. The Interim Design Standard must be simple to use. An approach similar to that of Section I or Section VIII-Division 1 would be most appropriate from this point of view. This approach essentially involves Design-by-Rule. The thickness of the pressure boundary is set by limiting the primary stresses to conservative allowable stress values, thus preventing burst and gross distortion. The remaining failure modes are prevented by liberal safety factors and accepted design practices. This approach, however, may result in greater component weight.

- Design-by-Analysis Alternative. It is considered useful to give an option of Design-by-Analysis. Thus the user may decide whether or not to perform additional analyses that might justify a reduction in wall thickness. This is especially important in view of the fact that modern computer methods of analysis are within reach of most engineers.

- Avoidance of Excessive Conservatism. One of the challenges in the development and commercialization of a viable solar power technology is the reduction in capital costs. A design standard which is unduly conservative will drive up the costs and price the technology out of the market.

- Appropriate Levels of Reliability. Although the prime consideration in the development of the Interim Design Standard is safety, effectiveness and reliability are also important. The Interim Design Standard must result in designs which are at least as reliable as the fossil-fuel power systems and preferably more so.

2.6 SELECTION AND MODIFICATION OF CODE RULES FOR SOLAR APPLICATION

The Interim Design Standard is specifically directed toward the first generation of water/steam systems. Four basic failure modes of prime importance that should explicitly be prevented are:

- Bursting and gross distortion from pressure
- Excessive plastic incremental distortion from cyclic loading
- Fatigue or creep fatigue from cyclic loading
- Buckling due to short- or long-term loading.

In addition to the above, consideration must also be given to brittle fracture, stress corrosion, and corrosion fatigue. In the Interim Design Standard, protection against these latter failure modes is left the responsibility of the designer.

Because solar thermal power systems are in an early stage of development without a reserve of explicit experience, the experiences of similar applications must be adapted for an interim solar standard. The following three approaches based on adaptations of the various Sections of the Code could give adequate protection against the four basic failure modes mentioned above.

- A combination of Sections I and VIII plus some additional rules based on the elevated temperature nuclear Code
- Section VIII plus some additional rules based on the elevated temperature nuclear Code
- Section III-Division 1 plus Code Case 1592 or Code Case 1481.

The third approach would involve very sophisticated and complex analyses and should result in unduly conservative designs. Hence it is not given any further consideration. The other two approaches are now evaluated in greater detail.

2.6.1 Basic Interim Code Rule Recommendation Based on Sections I and VIII

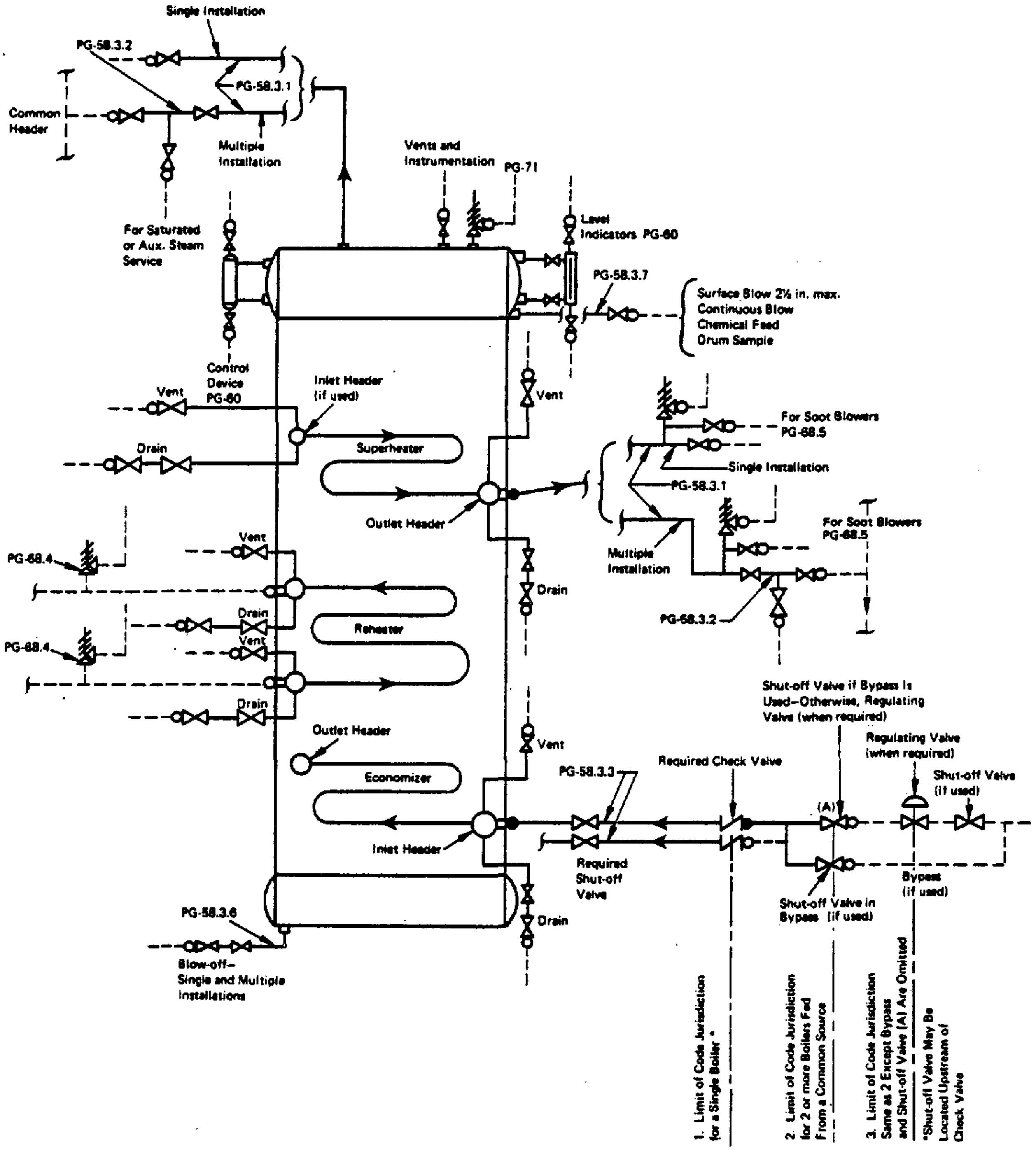
The steam/water solar receiver components are similar to those of a system that would be designed by Section I of the Code. In Figure 1, taken from Section I, Code jurisdictional limits of Section I for a drum-type boiler are shown. A similar figure applies for Section I-designed forced-flow boilers. Parts of the boiler outside this jurisdiction may be designed by other Codes, such as Section VIII or ANSI B31.1 for piping.

For the initial studies FWDC decided not only to divide consideration of the boiler into the jurisdiction shown in Section I, but also to differentiate between those components within the jurisdiction of Section I which did and did not "see" the radiation and to consider piping outside the jurisdiction of Section I separately. Thus the four groups to consider were:

A - Components within the jurisdictional limits of Section I that are not subjected to direct radiation, including drum, headers, and piping.

B - Components within the jurisdictional limits of Section I that are subjected to direct radiation. The components are essentially the heat-input system, superheater, and waterwalls.

C - Components other than piping that are outside the jurisdictional limits of Section I, Power Boilers. These may include a feedwater heater, storage tank, thermal storage heater, and steam generator from thermal storage. This steam generator may include a feedwater heater, evaporator, drum, superheater, and possibly a reheater.



LEGEND & NOTES:

●—— Piping and Joint — ASME Section I jurisdiction

○- - - Piping and Joint — Not ASME Section I jurisdiction (See applicable ANSI B31 Code)

Note: Only one drain valve may be required when the valve is not intended for blow-off purposes when the boiler is under pressure (see PG-58.3.7)

Figure 1 Code Jurisdictional Limits for Piping Drum-Type Boilers

D - Piping that is outside the jurisdictional limits of Section I, Power Boilers.

Because of the large number of cycles involved in a solar power system, there is a question of whether or not Section I experience will adequately cover possible fatigue caused by cyclic load with and without creep. If Section I experience is inadequate for temperatures below the creep range, an analysis may be made by means of the rules of Section VIII-Division 2. However, the required calculations are frequently fairly complex and expensive. Although Section VIII-Division 2 does have waiver rules, they are almost always difficult to meet for solar components. For temperatures in the creep range, creep damage could substantially reduce the number of allowable fatigue cycles. Code Case 1592 includes conservative methods for creep-fatigue analysis that may make it too conservative for solar applications.

Another important failure mode that could be caused by a combination of primary loads and cyclic behavior is incremental distortion from ratcheting (and if creep is also present--creep ratcheting). This behavior in many solar components, especially those subjected to a substantial number of additional cycles, may not be covered in the experience of Section I.

2.6.1.1 Group A. Essentially, these components form the transport and distribution system inside the boiler. They generally have thermal stresses much smaller than the pressure stresses. Most of the components covered by Group A operate at temperatures below the creep range, but some, such as the outlet header, may be subject to creep. Because thermal stresses are not severe, the experience of Section I should cover the requirements of fatigue, creep fatigue, and ratcheting, unless the number of cycles or the design lifetime are well beyond those expected in a power boiler designed by Section I. Thus, for components in Group A:

- Basis: Section I
- Fatigue or creep-fatigue analysis is not required. However, the Interim Design Standard should state that creep fatigue or fatigue should be considered for cyclic conditions significantly more severe than those normal for a Section I design.
- Ratcheting or creep-ratcheting analysis is not required. However, a statement should be included indicating that these analyses be considered.

2.6.1.2 Group B. These components experience direct radiation. Because of the substantial number of cycles, thermal stresses are generally much higher than pressure stresses. Keeping thermal stresses at a reasonable level, however, is still important. Unfortunately, the requirements to minimize pressure and thermal stresses conflict. For a given pressure, as thickness is increased, pressure stresses decrease. But a brief study of some superheater tubes indicates that for given operating conditions, as the thickness is increased, the thermal stresses are increased almost proportionately.

Because of the thermal stresses, highly cyclic behavior, and high temperatures, creep-fatigue will be important. The level of possible creep-fatigue damage is not covered by the experience of Section I design, and as previously pointed out, the rules of Code Case 1592 are difficult to meet. One possible source of relief lies in the nature of the stress situation in the superheater solar components. The major creep damage takes place under "compressive" conditions rather than under the tensile conditions for which the current rules of Code Case 1592 were developed. Determination of the effect of compressive creep on the number of cycles to failure would be helpful. This information could then be used for some relief from the creep fatigue restriction. However, another very important problem remains: Although the tests are generally simple tension or simple compression, in actuality the principal stresses are three-dimensional and therefore is difficult to determine which are tensile and which are compressive.

Because of the high thermal stresses and many thermal cycles, the possibility of creep-ratcheting for Group B may be greater than for Group A. However, since inspection is much simpler than for nuclear components, it does not seem necessary to require creep-ratcheting analysis as long as ductile failure and creep fatigue are prevented. Thus, for components in Group B:

- Basis: Section I
- Fatigue analysis is required, as in Section VIII-Division 2, for temperatures below the creep range. The waiver rules of Section VIII-Division 2 should be used until more appropriate waiver rules for the solar standard are established.
- Creep-fatigue analysis is required, as in Code Case 1592, for temperatures in the creep range. Waiver rules, such as those being proposed for Code Case 1481, should be modified for solar conditions.
- Ratcheting or creep-ratcheting analysis is not required. However, a statement should be included in the Interim Design Standard indicating that these analyses be considered.

2.6.1.3 Group C. These components are outside of Section I jurisdiction. Thus Section VIII-Divisions 1 and 2 are used. Division 2 permits thinner vessels than Division 1 in many cases for temperatures below the creep range. This result is based on more precise design procedures. However, there are also more limitations in Division 2 than in Division 1. For example, some common design details are prohibited; permissible fabrication procedures are specifically delineated; and more complete examination, testing, and inspection are required.

The components considered in this category will be below creep temperatures except possibly for the thermal storage heater. However, many will experience fairly sharp thermal gradients and many cycles. Thus explicit fatigue considerations are necessary whether Section VIII-Division 1 or Section VIII-Division 2 is used. For components in Group C:

- Basis: Section VIII

  Section VIII-Division 1 for all components. Section VIII-Division 2 may be used as an alternate for components at temperatures below the creep range.

- For components at temperatures below the creep range, fatigue analysis is required as promulgated in Section VIII-Division 2, whether Section VIII-Division 1 or Division 2 is used as a basis. Relief using the waiver rules of Section VIII-Division 2 is very limited with solar components. Solar-directed waiver rules should be developed.

- For components at temperatures in the creep range, Section VIII-Division 1 must be used. Creep-fatigue analysis is required as in Code Case 1592. Waiver rules from Code Case 1481 are available but are not of much use in solar applications. Solar-directed waiver rules in this case can be developed without much difficulty.

- Ratcheting or creep-ratcheting analysis is not required. However, a statement should be included indicating that these analyses be considered.

2.6.1.4 Group D. Because the piping outside the jurisdiction of Section I is for transport rather than heat transfer, the thermal gradients will not be as severe as for some components in Group C. The major cyclic consideration is expansion stress in a component such as the steam downcomer. ANSI B31.1 has rules to cover expansion stresses and should be used for Group D. A note should be included that for very large numbers of significant cycles, it may be necessary to consider fatigue or creep fatigue.

2.6.2 Basic Interim Code Rule Recommendation Based on Section VIII

One of the major problems with central receiver solar systems is weight. Since receivers are placed on a tower, the weight of the receiver components adds to the tower weight. To prevent bursting and gross distortion, the wall-thickness value from Section VIII-Division 1 could be as much as 10 percent less than for Section I, and the thickness from Section VIII-Division 2 possibly 25 percent less than for Section I. The latter value is valid only for temperatures below the creep range. For Section VIII-Division 2 at applicable temperatures and Section VIII-Division 1 at higher temperatures, there may be a "step" in the required thickness at the lowest temperature for which creep must be considered. Unfortunately, this is true even for components designed to nuclear Code (Section III) or high-temperature nuclear Code (Code Case 1592) specifications.

The design approach to be taken based on Section VIII is that Division 1 can be utilized at all temperatures and Division 2 only at temperatures below the creep range. There is no alternative for components with temperatures in the creep range. The general items defined for Section I that concern loads other than pressure loads, additional design requirements, and a manufacturer's report should also be included in a code based on Section VIII. Similarly, the four groups considered before should also be used for a code based on Section VIII.

2.6.2.1 <u>Group A</u>

- Basis: Section VIII.

  Section VIII-Division 1 for all components. Section VIII-Division 2 may be used as an alternative for components at temperatures below the creep range.

- For Section VIII-Division 1 designs, fatigue, or creep-fatigue analysis is not required. A statement that creep-fatigue or fatigue should be considered for cyclic conditions significantly more severe than those considered in the usual Section VIII design must be included in an Interim Design Standard.

- For Section VIII-Division 2 designs, fatigue analysis is required.

- For Section VIII-Division 1 designs, ratcheting, or creep-ratcheting analysis is not required. However, a statement should be included indicating that they should be considered.

- For Section VIII-Division 2 designs, the warning of the possibility of thermal stress ratcheting is already included.

2.6.2.2 <u>Group B</u>

- Basis: Section VIII

  Section VIII-Division 1 for all components. Section VIII-Division 2 is permitted for components at temperatures below the creep range.

- Fatigue analysis as defined in Section VIII-Division 2 is required for temperatures below the creep range for Section VIII-Division 1 as well as for Section VIII-Division 2.

- For components at temperatures in the creep range, Section VIII-Division 1 must be used as the basic code. Creep-fatigue analysis is required as in Code Case 1592. Waiver rules, if applicable, may be used.

- Ratcheting or creep-ratcheting analysis is not required for Section VIII-Division 1. A statement indicating that they should be considered must be included.
- For Section VIII-Division 2 designs, a warning of the possibility of thermal stress ratcheting is already included.

2.6.2.3 Group C. The information for this group is identical to that in Section 2.6.2.2 (Group B).

2.6.2.4 Group D. The use of ANSI B31.1 and B31.3 for the piping in Group D seems applicable.

2.6.3 Choice

After considering these two options (2.6.1 and 2.6.2), the second option was chosen for the Interim Design Standard for the following reasons:

- It is more consistent: In the first approach the receiver alone is to be designed according to Section I and the rest of the components according to Section VIII; in the second approach Section VIII may be used for all components including the receiver.
- Section VIII - Division 1 may result in a lighter and less conservative design than Section I. By using the Design-by-Analysis alternative of Division 2, components can be made even lighter. This is important because the receiver is placed atop a tower which could be several hundred feet high.
- Section VIII has a wider material choice.
- The rules of Section I are based on specific experience which may not be applicable to solar requirements. Section VIII is written for a broader scope of vessel.

In summary, Section VIII-Division 1 was chosen as the base code. The following additions and modifications were made:

- A Design-by-Analysis alternative to Section VIII-Division 2.

- Fatigue analysis requirements and exemption rules in the subcreep-temperature regime.
- Creep-fatigue analysis requirements and exemption rules for elevated-temperature service. The creep-fatigue criteria are a simplified and less conservative version of the nuclear Code criteria.
- No ratcheting analysis is required.
- Additional guidelines for short-time buckling analysis.
- No creep buckling requirement.

SECTION 3

AN INTERIM STRUCTURAL DESIGN STANDARD FOR SOLAR ENERGY APPLICATIONS WITH APPENDICES

Section 3

AN INTERIM STRUCTURAL DESIGN STANDARD FOR SOLAR ENERGY APPLICATIONS

SCOPE

The requirements of this code apply to all pressure vessel and piping components, parts, and appurtenances that are contained in Central Receiver Solar Thermal Power Systems (CRSTPS) of the water/steam type except the following:

- Pressure containers which are integral parts of components of rotating or reciprocating mechanical devices, such as pumps, compressors, turbines, generators, engines, and hydraulic or pneumatic cylinders where the primary design considerations and/or stresses are derived from the functional requirements of the device.
- Components of solar power systems having a pressure exceeding 3000 lb/in^2g (20,670 kPa). For such components, deviations from and additions to these rules may be necessary.
- Vessels having an internal or external pressure not exceeding 15 lb/in^2g (103 kPa).
- Nonmetallic components.

-3000 DESIGN

-3100 GENERAL REQUIREMENTS FOR DESIGN

-3111 ACCEPTABILITY - An acceptable design is one which meets the requirements given below:

(a) The design satisfies the general design requirements of -3100 and the appropriate component rules in -3200 and -3300.

(b) The design shall guard against failure from low-energy fracture. The design specification may contain additional requirements as to the tests, analyses, or other methods by which the designer can demonstrate proper consideration of this failure mode.

(c) The Certificate Holder may invoke alternative methods for demonstrating compliance to those requirements and rules of -3111 (a) that relate to buckling and creep-fatigue failure. However, these alternative methods shall be approved by the owner.

-3112 DESIGN REPORT AND CERTIFICATION

(a) Reporting and certification procedures of Section VIII-Division 1 of the ASME Pressure Vessel and Piping Code shall apply for all components except those listed in -3112 (b).

(b) Reporting and certification procedures of Section VIII-Division 2 of the ASME Pressure Vessel and Piping Code shall apply for those components which satisfy any of the following:

(1) Designed according to Section VIII-Division 2.
(2) Designed using the buckling rules in Paragraph -3260.
(3) Designed using the fatigue rules in Paragraph -3251.2 or the creep-fatigue rules in Paragraph -3252.1.

-3200 DESIGN RULES (VESSEL)

-3210 GENERAL - The design of the pressure vessels and the vessel parts shall conform to the design requirements of -3200.

-3220 BASE DESIGN RULES

(a) The design shall conform to the requirements of Section VIII-Division 1 of the ASME Boiler and Pressure Vessel Code. Additional requirements stated in -3250 shall also be met.

(b) The requirements of Section VIII-Division 1 relating to materials, fabrication, inspection, testing, and pressure relief devices shall apply.

(c) Materials other than those allowed by Section VIII-Division 1 may not be used, unless data thereon are submitted to and approved by the ASME Solar Energy Committee in accordance with Appendix B of Section VIII-Division 1.

(d) In addition to the loads specified in UG-22 of Section VIII-Division 1 of the ASME Boiler and Pressure Vessel Code, snow loads, shipping loads, and vibrations shall also be considered where required.

(e) The buckling limits of -3260 may be used for those configurations and loading conditions for which buckling rules or charts are not provided in Section VIII-Division 1.

-3230 ALTERNATIVE DESIGN RULES

(a) The requirements of -3220 may be replaced by the alternative rules of -3230 for service at temperatures for which the design stress intensity is given in Section VIII-Division 2 of the ASME Boiler and Pressure Vessel Code.

(b) The design in accordance with -3230 shall conform to the requirements of Section VIII-Division 2 of the ASME Boiler and Pressure Vessel Code. The additional requirements of -3250 are already included in Section VIII-Division 2.

(c) Section VIII-Division 2 shall be used as a whole including the requirements relating to the materials, fabrication, inspection, tests, and certification.

(d) Materials other than those allowed by Section VIII-Division 2 may not be used, unless data thereon are submitted to and approved by the ASME Solar Energy Committee in accordance with Appendix 16 of Section VIII-Division 2.

(e) The buckling limits of -3260 may be used for those configurations and loading conditions for which buckling rules or charts are not provided in Section VIII-Division 1.

-3250 ADDITIONAL REQUIREMENTS - The additional requirements of -3251 and -3252 shall be satisfied if -3220 is used.

-3251 FATIGUE EVALUATION - The following requirements on fatigue evaluation apply to service temperatures for which stress intensity values are given in Section VIII-Division 2 of the ASME Boiler and Pressure Vessel Code.

-3251.1 FATIGUE EVALUATION NOT REQUIRED - The following is a list of components for which fatigue evaluation is not mandatory.

(a) Receiver components which are not directly exposed to the solar heat flux.

(b) A component exempted from fatigue analysis by an explicit statement in the design specifications.

-3251.2 FATIGUE EVALUATION REQUIRED

(a) The components not exempted from fatigue evaluation as per -3251.1 shall be required to meet the fatigue limits in accordance with Article AD-160 of Section VIII-Division 2.

(b) Fatigue evaluation exemption rules in AD-160.2 and AD-160.3 of Section VIII-Division 2 may be used to determine the need for a detailed fatigue analysis.

(c) If the exemption rules of AD-160.2 and AD-160.3 are not met, a detailed fatigue analysis shall be made in accordance with the rules of Appendices 4 and 5 of Section VIII-Division 2.

-3252 CREEP-FATIGUE EVALUATION - The following requirements on creep-fatigue evaluation apply to elevated temperature service.

-3252.1 CREEP-FATIGUE EVALUATION NOT REQUIRED - The following is a list of components for which creep-fatigue evaluation is not required.

(a) Receiver components which are not directly exposed to the solar heat flux.

(b) A component which, by an explicit statement in the design specification, may be exempted from a creep-fatigue evaluation by the owner.

-3252.2 RULES TO DETERMINE NEED FOR CREEP-FATIGUE ANALYSIS - A creep-fatigue evaluation need not be made provided the total number of significant load cycles is less than 25. If this condition is not met, a detailed creep-fatigue analysis shall be made in accordance with -3252.3. A load cycle is significant if any of the following is true:

(a) The range of the elastically calculated primary stress intensity (see Appendix A) is greater than 1.25 times the maximum allowable stress in Section VIII-Division 1.

(b) The range of the elastically calculated secondary stress intensity (see Appendix A) is greater than 1.5 times the maximum allowable stress in Section VIII-Division 1.

(c) The range of the elastically calculated peak stress intensity (see Appendix A) using a stress concentration factor of 2.5 at local structural discontinuities (see Appendix A), unless otherwise specified, is greater than twice the allowable stress amplitude at 10^6 cycles from the design fatigue curves in Figures -3252.2(a) and -3252.2(b).

-3252.3 CREEP-FATIGUE ANALYSIS

(a) All significant load conditions shall be evaluated for accumulated creep and fatigue damage including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage shall satisfy the following relation:

$$\sum_{j=1}^{p} \left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q} \left(\frac{t}{T_d}\right)_k \leq D \qquad (1)$$

where

D - total creep-fatigue damage [Figure -3252.3(a)].

n = number of applied cycles of loading condition, j.

N_d = number of design allowable cycles of loading condition, j. N_d is determined from one of the design fatigue curves in Figures -3252.3(b) or (c) and Tables -3252.3(a) and (b) corresponding to the maximum metal temperature during the cycle. The design fatigue curves were determined from completely reversed loading conditions at strain rates greater than, or equal to those noted on the curves.

t = time duration of the load condition, k.

T_d = allowable creep rupture time at a given stress or an effective stress from load, k. T_d values are obtained by the procedure outlined in -3252.3(c).

(b) Equivalent Strain Range Calculation - An equivalent strain range is used to determine N_d. When the Design Specification contains a histogram delineating a specific loading sequence, the strain range shall be calculated for the cycles described by the histogram. If the sequence of loading is not defined by the Design Specification,

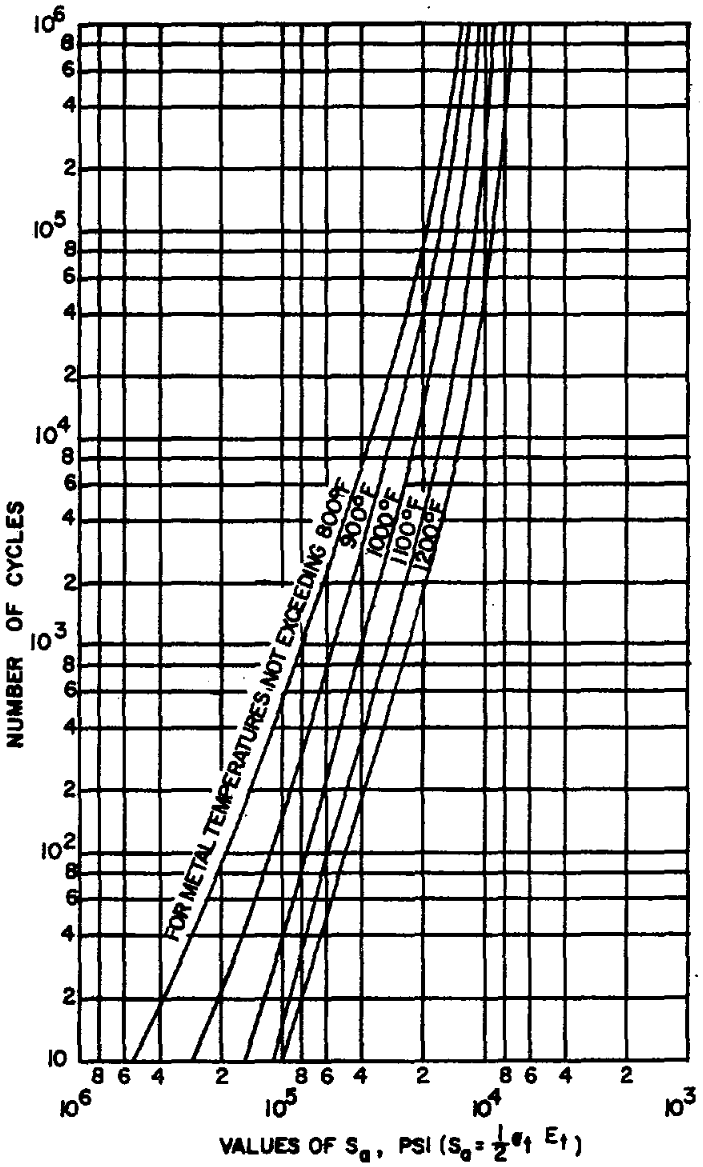


Figure 3252.2(a) Design of Fatigue Strength, S_a, for Carbon and Low-Alloy Steels Through 5%Cr up to 1100°F

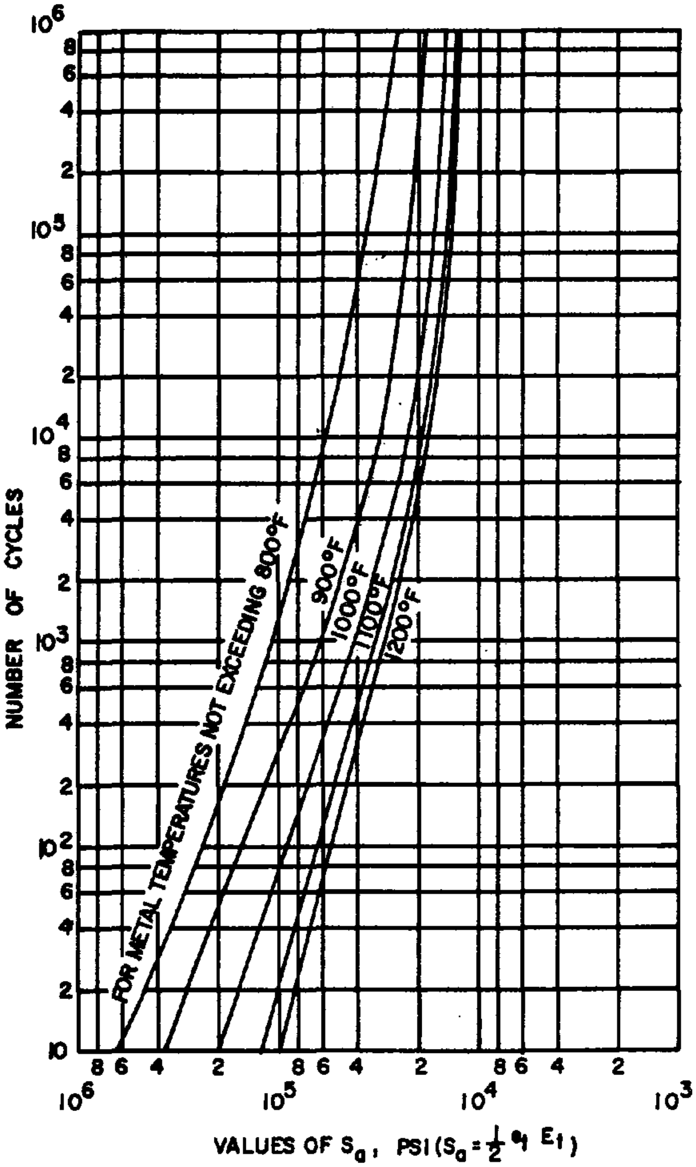


Figure 3252.2(b) Design Fatigue Strength, S_a, for High-Alloy Steels and Nickel-Chrome-Iron Alloy up to 1200°F

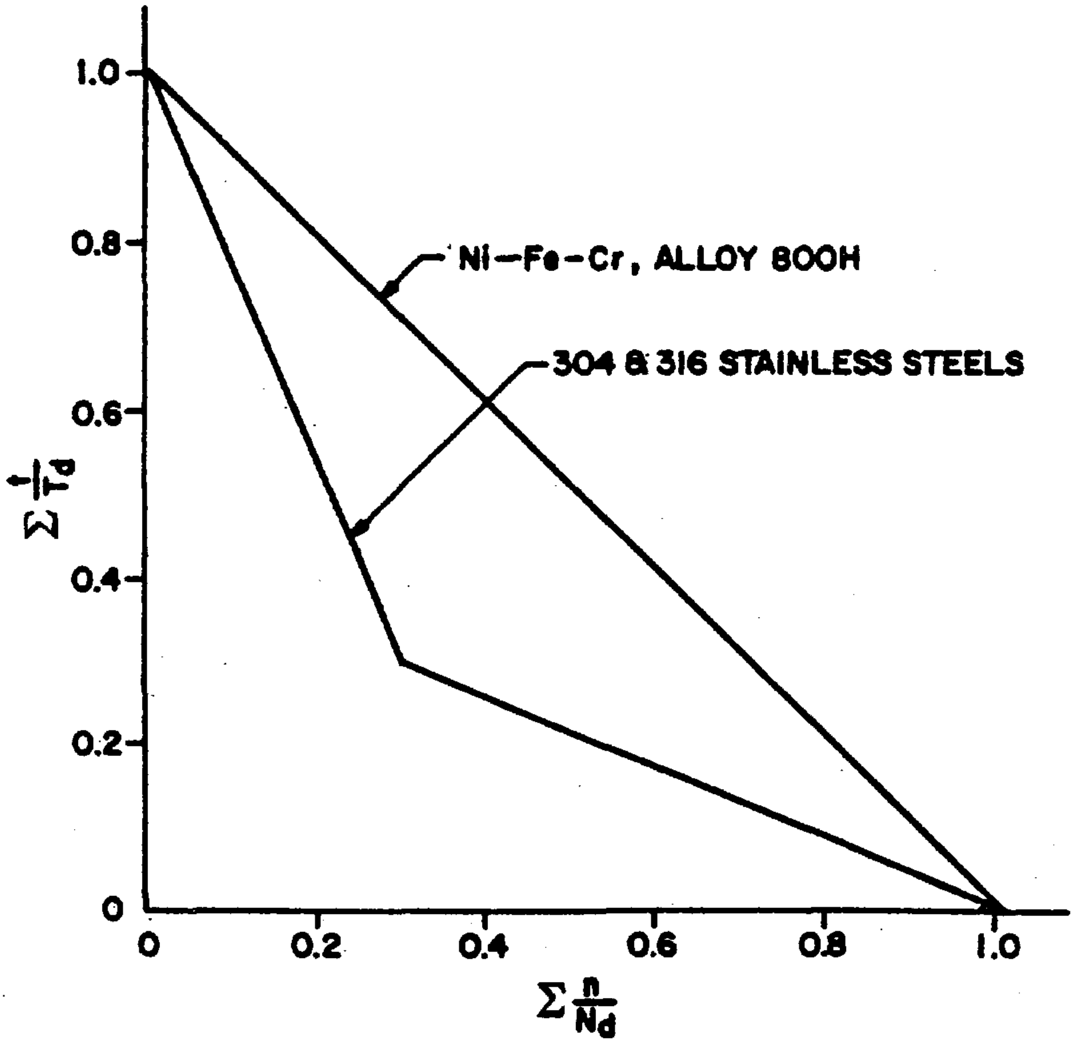


Figure 3252.3(a) Creep-Fatigue Damage Envelope

Table 3252.3(a) Design Fatigue Strain Range, ε_t, for 304SS and 316SS

N_d Number of Cycles*	ϵ_t, Strain Range (in./in.) at Temperature				
	100 F	800 F	900 F	1000-1200 F	1300 F
10^1	.0507	.0438	.0378	.0318	.0214
2×10^1	.0357	.0318	.0251	.0208	.0149
4×10^1	.026	.0233	.0181	.0148	.0105
10^2	.0177	.0159	.0123	.00974	.00711
2×10^2	.0139	.0125	.00961	.00744	.00551
4×10^2	.0110	.00956	.00761	.00574	.00431
10^3	.00818	.00716	.00571	.00424	.00328
2×10^3	.00643	.00581	.00466	.00339	.00268
4×10^3	.00518	.00476	.00381	.00279	.00226
10^4	.00403	.00376	.00301	.00221	.00186
2×10^4	.00343	.00316	.00256	.00186	.00162
4×10^4	.00293	.00273	.00221	.00161	.00144
10^5	.00245	.00226	.00182	.00136	.00121
2×10^5	.00213	.00196	.00159	.00121	.00108
4×10^5	.00188	.00173	.00139	.00109	.000954
10^6	.00163	.00151	.00118	.000963	.000834

*Cyclic strain rate : 1×10^{-3} in./in./sec.

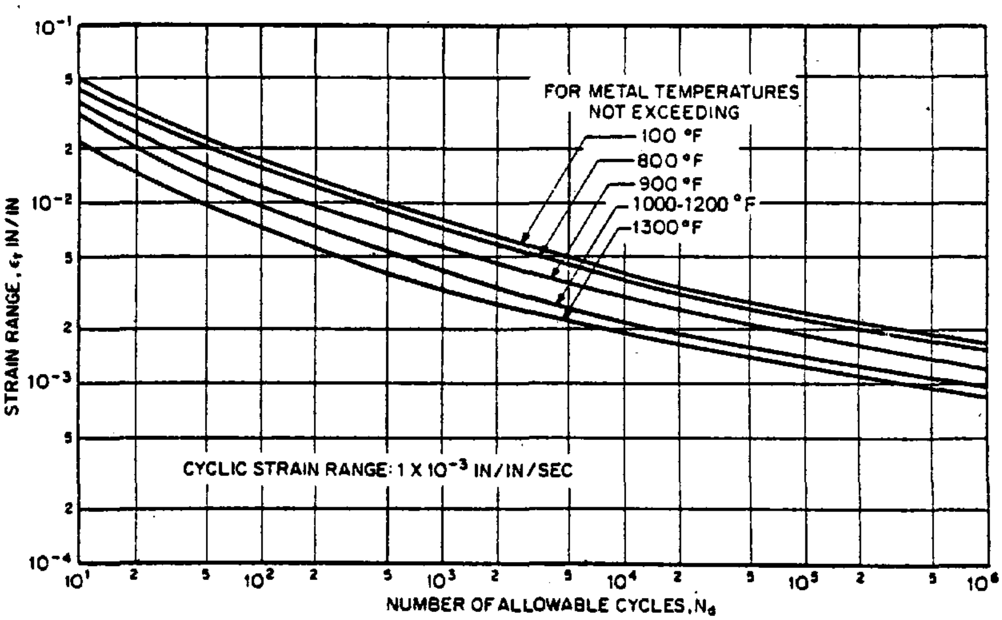
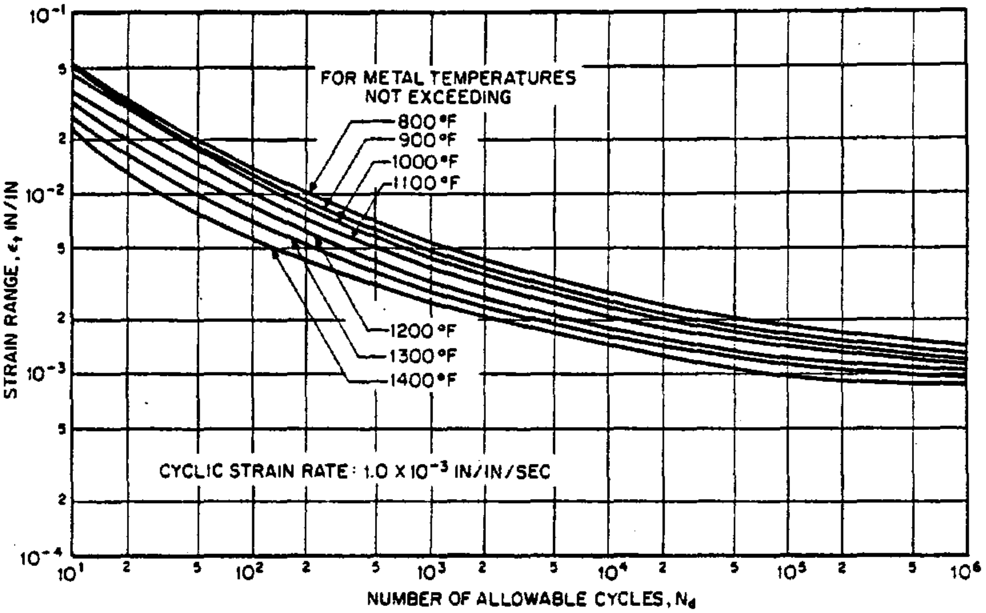


Figure 3252.3(b) Design Fatigue Strain Range, ε_t, for 304SS and 316SS

Table 3252.3(b) Design Fatigue Strain Range, ε_t, for Ni-Fe-Cr Alloy 800H



N_d Number of Cycles*	ε_t, Strain Range (in./in.) at Temperature						
	800 F	900 F	1000 F	1100 F	1200F	1300 F	1400 F
10^1	.0513	.0498	.0468	.0378	.0308	.0263	.0231
2×10^1	.0328	.0313	.0298	.0243	.0198	.0168	.0129
4×10^1	.0218	.0208	.0190	.0163	.0130	.0113	.00866
10^2	.0139	.0129	.0119	.01	.00823	.00725	.00566
2×10^2	.0103	.00939	.00861	.00722	.00603	.00535	.00426
4×10^2	.00777	.00699	.00641	.00542	.00463	.00405	.00331
10^3	.00537	.00489	.00441	.00392	.00328	.00285	.00254
2×10^3	.00427	.00379	.00351	.00312	.00261	.0023	.00209
4×10^3	.00347	.00314	.00291	.00259	.00213	.00195	.00176
10^4	.00277	.00249	.00233	.0021	.00174	.00159	.00143
2×10^4	.00242	.00219	.00201	.00182	.00155	.00142	.00125
4×10^4	.00215	.00193	.0018	.00162	.0014	.00127	.00109
10^5	.00187	.00164	.00151	.00139	.00122	.00115	.000959
2×10^5	.00169	.00149	.00141	.00128	.00113	.00105	.000919
4×10^5	.00157	.00139	.00129	.00121	.00108	.000987	.000889
10^6	.00139	.00129	.00119	.00112	.00103	.000937	.000869

*Cyclic strain rate: 1×10^{-3} in./in./sec.

Figure 3252.3(c) Design Fatigue Strain Range, ε_t, for Ni-Fe-Cr Alloy 800H then an appropriate method of combining cycles shall be applied. The equivalent strain range is computed according to one of the following procedures:

Procedure 1 - General Case

Step 1. Calculate all strain components for the strain history (ε_x, ε_y, ε_z, γ_{xy}, γ_{yz}, γ_{zx}, versus time) for the complete cycle. Stress concentration factors are added at this step.

Step 2. Select a time when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript i. In some cases it may be necessary to try different points in time to find the one which results in the largest value of equivalent strain range.

Step 3. Calculate the history of the change in strain components by subtracting the values at the time, t, from the corresponding components at each point in time during the cycle. For example:

$$\Delta\,\varepsilon_x = \varepsilon_x - \varepsilon_{xi}$$

$$\Delta\,\varepsilon_y = \varepsilon_y - \varepsilon_{yi}$$

Step 4. Calculate the equivalent strain range for each point in time.

$$\Delta\varepsilon_{\text{equiv.}} = \frac{\sqrt{2}}{3}\Big[(\Delta\varepsilon_x - \Delta\varepsilon_y)^2 + (\Delta\varepsilon_y - \Delta\varepsilon_z)^2 + (\Delta\varepsilon_z - \Delta\varepsilon_x)^2 + \frac{3}{2}\,(\Delta\gamma^2_{xy} + \Delta\gamma^2_{yz} + \Delta\gamma^2_{zx})\Big]^{1/2} \qquad (2)$$

Step 5. Use the maximum equivalent strain range calculated as the range of strain ($\varepsilon_t = \Delta\varepsilon_{\text{equivalent}}$) to enter the fatigue curves.

Procedure 2 - Applicable Only When the Principal Strains do not Rotate.

Step 1. No change from Step 1 of Procedure 1.

Step 2. Determine the principal strains versus time for the cycle.

Step 3. At each time interval of Step 2, determine the strain differences $\varepsilon_1 - \varepsilon_2$, $\varepsilon_2 - \varepsilon_3$, $\varepsilon_3 - \varepsilon_1$.

Step 4. Determine the history of the change in strain differences by subtracting the values at the time, t, from the corresponding values at each point in time during the cycle. Designate these strain difference changes as

$$\Delta(\varepsilon_1-\varepsilon_2) = \varepsilon_{12}-\varepsilon_{12_i}$$

$$\Delta(\varepsilon_2-\varepsilon_3) = \varepsilon_{23}-\varepsilon_{23_i}$$

$$\Delta(\varepsilon_3-\varepsilon_1) = \varepsilon_{31}-\varepsilon_{31_i}$$

Step 5. Compute the equivalent strain range as:

$$\Delta\varepsilon_{\text{equiv.}} = \frac{\sqrt{2}}{3}\left\{[\Delta(\varepsilon_1-\varepsilon_2)]^2 + [\Delta(\varepsilon_2-\varepsilon_3)]^2 + [\Delta(\varepsilon_3-\varepsilon_1)]^2\right\}^{1/2} \quad (3)$$

Step 6. Use the maximum equivalent strain range calculated as the range of strain ($\varepsilon_t = \Delta\varepsilon_{\text{equivalent}}$) to enter the fatigue curves.

(c) Creep-Damage Calculation - For Type 304 and 316 stainless steels creep damage calculations may be done by the following procedure; elastic or inelastic analysis may be used.

Step 1. Inelastic Analysis - Calculate the maximum tensile principal stress for each loading condition k. To account for creep effects isochronous creep curves given in Appendix T or applicable creep formulae may be used. Elastic Analysis - Calculate the following stress quantities:

(1) 1.25 $S_{y\ k}$, where $S_{y\ k}$ is the average of the expected minimum yield strengths at the maximum and minimum wall-averaged temperatures of the load condition.

(2) The largest principal tensile component of the primary-plus-secondary stresses (defined in Appendix A) during the sustained portions of the loading cycle.

Determine the smaller of the above quantities.

Step 2. Enter the stress from Step 1 into the stress-to-rupture curves in Figure -3252.3(d) through (h) and Tables -3252(c) through (g) and determine the corresponding value of allowable time, T_d.

For materials other than Type 304 and 316 stainless steel, the principal tensile stress should be replaced by 'effective stress' or 'stress intensity' unless it can be shown by consistent experimental data that principal tensile stress governs creep rupture.

(d) Creep-rupture damage in Equation (1) may also be calculated by using the integral form

$$\text{Creep damage} \quad {}_0\!\int^t \frac{1}{T_d}\,dt$$

Table 3252.3(c) Expected Minimum Stress-to-Rupture Values for Type 304SS, 1000 psi

Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	57	57	57	57	57	57	57	57	51	44.3	39
850	56.5	56.5	56.5	56.5	56.5	56.5	50.2	45.4	40	34.7	30.5
900	55.5	55.5	55.5	55.5	51.5	46.9	41.2	36.1	31.5	27.2	24
950	54.2	54.2	51	48.1	43	38.0	33.5	28.8	24.9	21.2	18.3
1000	52.5	50	44.5	39.8	35	30.9	26.5	22.9	19.7	16.6	14.0
1050	50	41.9	37	32.9	28.9	25.0	21.6	18.2	15.5	13.0	11.0
1100	45	35.2	31	27.2	23.9	20.3	17.3	14.5	12.3	10.2	8.6
1150	38	29.5	26	22.5	19.3	16.5	13.9	11.6	9.6	8.0	6.6
1200	32	24.7	21.5	18.6	15.9	13.4	11.1	9.2	7.6	6.2	5.0
1250	27	20.7	17.9	15.4	13	10.8	8.9	7.3	6.0	4.9	4.0
1300	23	17.4	15	12.7	10.5	8.8	7.2	5.8	4.8	3.8	3.1
1350	19.5	14.6	12.6	10.6	8.8	7.2	5.8	4.6	3.8	3.0	2.4
1400	16.5	12.1	10.3	8.8	7.2	5.8	4.7	3.7	3.0	2.3	1.9
1450	14.0	10.2	8.8	7.3	5.8	4.6	3.8	2.9	2.3	1.8	1.4
1500	12.0	8.6	7.2	6.0	4.9	3.8	3.0	2.4	1.8	1.4	1.1

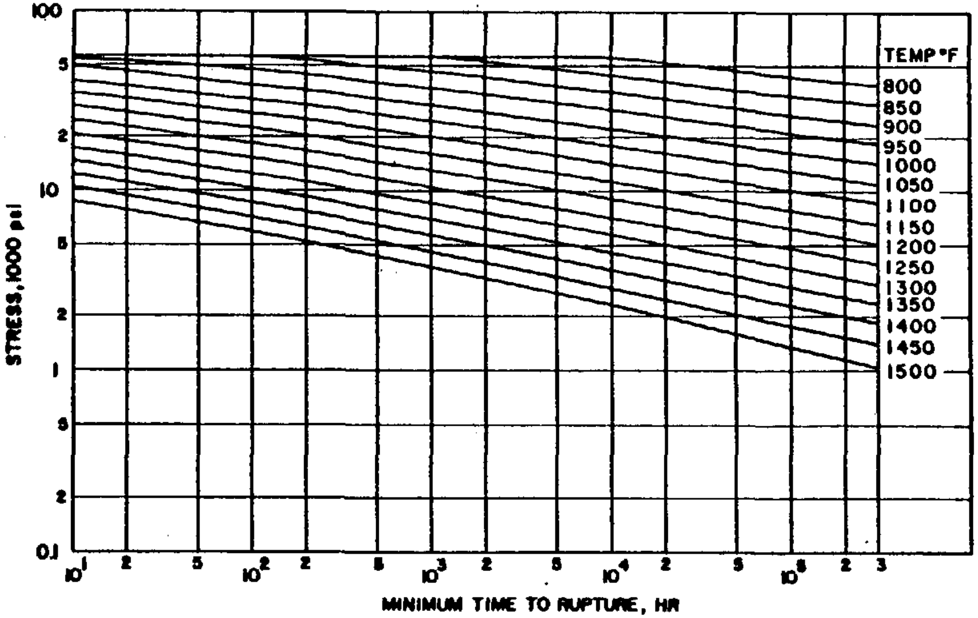


Figure 3252.3(d) Stress-to-Rupture (Minimum)

Table 3252.3(d) Expected Minimum Stress-to-Rupture Values for Type 316SS, 1000 psi

Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
850	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	60	56	52
900	62.2	62.2	62.2	62.2	62.1	62	58	54.1	48	42.6	38
950	60	60	60	60	56	51.6	46.5	42.6	37.5	32.4	28.3
1000	58.5	58.5	55	51.7	47	42.1	37.5	33.6	28.8	24.6	21
1050	56	52.9	47.5	43.4	38.2	34.4	30.2	26.4	22.3	18.8	16
1100	53.5	45.1	40	36.4	32.2	28.1	24.2	20.8	17.3	14.3	11.7
1150	46.5	38.4	34	30.5	26.6	23.0	19.5	16.4	13.4	10.9	8.8
1200	40	32.7	29	25.6	22	18.8	15.6	12.9	10.3	8.3	6.7
1250	35	27.8	24.3	21.4	18.1	15.4	12.7	10.2	8.1	6.3	4.9
1300	30	23.7	20.8	18.0	15	12.5	10.0	8.0	6.2	4.8	3.7
1350	26	20.0	17.5	15.0	12.7	10.4	8.2	6.4	4.9	3.6	2.7
1400	22.5	17.1	14.8	12.4	10.2	8.4	6.6	5.0	3.8	2.8	2.1
1450	19.5	14.6	12.6	10.5	8.6	6.8	5.2	3.9	2.9	2.1	1.5
1500	17	12.5	10.6	8.8	7.2	5.6	4.2	3.1	2.3	1.6	1.2

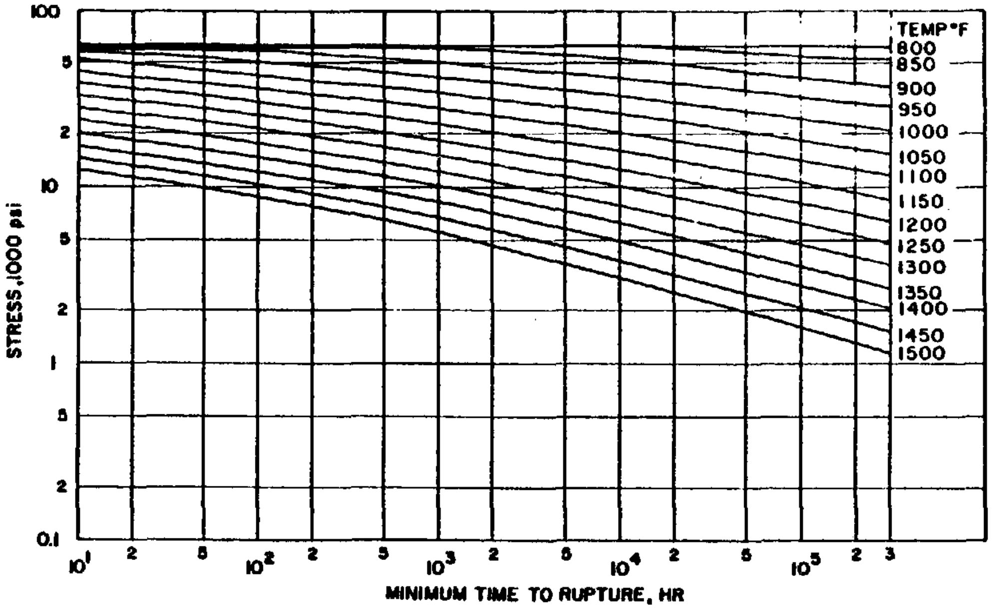


Figure 3252.3(e) Stress-to-Rupture (Minimum)

Table 3252.3(e) Ni-Fe-Cr (Alloy 800H), Expected Minimum Stress-to-Rupture Values, ksi

Temp., °F	1 hr	3 hr	10 hr	30 hr	100 hr	300 hr	1000 hr	3000 hr	10000 hr	30000 hr	100000 hr	300000 hr
800	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.0	55.0
850	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	57.5	53.5	49.3	45.6
900	60.7	60.7	60.7	60.7	60.7	60.7	57.9	53.8	49.4	45.5	41.5	38.0
950	60.7	60.7	60.7	60.7	59.0	54.7	50.1	46.1	41.9	38.2	34.4	31.2
1000	60.7	60.7	60.7	56.3	51.5	47.2	42.8	39.0	35.0	31.6	28.2	25.4
1050	60.7	58.5	53.5	49.0	44.3	40.3	36.1	32.6	29.0	25.9	22.9	20.4
1100	56.1	51.4	46.5	42.2	37.8	34.0	30.1	26.9	23.7	21.1	18.4	16.3
1150	49.3	44.7	40.0	36.0	31.8	28.4	24.9	22.1	19.3	17.0	14.7	12.9
1200	42.9	38.5	34.1	30.3	26.6	23.5	20.5	18.0	15.5	13.6	11.7	10.2
1250	37.0	32.9	28.8	25.4	22.1	19.3	16.7	14.5	12.5	10.9	9.3	8.1
1300	31.6	27.8	24.1	21.0	18.2	15.8	13.5	11.7	10.0	8.6	7.4	6.4
1350	26.8	23.4	20.1	17.5	14.9	12.9	10.9	9.4	8.0	6.9	5.8	5.0
1400	22.6	19.6	16.7	14.4	12.2	10.4	8.8	7.5	6.4	5.5	4.6	4.0

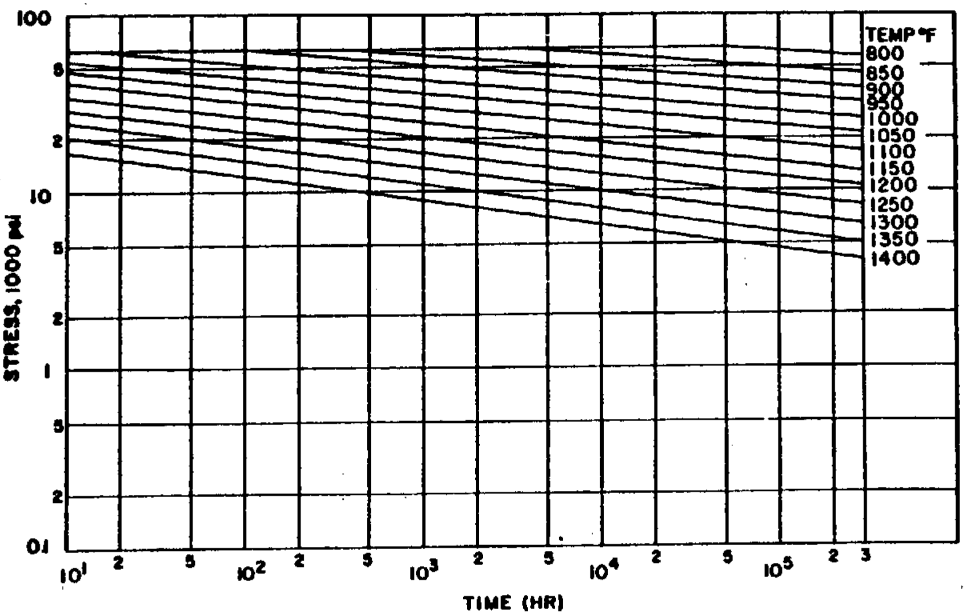


Figure 3252.3(f) Stress-to-Rupture (Minimum)--Ni-Fe-Cr (Alloy 800H)

Table 3252.3(f) 2-1/4%Cr-1%Mo--Expected Minimum Stress-to-Rupture Values, ksi

Temp., °F	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
700	59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0	54.0	49.0
750	58.0	57.0	56.0	54.6	53.0	51.2	48.0	43.3	37.5	34.1
800	56.0	55.5	54.0	48.5	43.0	37.5	34.5	30.5	27.0	24.0
850	52.0	50.5	46.0	40.5	35.0	31.0	27.5	24.0	21.0	18.5
900	46.0	41.0	36.0	32.0	28.0	25.0	21.6	19.0	16.4	14.1
950	40.0	35.0	30.0	26.0	22.2	19.5	17.0	14.6	12.6	11.0
1000	31.5	27.5	24.0	21.0	17.9	15.2	13.1	11.0	9.4	7.9
1050	26.0	22.5	19.0	16.5	14.0	12.0	10.0	8.3	7.0	5.8
1100	21.0	18.0	15.1	13.0	10.8	9.1	7.5	6.2	5.0	4.1
1150	17.0	14.1	11.8	9.8	8.0	6.7	5.4	4.4	3.5	2.8
1200	13.5	11.1	9.2	7.6	6.2	5.0	4.0	3.2	2.5	2.0

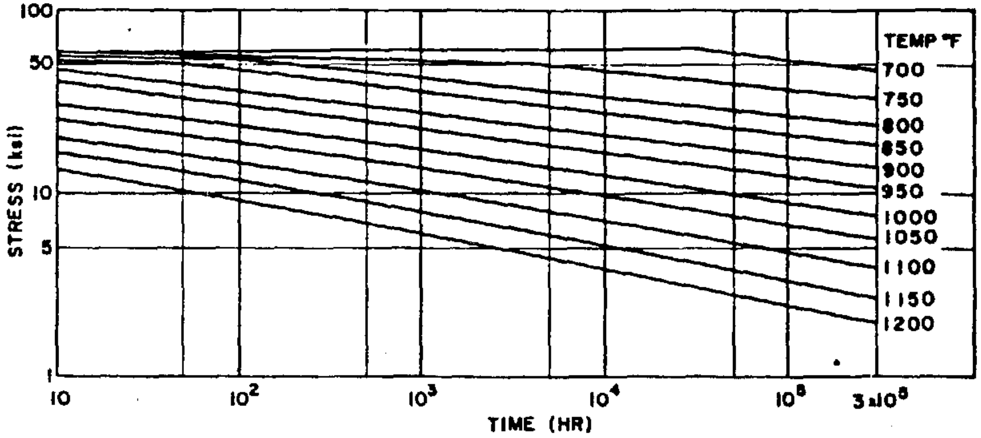


Figure 3252.3(g) 2-1/4%Cr-1%Mo--100 Percent of the Minimum Stress-to-Rupture

Table 3252.3(g) Ni-Cr-Fe-Cb (Alloy 718) Expected Minimum Stress-to-Rupture Values, ksi

Temp., °F	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	–	–	–	–	–	–	–	–	–	–
850	–	–	–	–	–	–	159	151	146	140
900	–	–	–	–	158	151	144	138	130	124
950	–	–	158	150	144	136	129	122	114	106
1000	–	150	144	136	130	122	114	106	98	90
1050	146	138	130	124	114	106	98	91	81	74

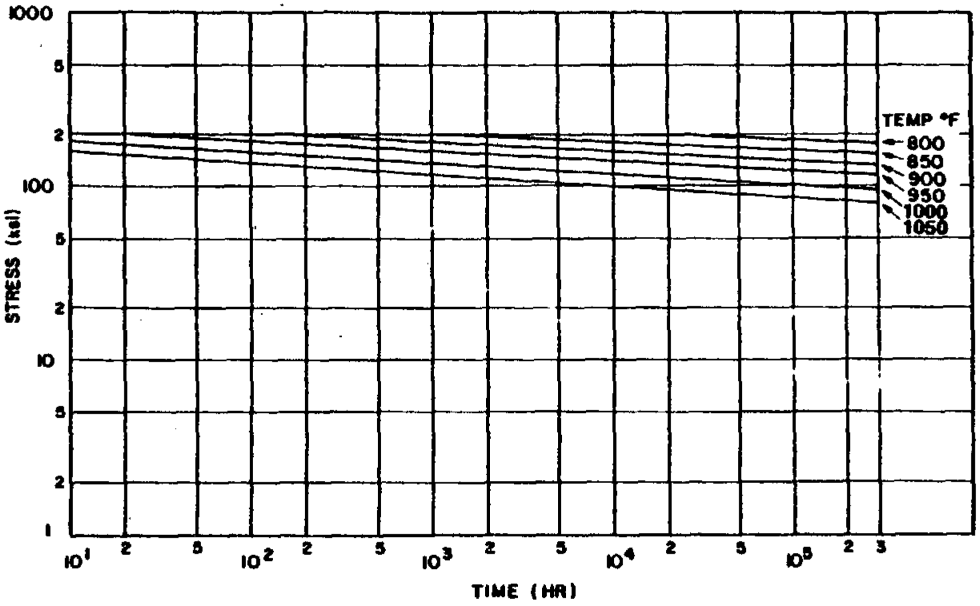


Figure 3252.3(h) Stress-to-Rupture (Minimum) Ni-Cr-Fe-Cb (Alloy 718), ksi

-3260 BUCKLING INSTABILITY LOADS

-3261 GENERAL REQUIREMENTS

(a) Scope of Rules - The stability limits in Section VIII-Division 1 and 2 pertain only to specific geometrical configurations under specific loading conditions. These limits include the effects of initial geometrical imperfections permitted by fabrication tolerances. The rules in Paragraphs -3131, and -3132 provide additional limits which are applicable to general configurations and loading conditions that may cause buckling or instability.

(b) Load-Controlled and Strain-Controlled Buckling - For the limits specified in -3262.2, distinction is made between load-controlled buckling and strain-controlled buckling. Load-controlled buckling is characterized by continued application of an applied load in the post-buckling regime leading to failure, as exemplified by collapse of a tube under external pressure. Strain-controlled buckling is characterized by the immediate reduction of load due to strain-induced deformations. Even though it is self-limiting, strain-controlled buckling should be avoided to guard against failure by fatigue, excessive strain, loss of function due to excessive deformation, and interaction with load-controlled buckling.

(c) Interaction of Load-Controlled and Strain-Controlled Buckling - For conditions under which strain-controlled and load-controlled buckling may interact, as exemplified by elastic follow-up, the higher load factors applicable to load-controlled buckling shall be used for the combination of load-controlled and strain-controlled loadings.

(d) Effect of Initial Geometry Imperfections - For load-controlled buckling, the effects of initial geometrical imperfections and tolerances shall be considered in the time-independent calculations according to the requirements of Paragraph -3262.2. In calculating the instability strain under pure strain-controlled buckling, the effects of geometrical imperfections and tolerances, whether initially present or induced by service, need not be considered.

(e) Strain-Controlled Buckling - The evaluation of strain-controlled buckling is not mandatory. However, the strain-controlled buckling limits provided in -3262.2 may be used if such evaluation is deemed necessary.

(f) Creep Buckling - The evaluation of time-dependent buckling is not mandatory.

-3262 BUCKLING LIMITS (Time-Independent)

-3262.1 Buckling limits of Section VIII-Division 1 or Division 2 shall apply. These rules provide buckling charts which are applicable to limited geometrical configurations under specific loading conditions. For general configurations and loading conditions, and for materials and temperatures for which limits of Section VIII-Divisions 1 or 2 do not apply, the limits of -3132.2 shall be used.

-3262.2 For load-controlled buckling, the load factor, and for strain-controlled buckling, the strain factor, shall equal or exceed the values given in Table -3262-1.

Table -3262-1 Buckling Limits

Loads	Load Factor[1]	Strain Factor[1,3]
Design	3.0[2]	1.67
Testing[4]	2.25	1.67

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[1] Load (Strain) = [Load (strain) which would cause instant instability at the design or actual service temperature] ÷ [Design or expected load (strain).]

[2] Changes in configuration induced by service need not be considered in calculating the buckling load.

[3] For thermally-induced strain-controlled buckling, the strain factor is applied to loads induced by thermal strain. To determine the buckling strain, it may be necessary to artificially induce high strains concurrent with the use of realistic stiffness properties. The use of an "adjusted" thermal expansion coefficient is one technique for enhancing the applied strains without affecting the associated stiffness characteristics.

[4] These factors apply to hydrostatic, pneumatic, and leak tests.

-3300 DESIGN RULES (Piping)

-3310 GENERAL

(a) The design of the piping components shall conform to the requirements of ANSI B31.1, Power Piping Code.

(b) For the piping components outside the jurisdiction of ANSI B31.1, the requirements of ANSI B31.3 shall apply.

Appendix A

DEFINITIONS

A-1 TERMS RELATING TO STRESS ANALYSIS

A-1.1 Stress Intensity is the equivalent intensity of combined stress, i.e., the stress intensity is defined as twice the maximum shear stress. In other words, the stress intensity is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. Tensile stresses are considered positive and compressive stresses are considered negative.

A-1.2 Primary Stress is any normal stress or a shear stress developed by an imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary-membrane stress is divided into general and local categories. A general primary-membrane stress is one which is so distributed in the structure that no redistribution of stress occurs as a result of yielding. Examples of primary stresses are:

(a) General membrane stress in a circular, cylindrical or a spherical shell due to internal pressure or to distributed live loads;

(b) Bending stress in the central portion of a flat head due to pressure;

(c) Net cross section load forces (normal or shear) arising from thermal expansion of structural material.

A-1.3 Secondary Stress is a normal or shear stress developed by the constraint of adjacent material or by self-constraint of the structure and thus it is normally associated with a deformation-controlled quantity at elevated temperatures. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions which cause the stress to occur and failure from one application of the stress is not expected. Examples of secondary stresses are:

(a) Bending stress at a gross structural discontinuity (see A-1.6).

(b) Bending stress in piping where loads cannot cause excessive creep deformation (e.g., buckling or dimpling) in a local region.

(c) Bending stress due to a linear radical thermal strain (αT) profile through the thickness of a section.

(d) Bending stress due to an equivalent linear thermal strain profile for the actual (nonlinear) strain profile. The equivalence is based on having the linear profile exert the same net bending moment as that from the actual profile.

(e) Stress produced by the temperature difference between a nozzle and the shell to which it is attached.

(f) Stress produced by the temperature difference between a nozzle and the shell to which it is attached.

A-1.4 Peak Stress is that increment of stress which is additive to the primary-plus-secondary stresses by reason of local discontinuities or local thermal stress including the effects (if any) of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or brittle fracture, and, at elevated temperatures, as a possible source of localized rupture or creep-fatigue failure. A stress which is not highly localized falls into this category if it is of a type which cannot cause noticeable distortion. Examples of peak stresses are:

(a) The thermal stress in the austenitic steel cladding of a carbon steel component

(b) Certain thermal stresses which may cause fatigue but not distortion

(c) The stress at a local structural discontinuity

(d) Surface stresses produced by thermal shock.

A-1.5 Local Structural Discontinuity is a geometric or material discontinuity which affects the stress or strain distribution through a fractional part of the wall thickness. The stress distribution associated with a local discontinuity causes only very localized types of deformation or strain and has no significant effect on the shell-type discontinuity deformation. Examples are small fillet radii, small attachments, and partial penetration welds.

A-1.6 Gross Structural Discontinuity is a geometric or material discontinuity which affects the stress or strain distribution through the entire wall thickness of the pressure-retaining member. Gross-discontinuity-type stresses are those portions of the actual stress distributions which produce net bending and membrane force resultants when integrated through the wall thickness. Examples of gross structural discontinuities are head-to-shell and flange-to-shell junctions, nozzles, and junctions between shells of different diameters or thicknesses.

A-1.7 Thermal Stress is a self-balancing stress produced by a nonuniform distribution of temperature or by differing thermal coefficients of expansion. Thermal stress is developed in a solid body whenever a volume of material is prevented from assuming the size and shape that it normally should after a change in temperature. For the purpose of establishing allowable stresses, two types of thermal stress are recognized, depending on the volume or area in which distortion takes place, as described in the following subparagraphs.

(a) General thermal stress is associated with distortion of the structure in which it occurs.

(b) Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as peak stresses. Examples of local thermal stresses are:

(1) The stress in a small hot spot in a vessel wall

(2) The difference between the actual stress and the equivalent linear stress resulting from a radial temperature distribution in a cylindrical shell

(3) The thermal stress in a cladding material which has a coefficient of expansion different from that of the base metal.

A-2 Elevated Temperature Service is that service where metal temperatures exceed those for which allowable stress values are given by Section VIII-Division 2 of the ASME Boiler and Pressure Vessel Code.

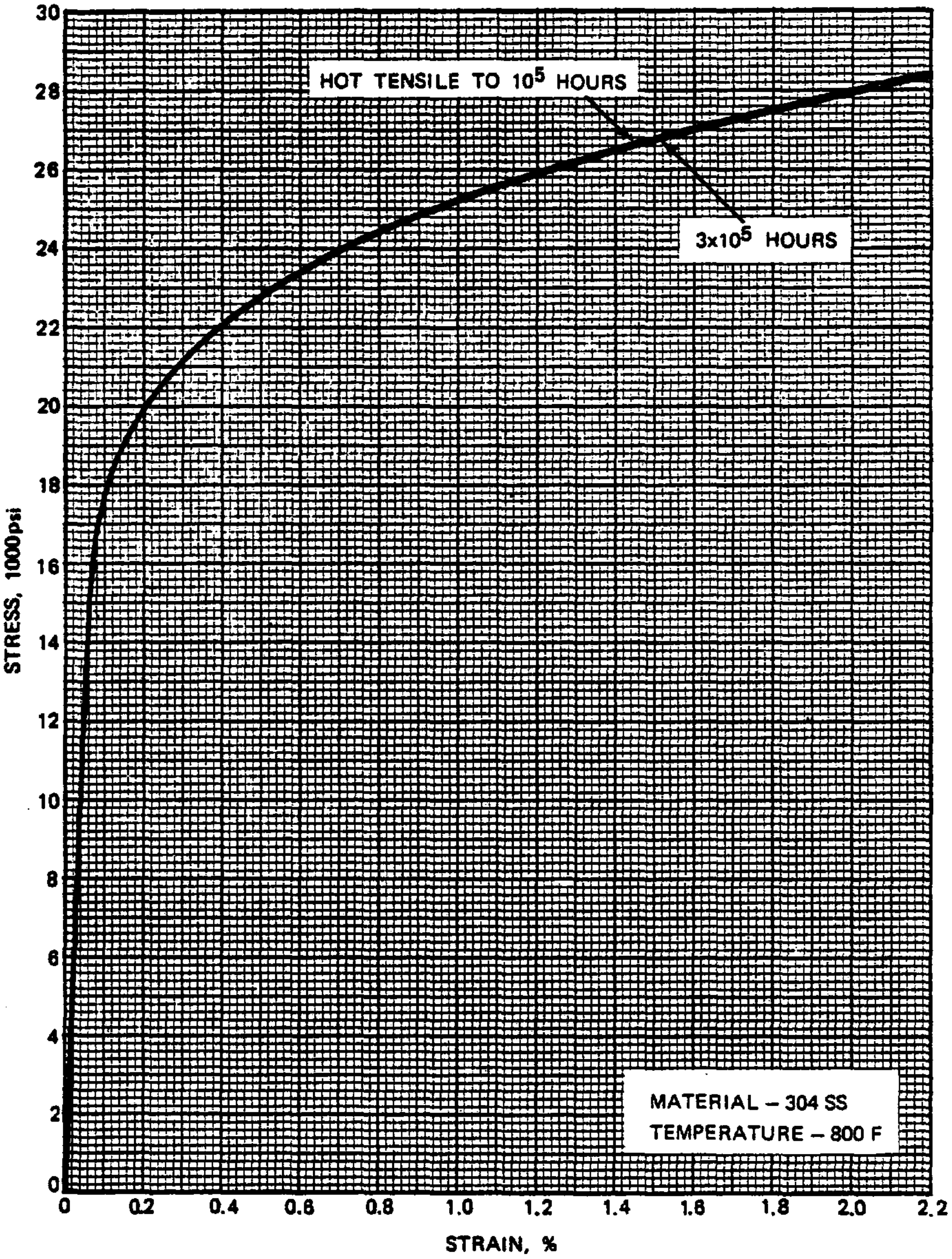

Fig. T–1800-A-1 Average isochronous stress-strain curves

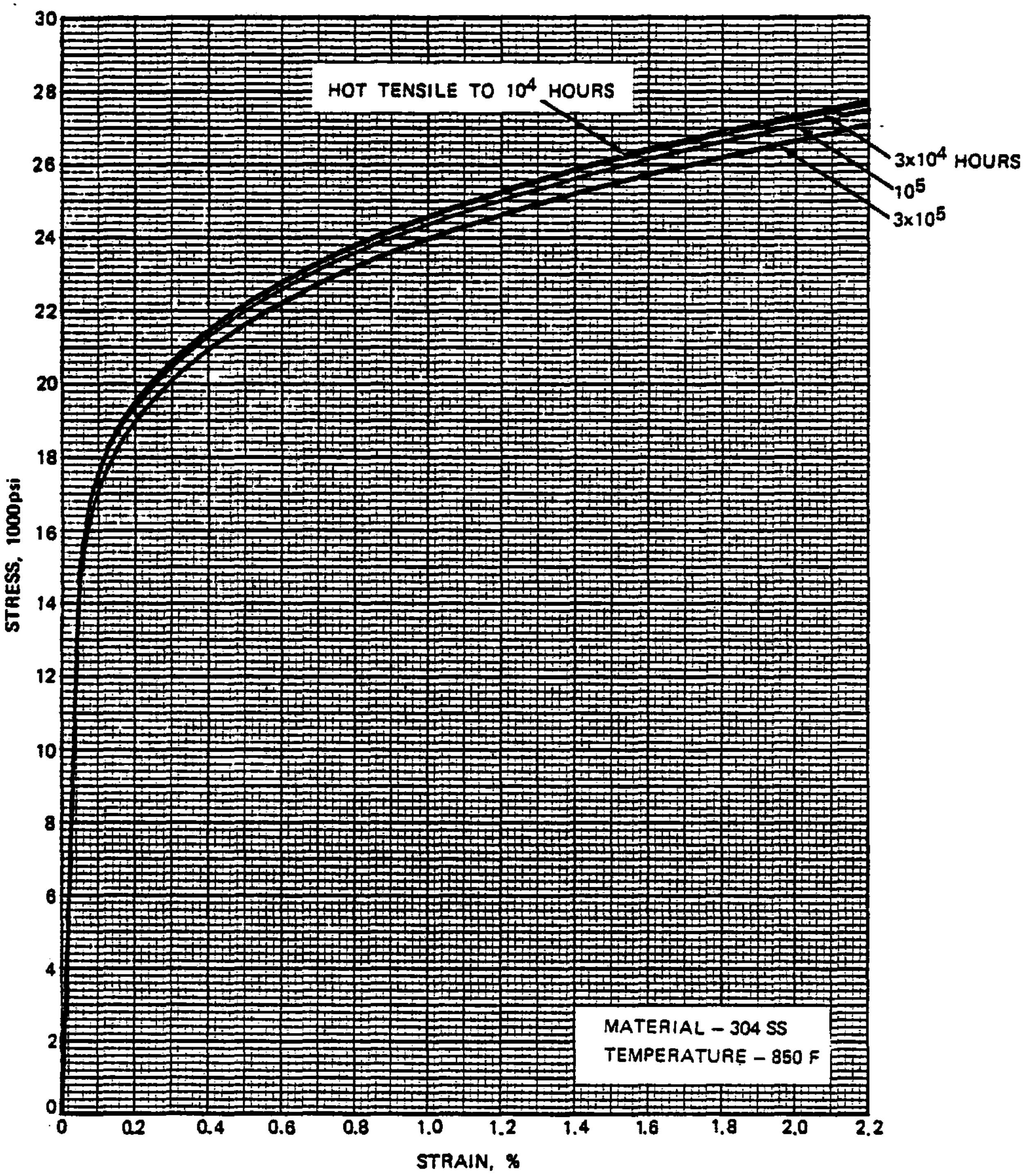

Fig. T–1800-A-2 Average isochronous stress-strain curve

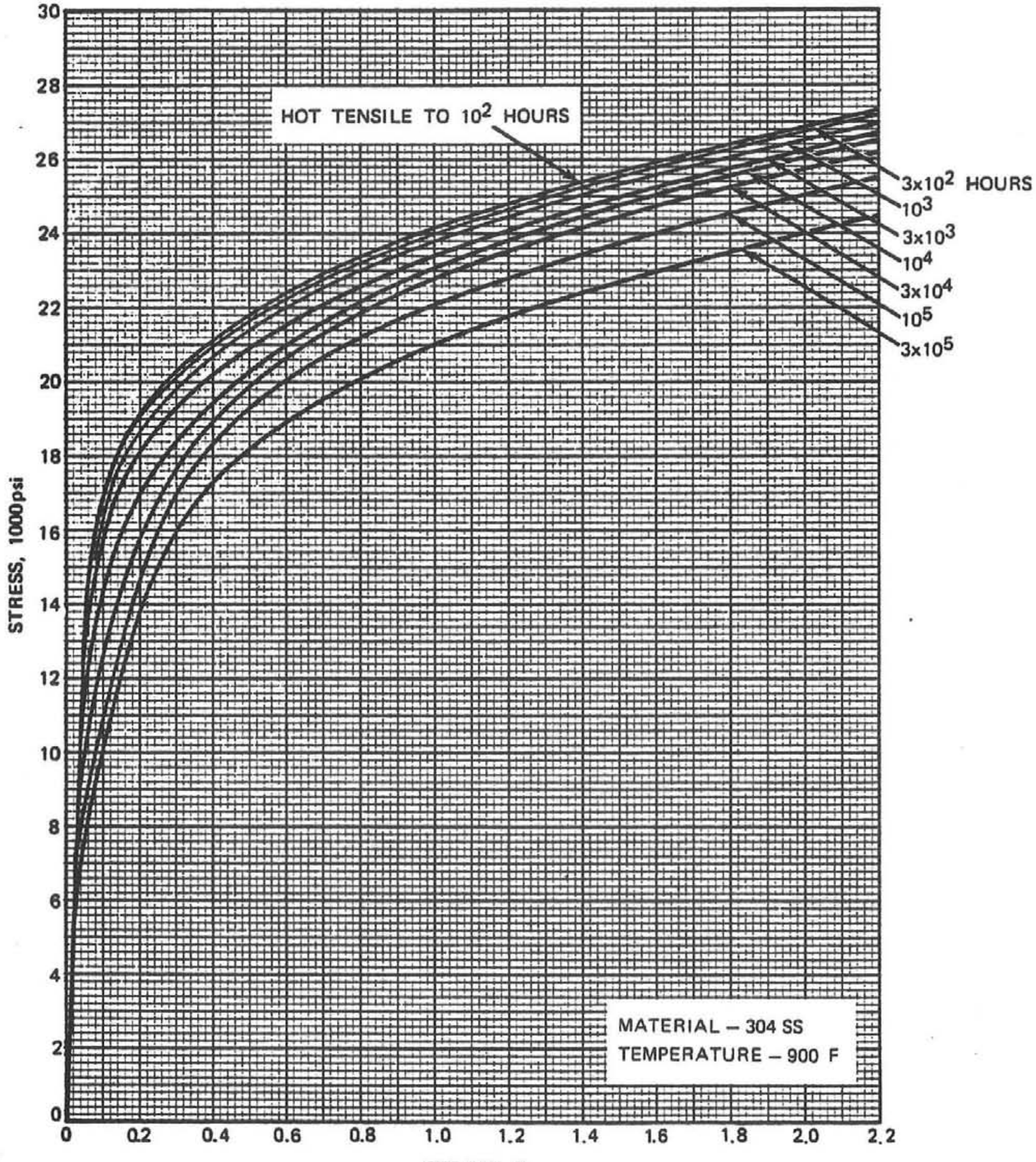

Fig. T–1800-A-3 Average isochronous stress-strain curves

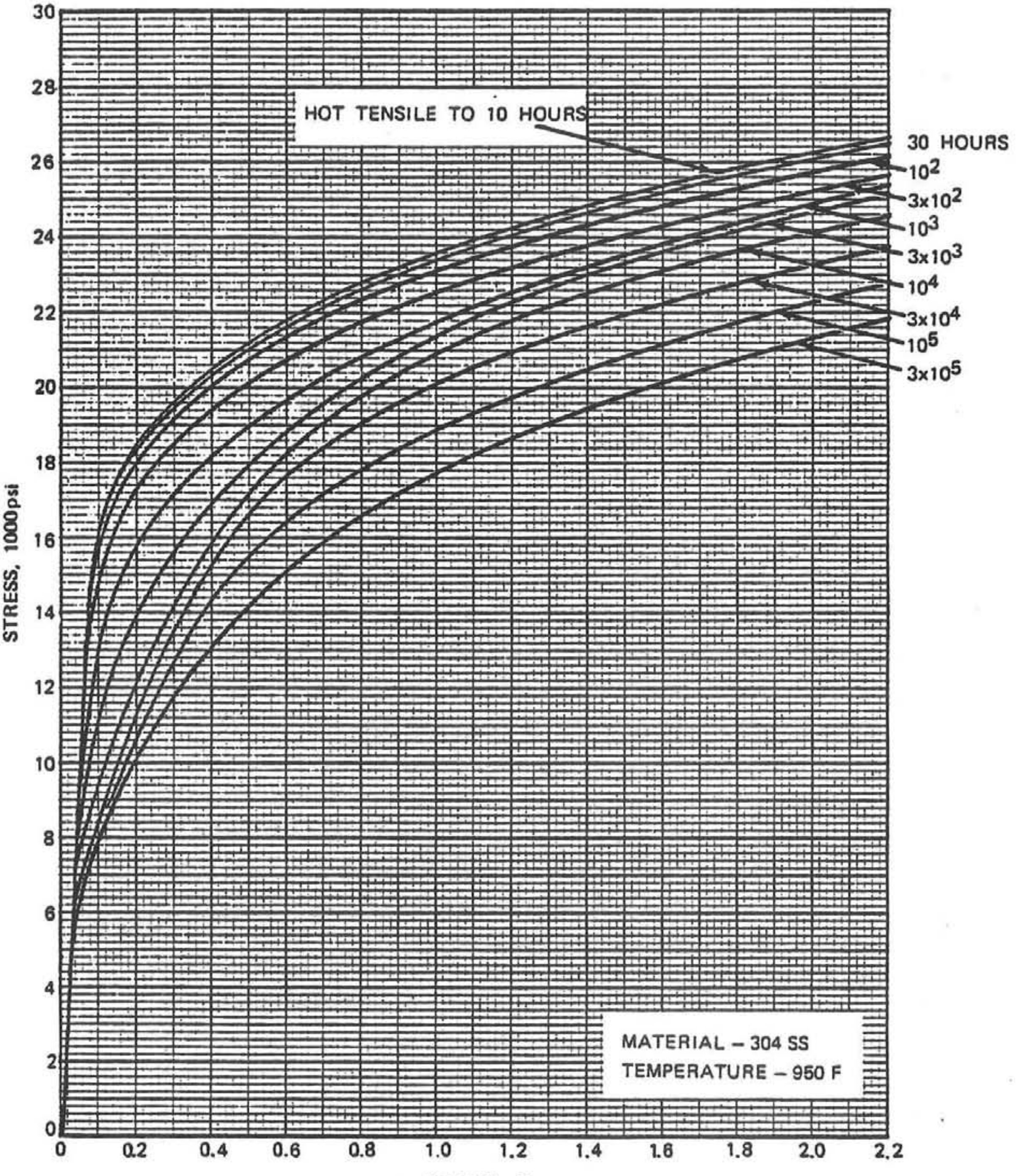

Fig. T–1800-A-4 Average isochronous stress-strain curves

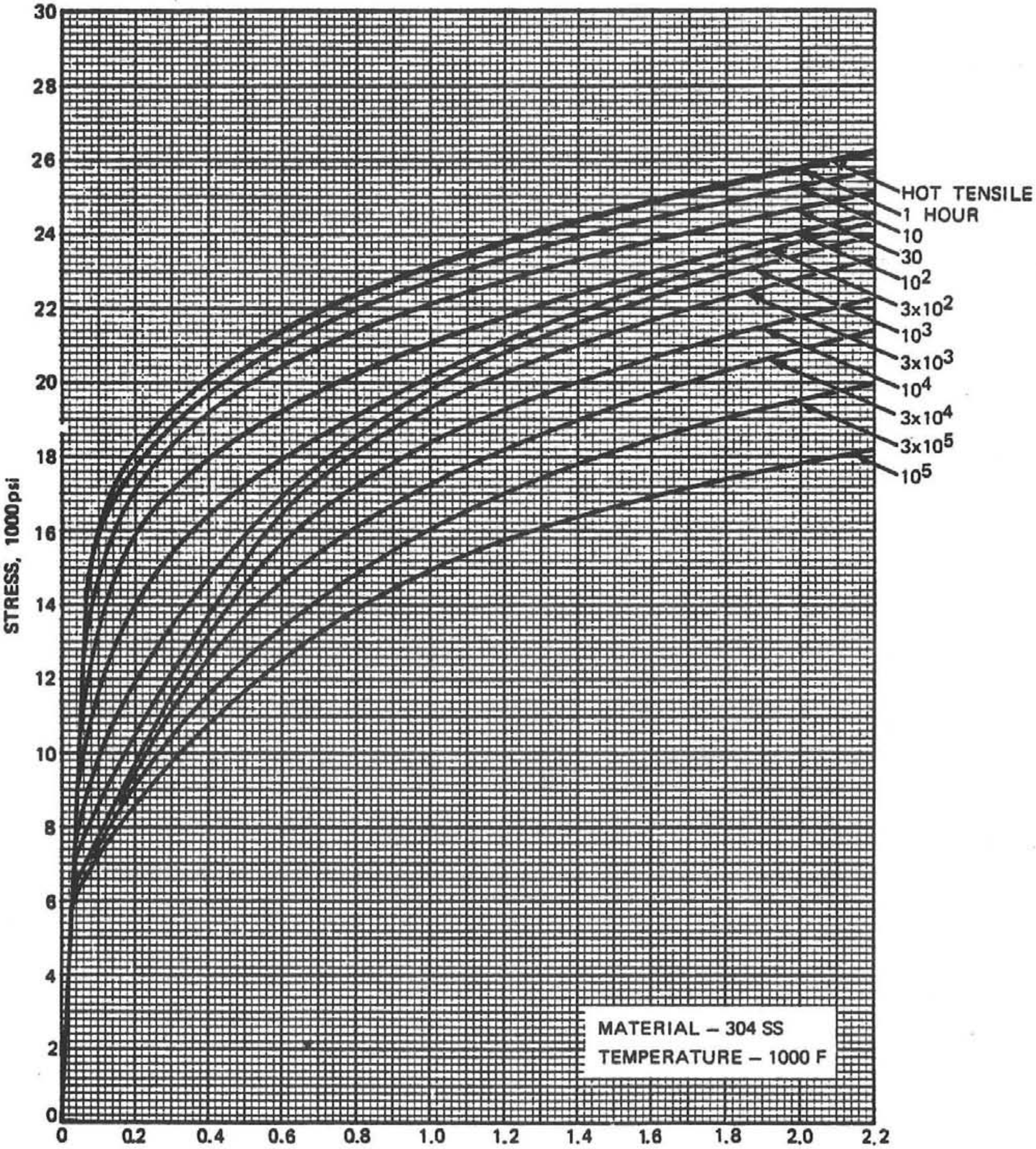

Fig. T–1800-A-5 Average isochronous stress-strain curve

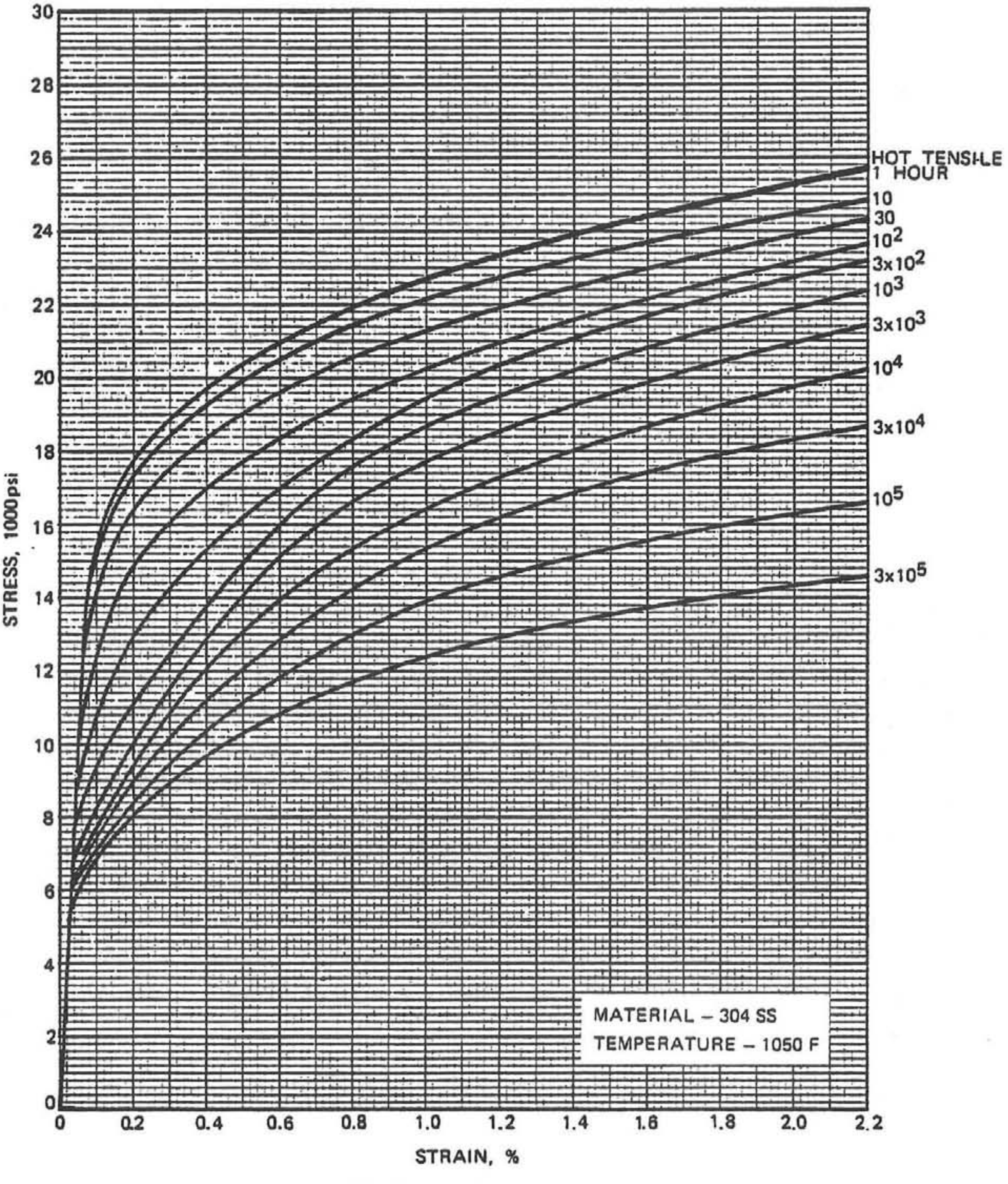

Fig. T–1800-A-6 Average isochronous stress-strain curves

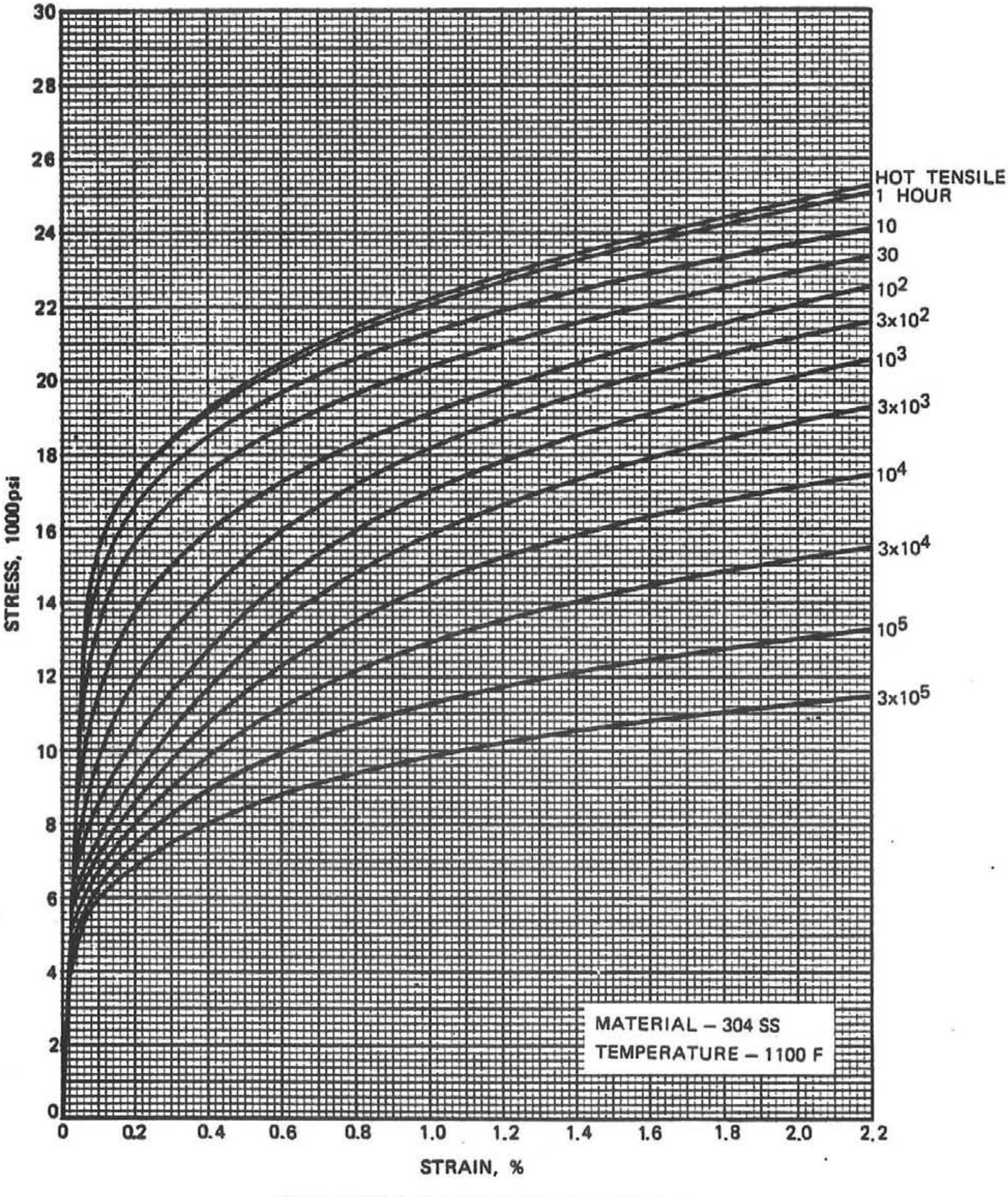

Fig. T–1800-A-7 Average isochronous stress-strain curve

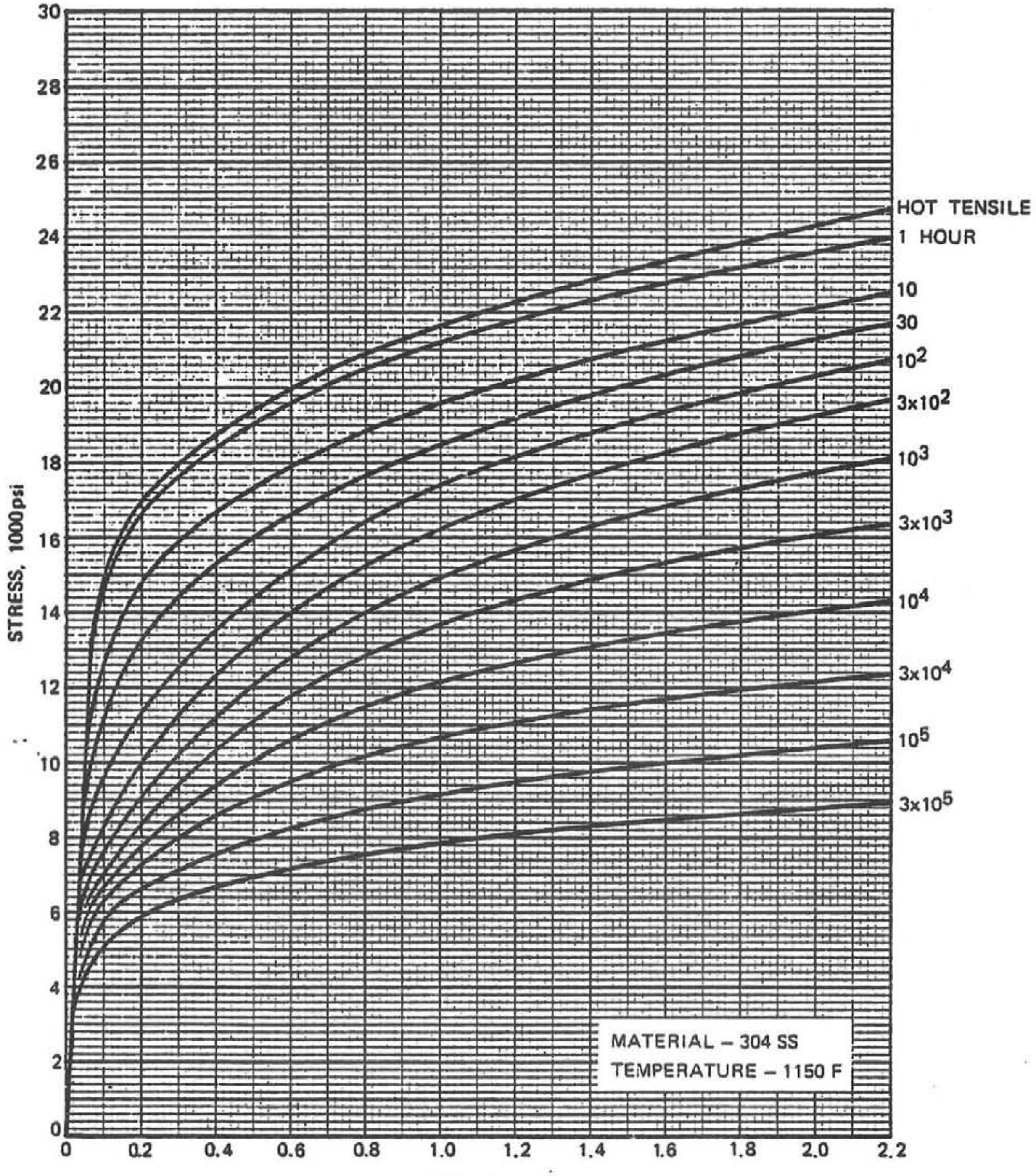

Fig. T–1800-A-8 Average isochronous stress-strain curve

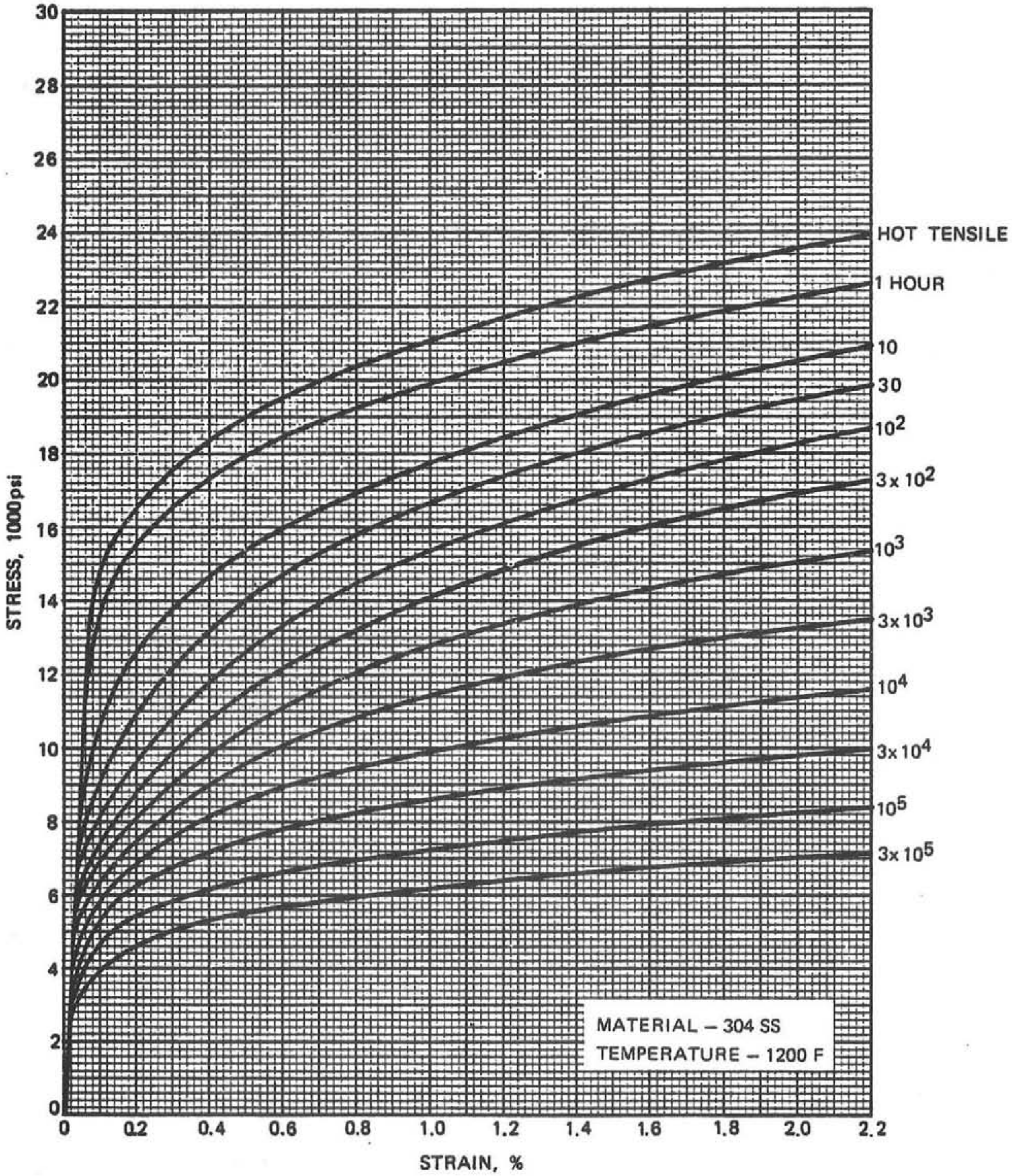

Fig. T–1800-A-9 Average isochronous stress-strain curve

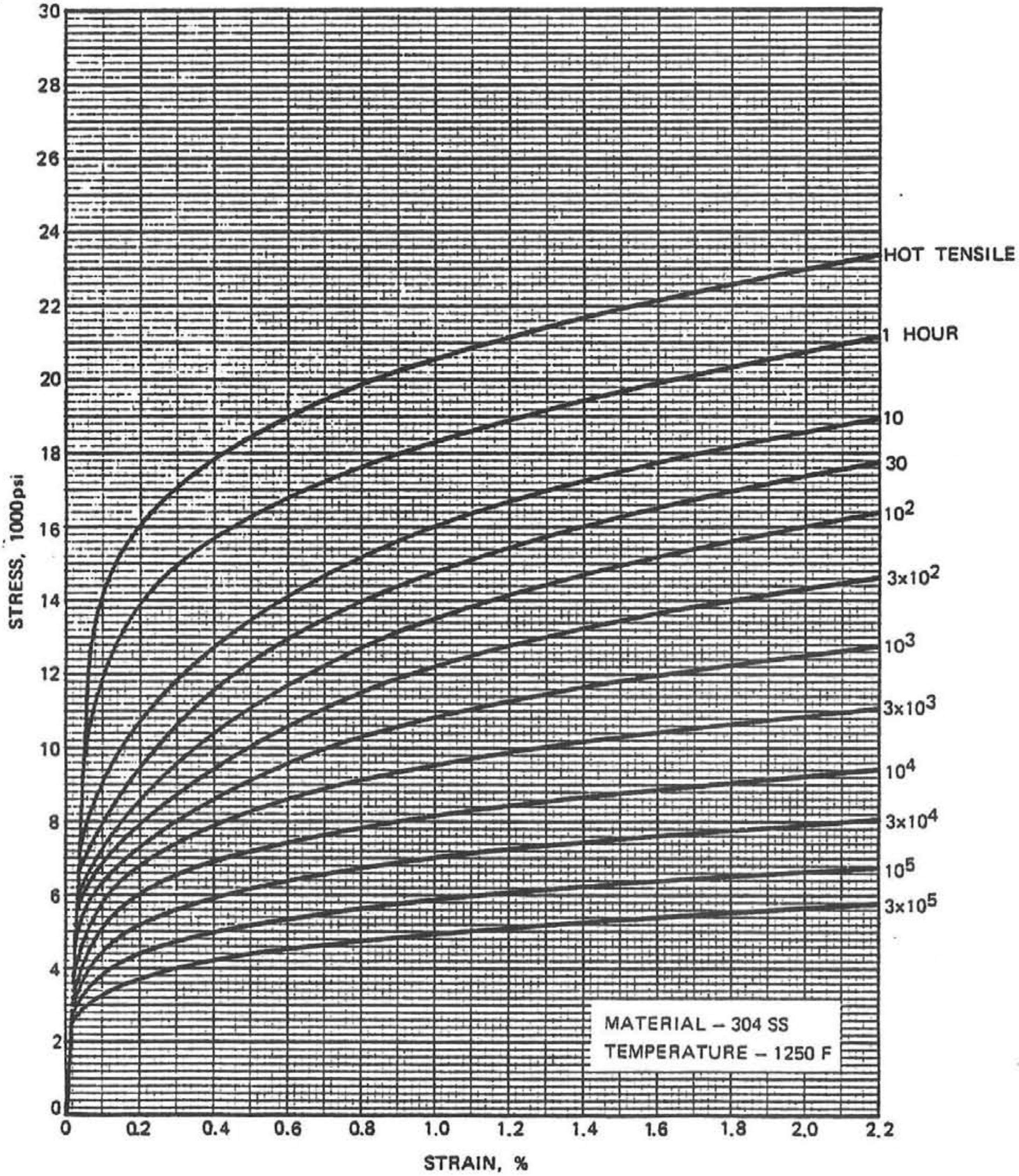

Fig. T–1800-A-10 Average isochronous stress-strain curve

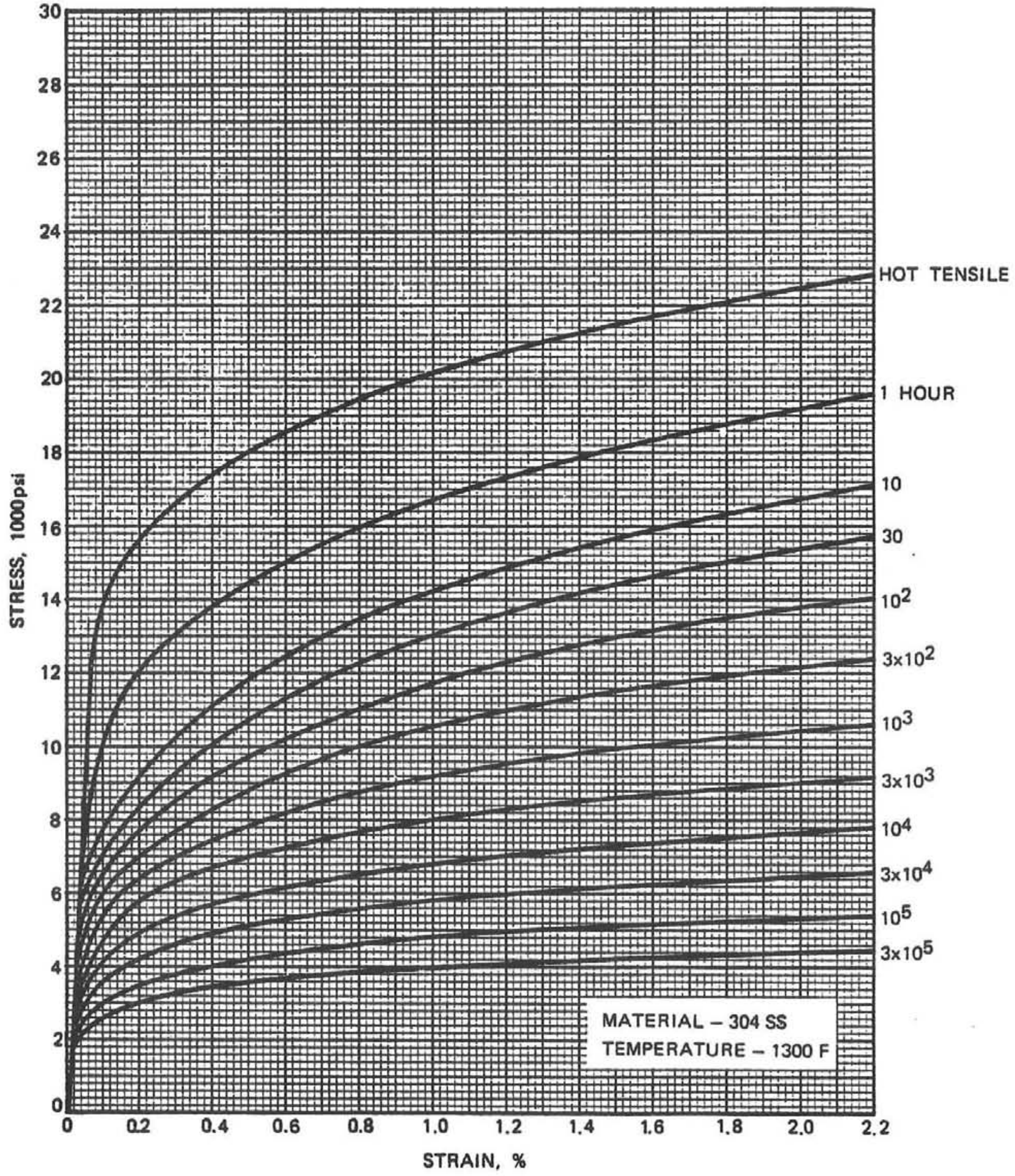

Fig. T–1800-A-11 Average isochronous stress-strain curve

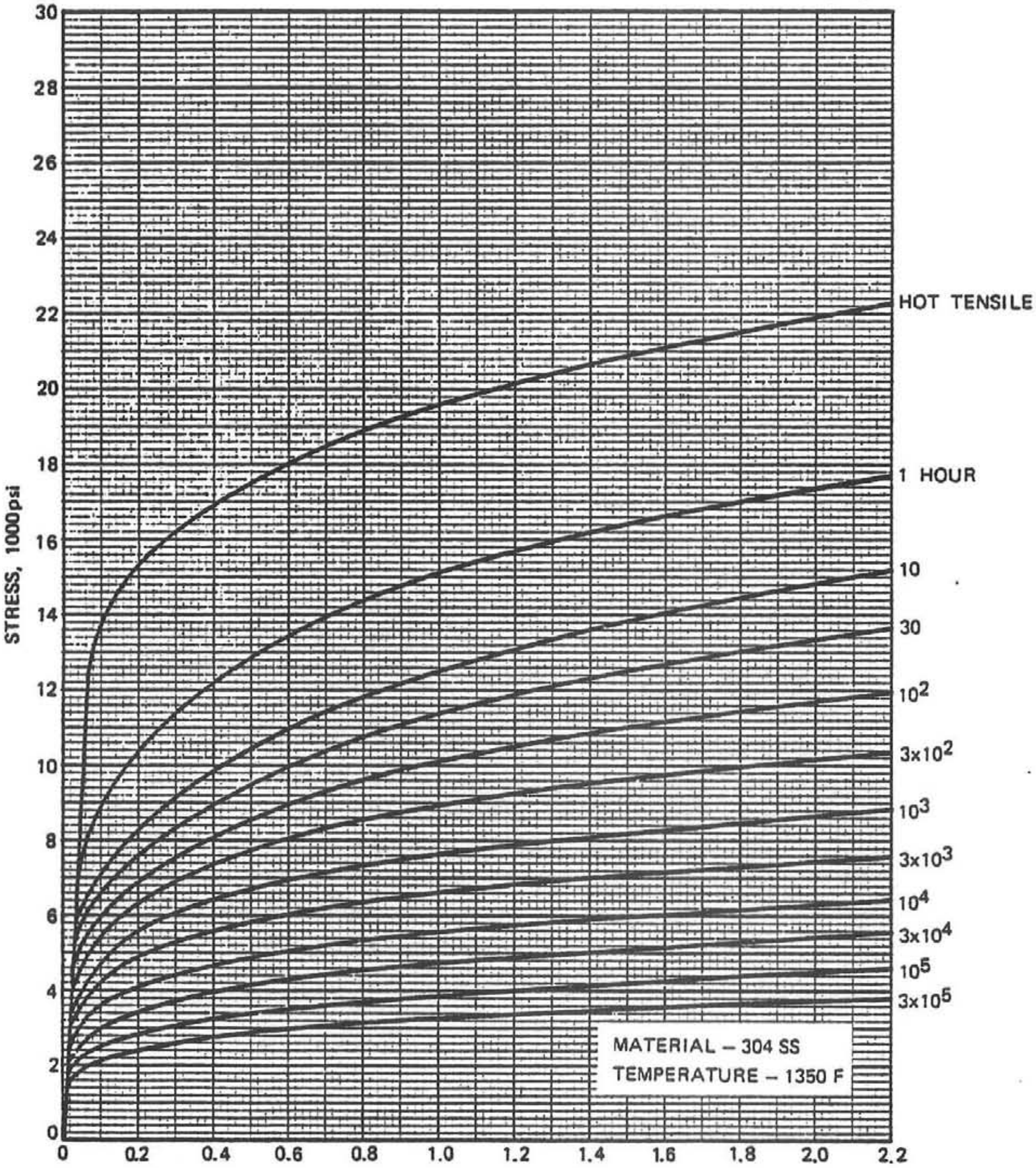

Fig. T–1800-A-12 Average isochronous stress-strain curve

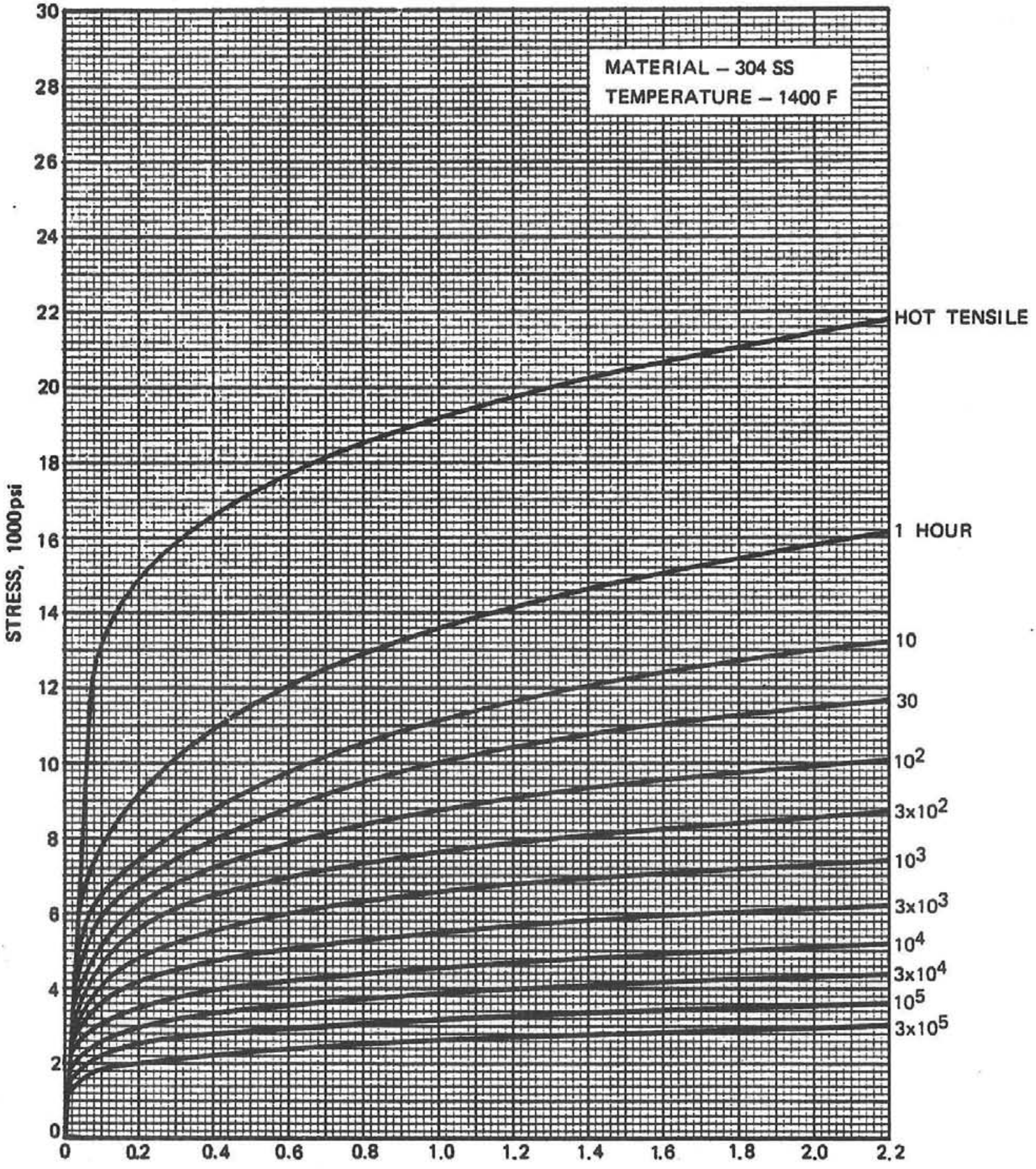

Fig. T–1800-A-13 Average isochronous stress-strain curve

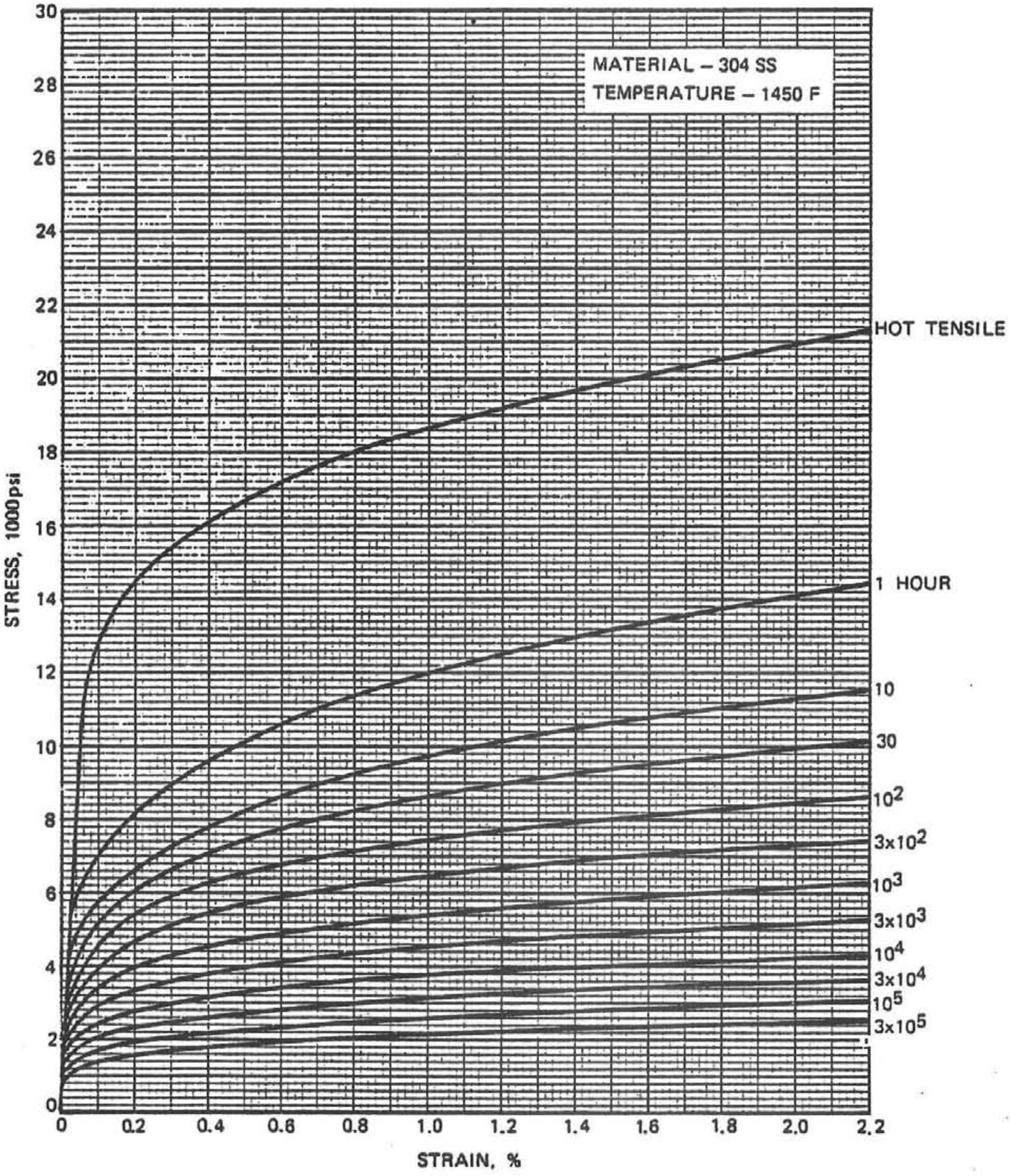

Fig. T–1800-A-14 Average isochronous stress-strain curve

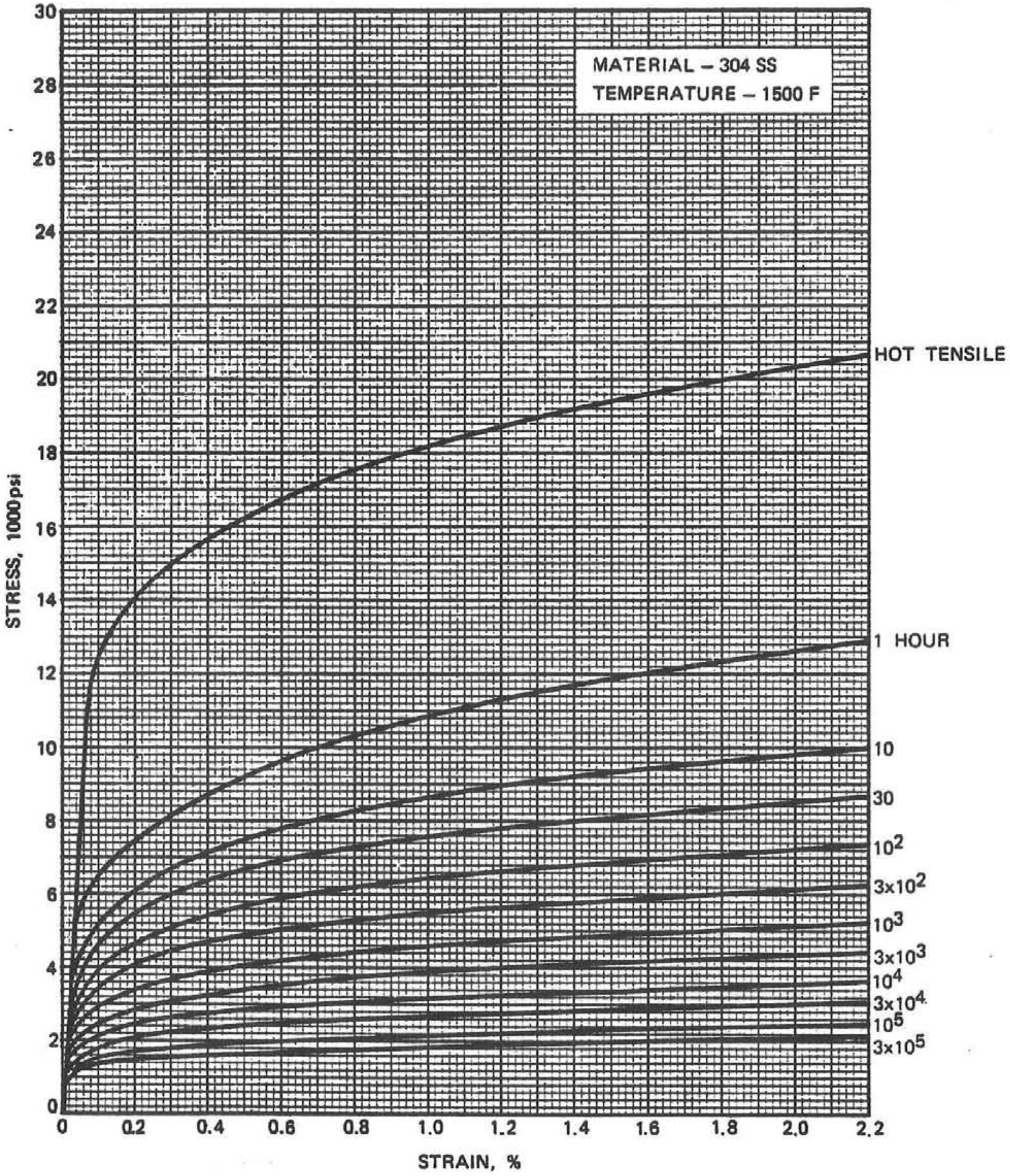

Fig. T–1800-A-15 Average isochronous stress-strain curve

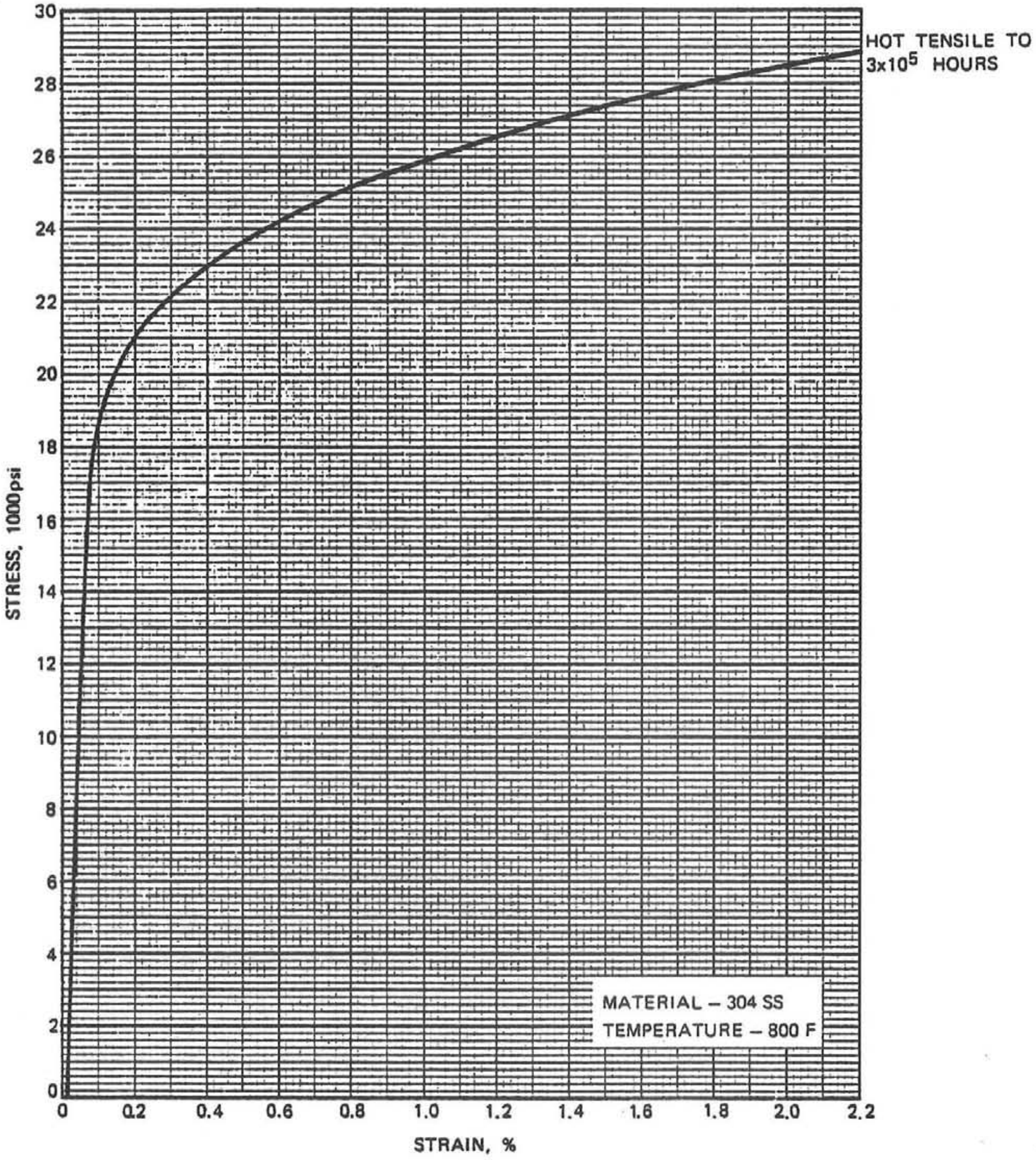

Fig. T–1800-B-1 Average isochronous stress-strain curves

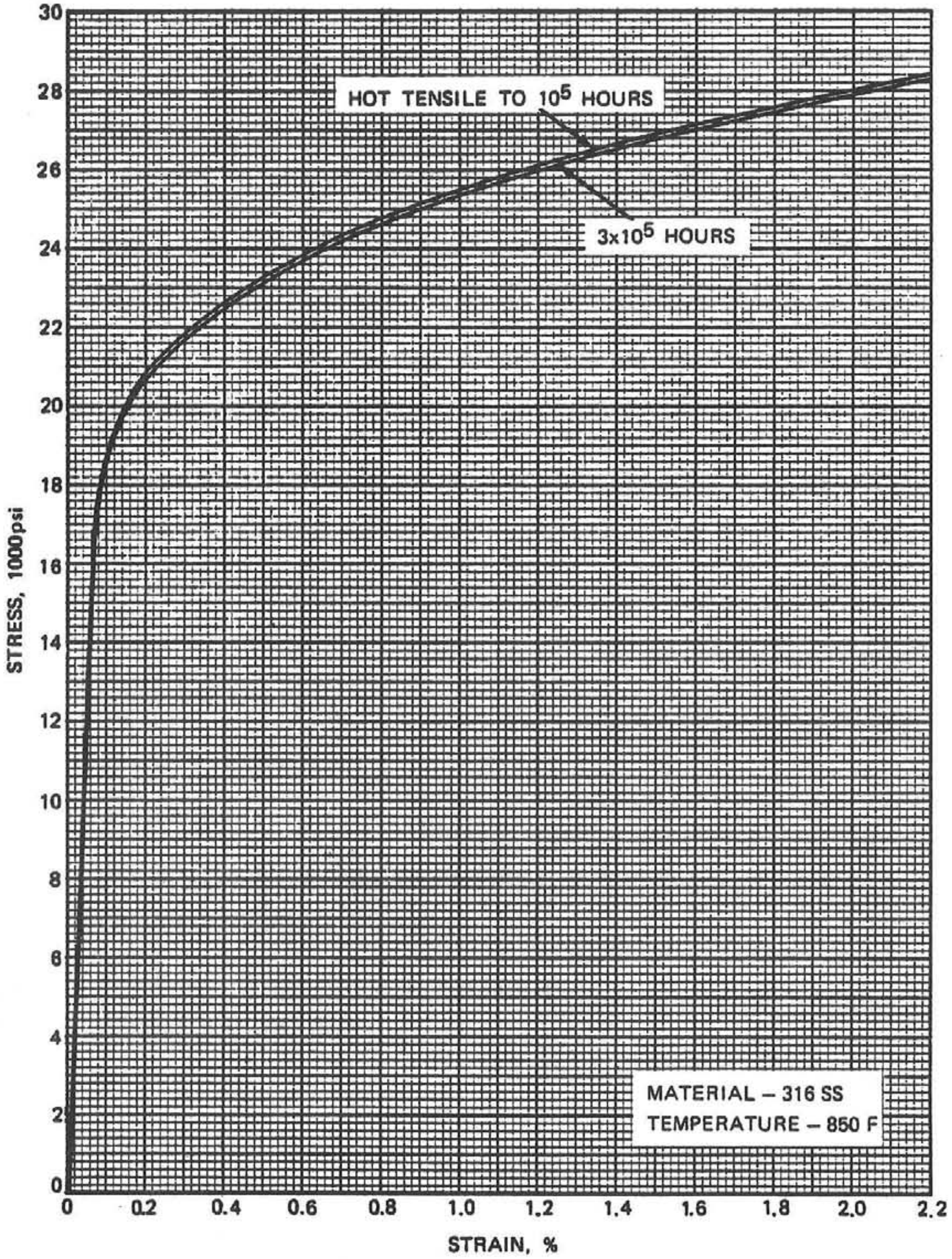

Fig. T–1800-B-2 Average isochronous stress-strain curves

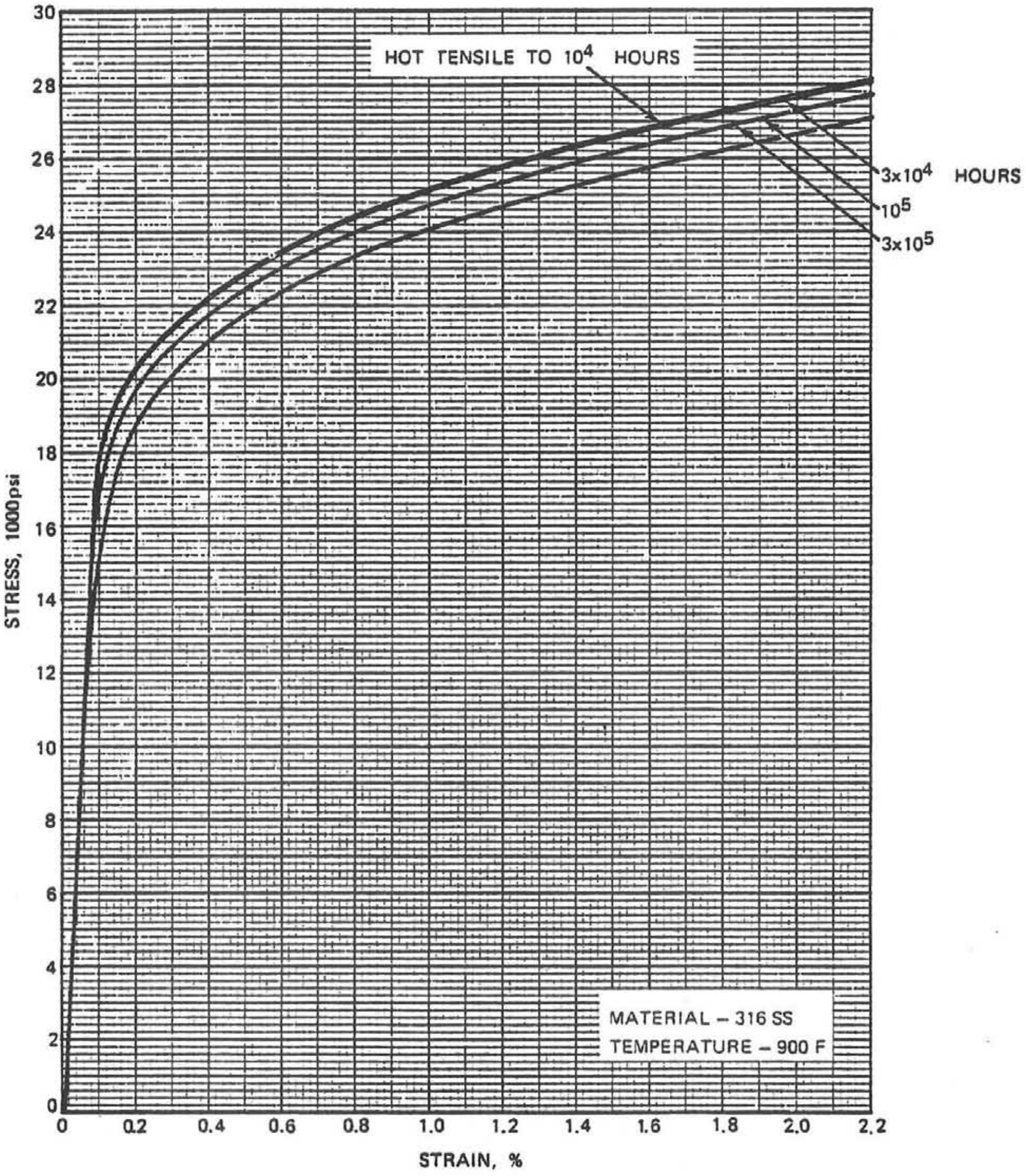

Fig. T–1800-B-3 Average isochronous stress-strain curves

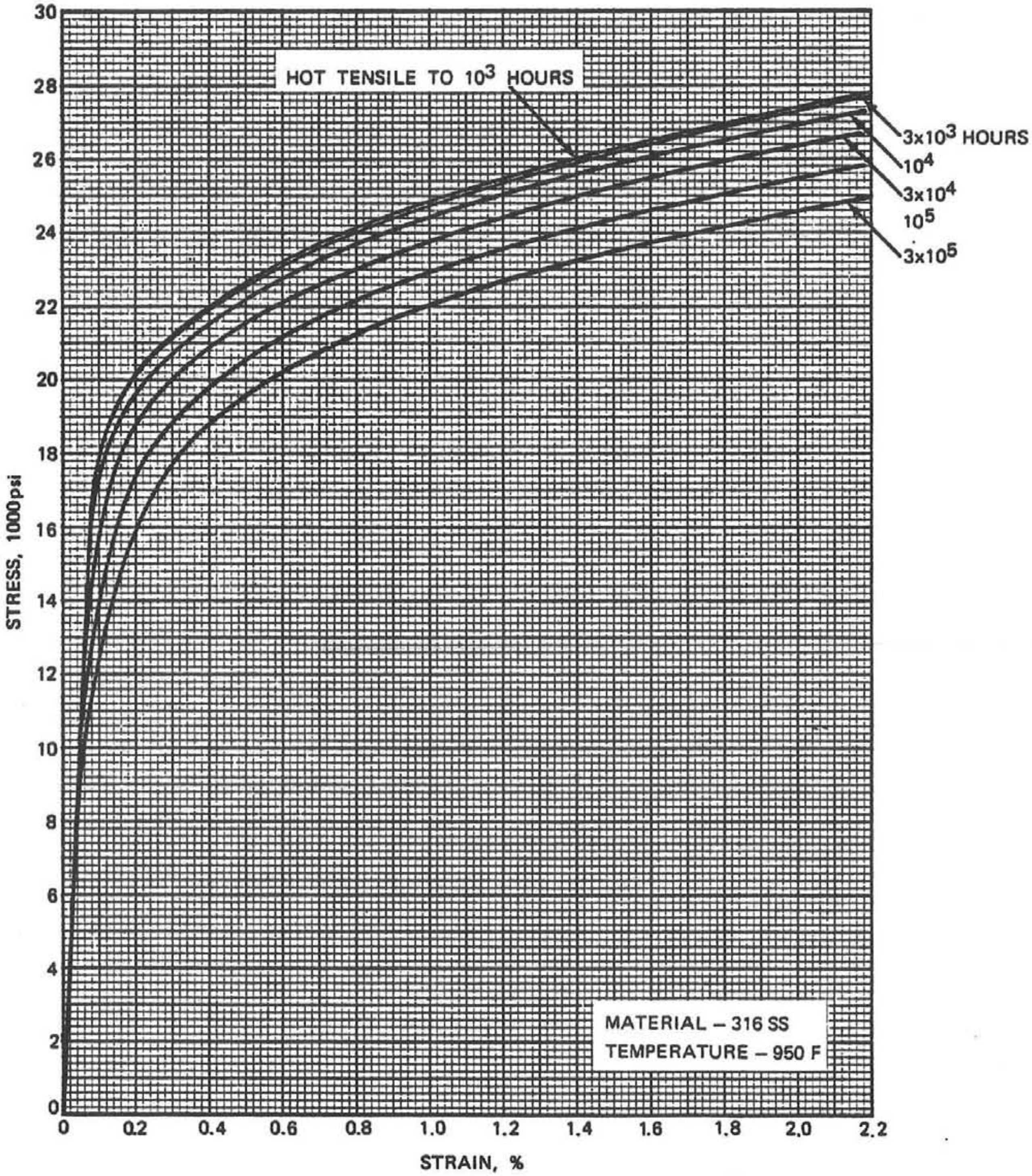

Fig. T–1800-B-4 Average isochronous stress-strain curves

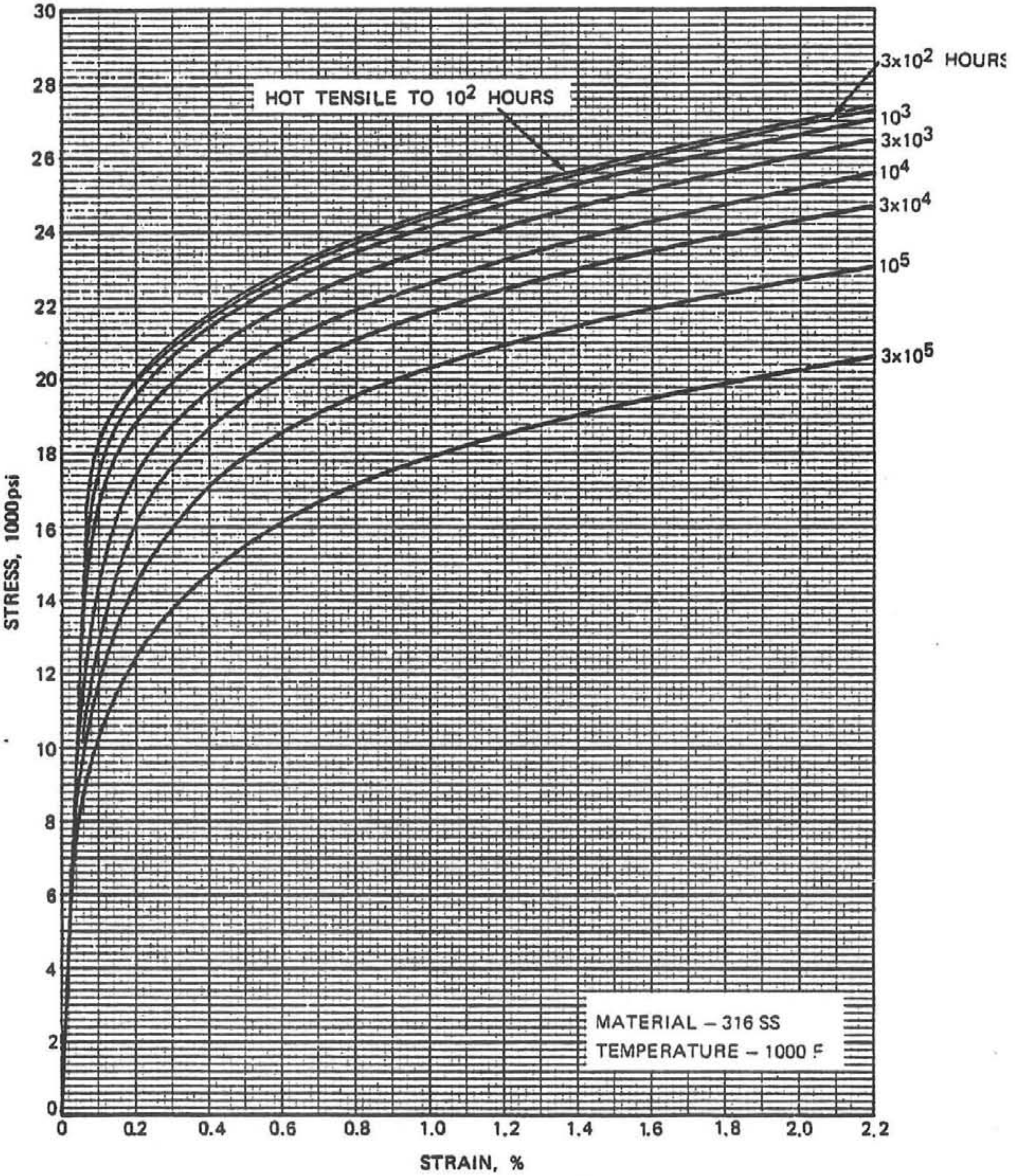

Fig. T–1800-B-5 Average isochronous stress-strain curves

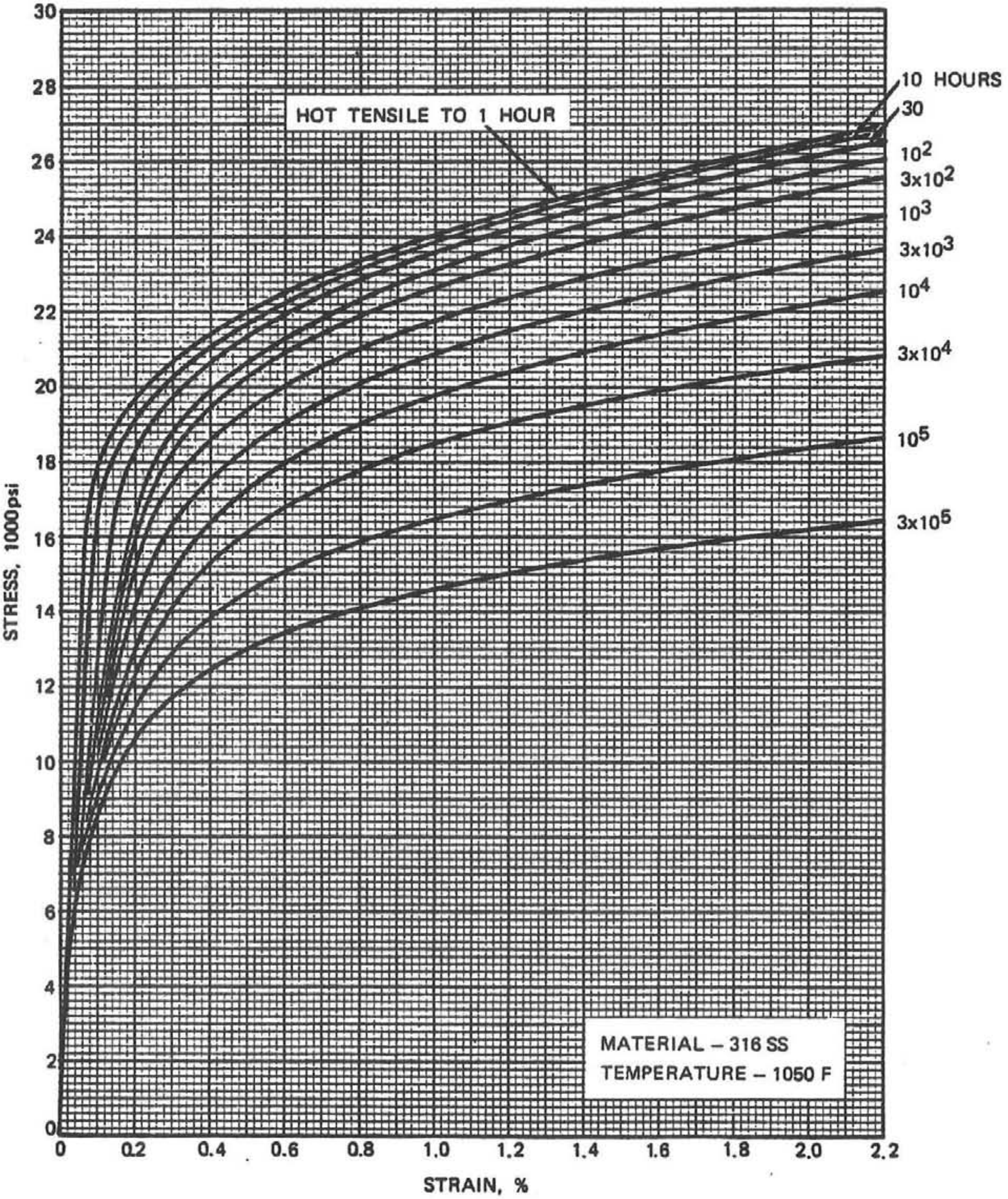

Fig. T–1800-B-6 Average isochronous stress-strain curves

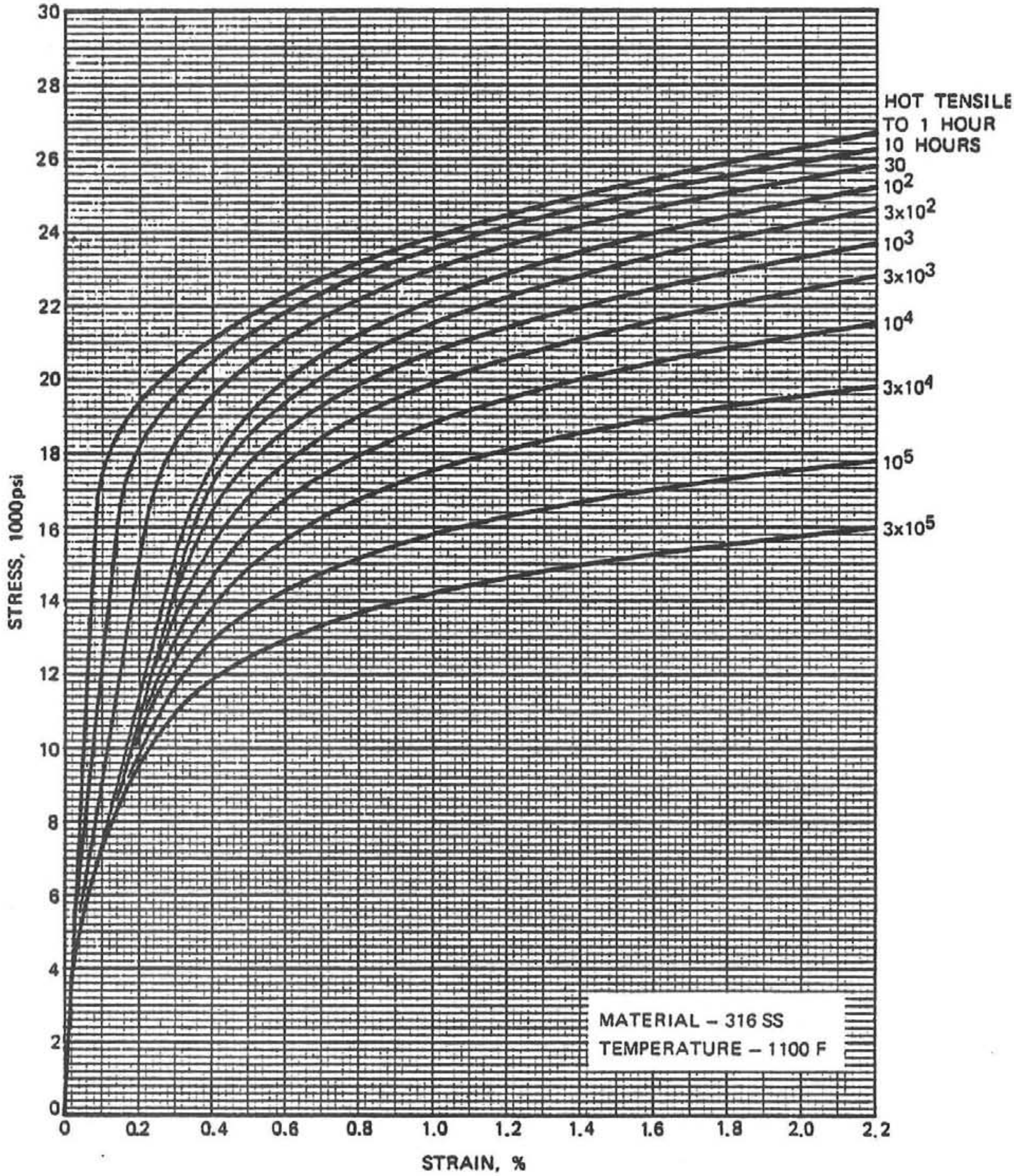

Fig. T–1800-B-7 Average isochronous stress-strain curves

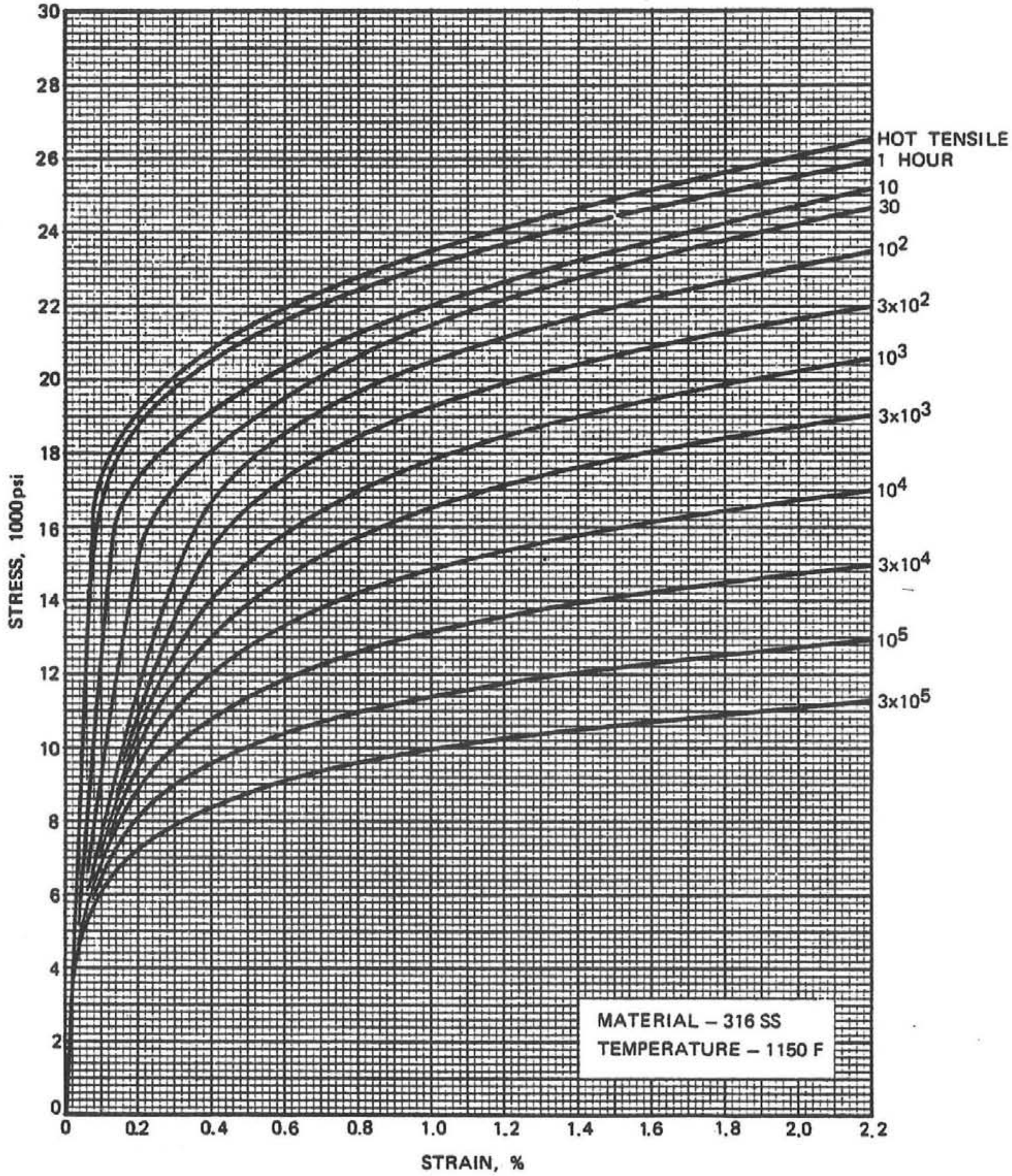

Fig. T—1800-B-8 Average isochronous stress-strain curves

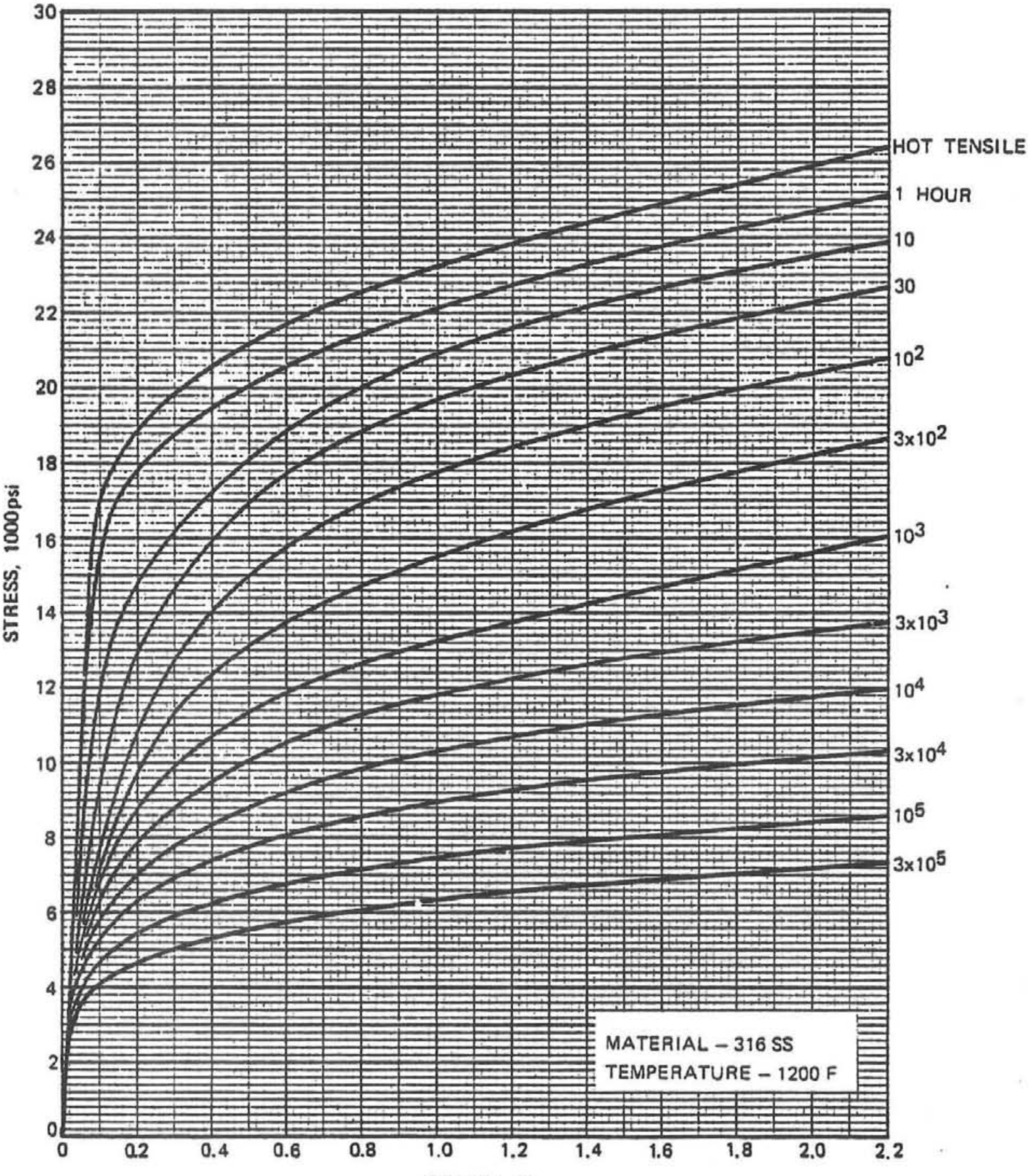

Fig. T–1800-B-9 Average isochronous stress-strain curves

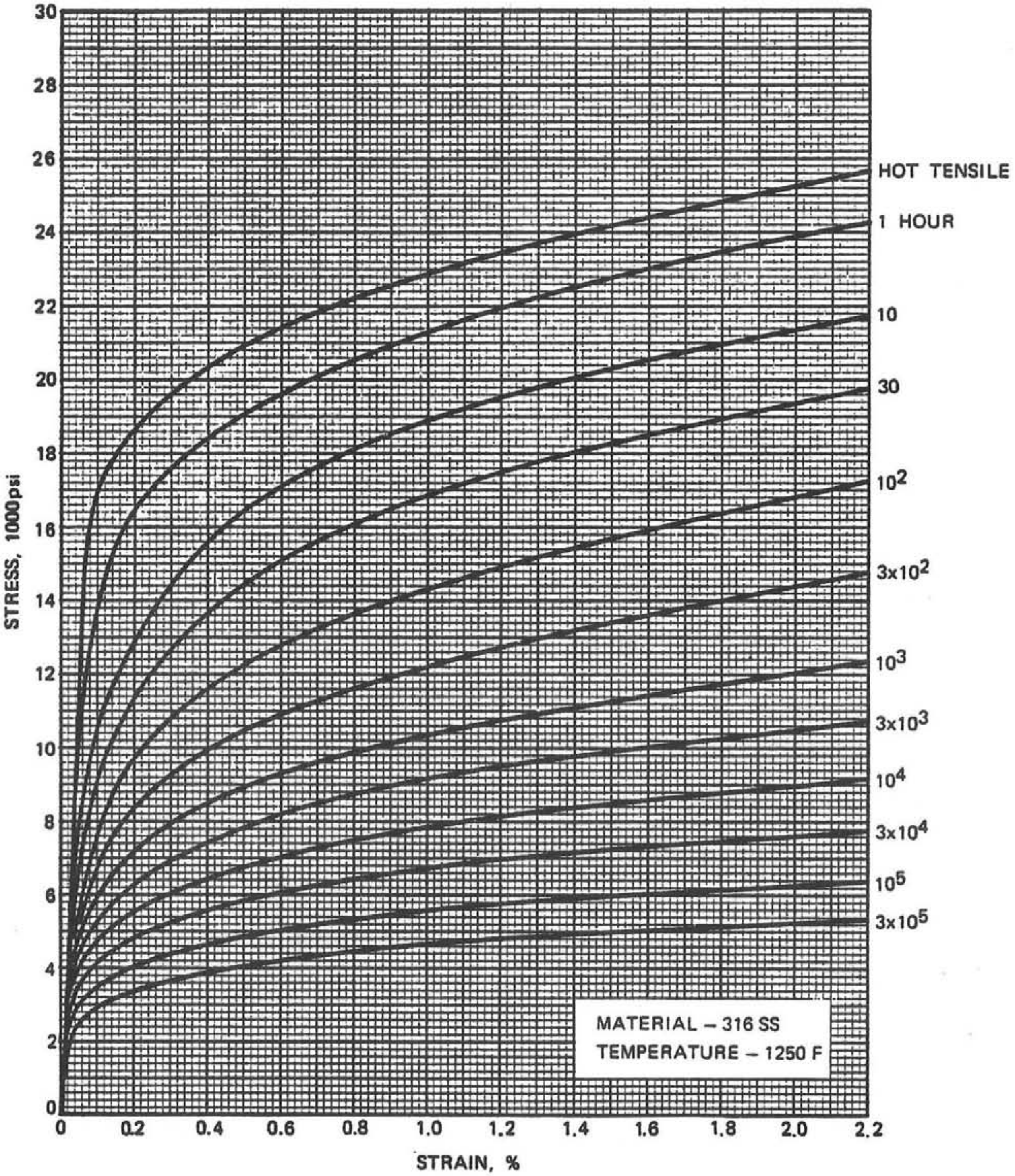

Fig. T—1800-B-10 Average isochronous stress-strain curves

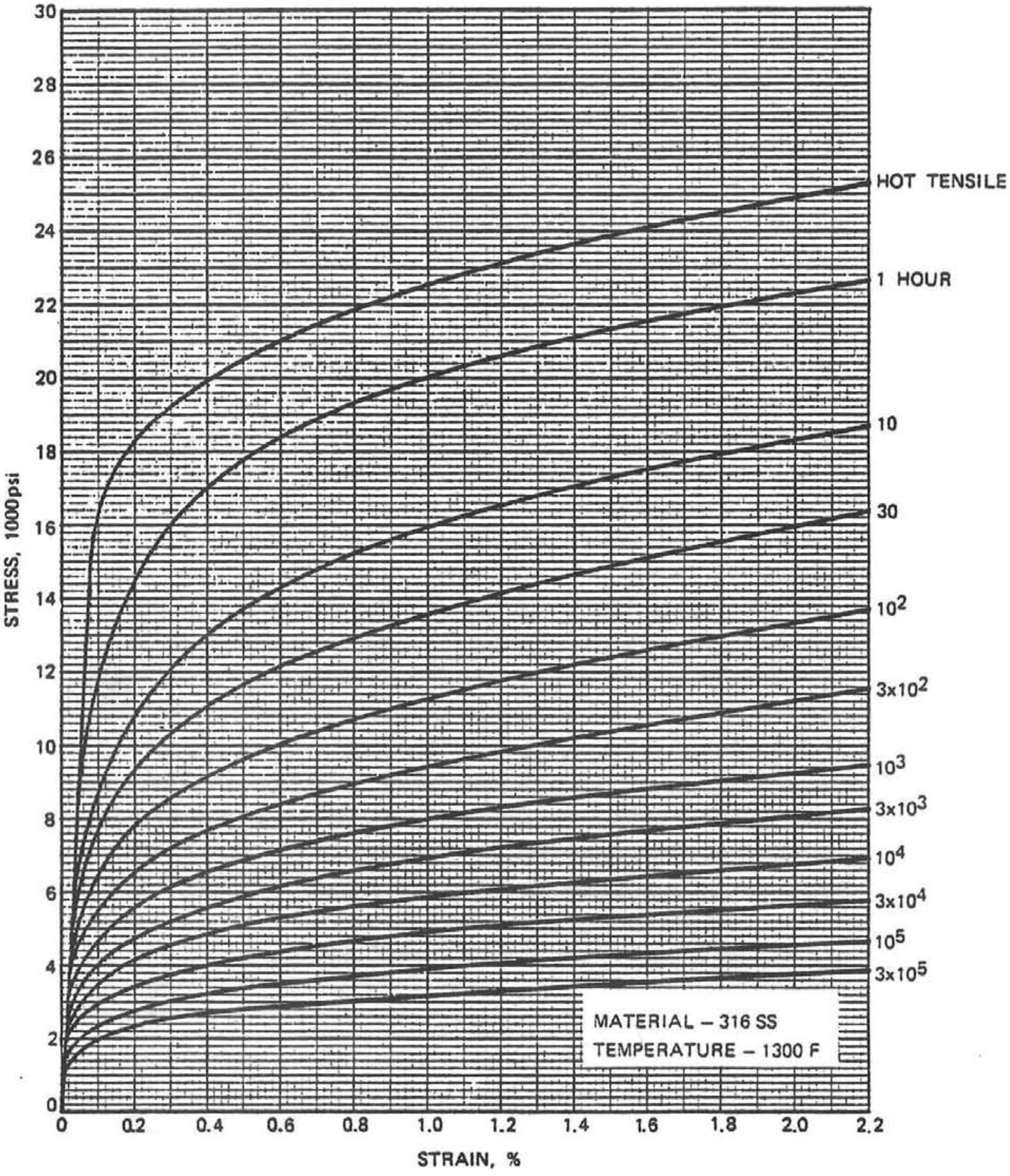

Fig. T–1800-B-11 Average isochronous stress-strain curves

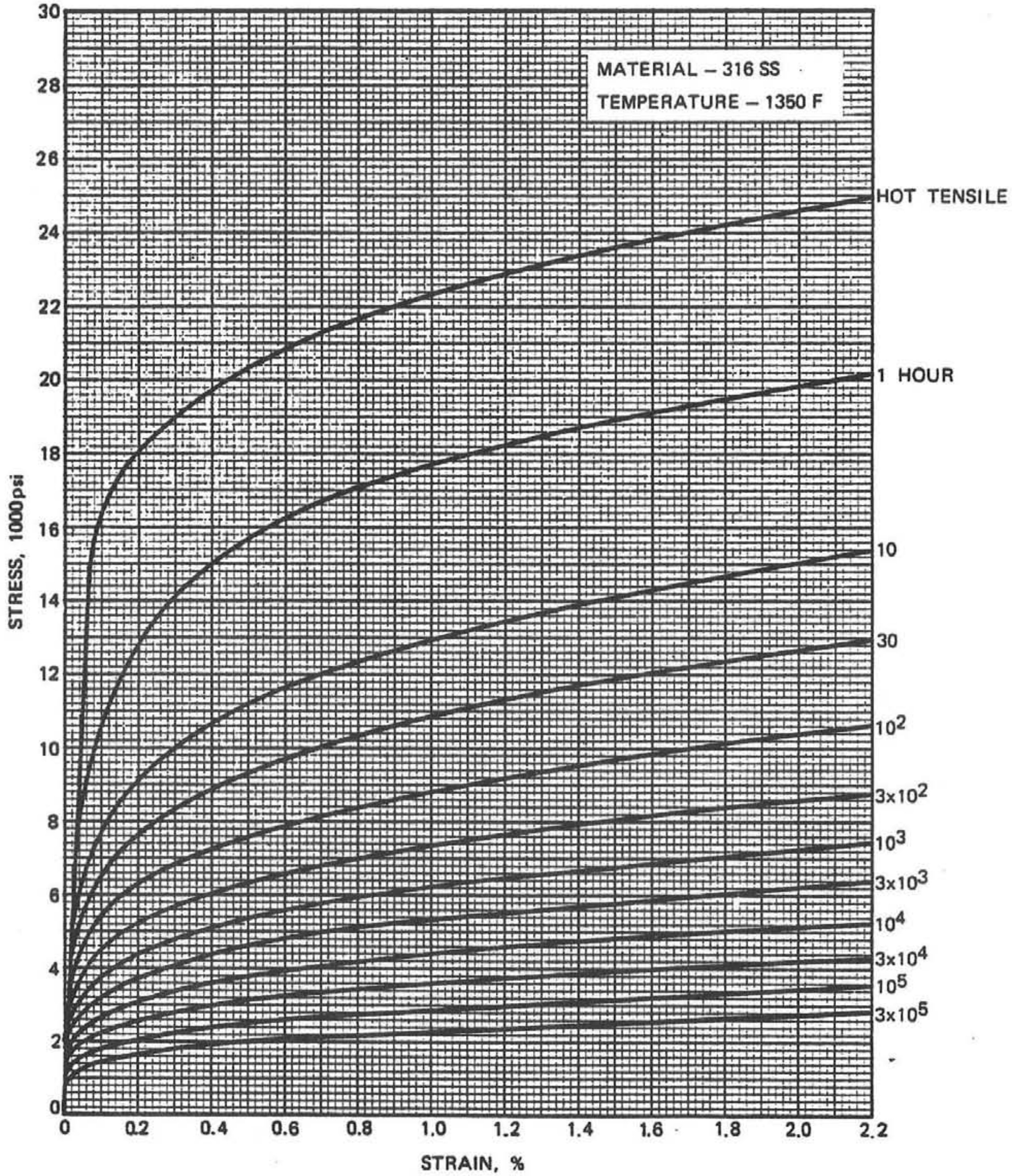

Fig. T–1800-B-12 Average isochronous stress-strain curves

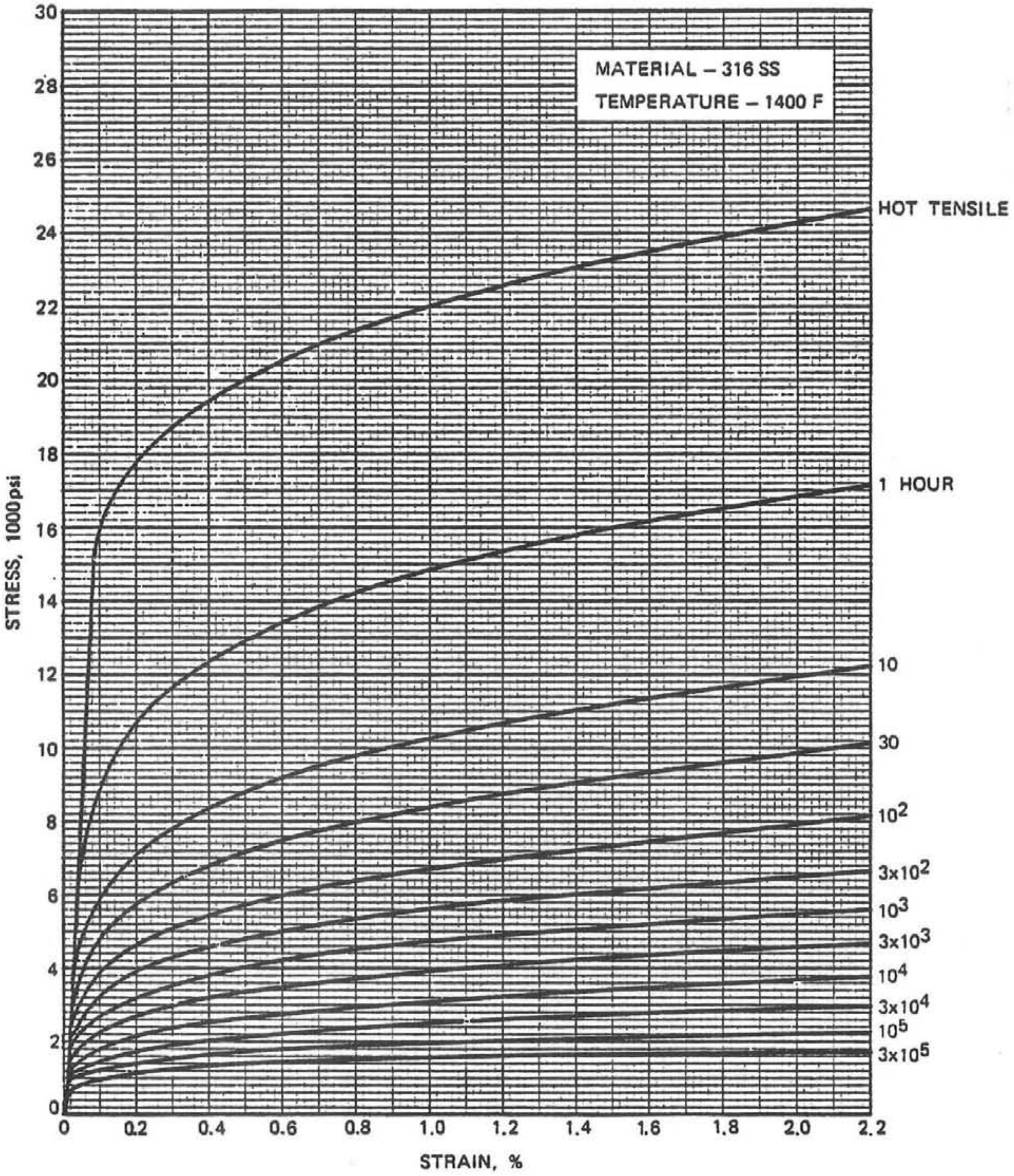

Fig. T–1800-B-13 Average isochronous stress-strain curves

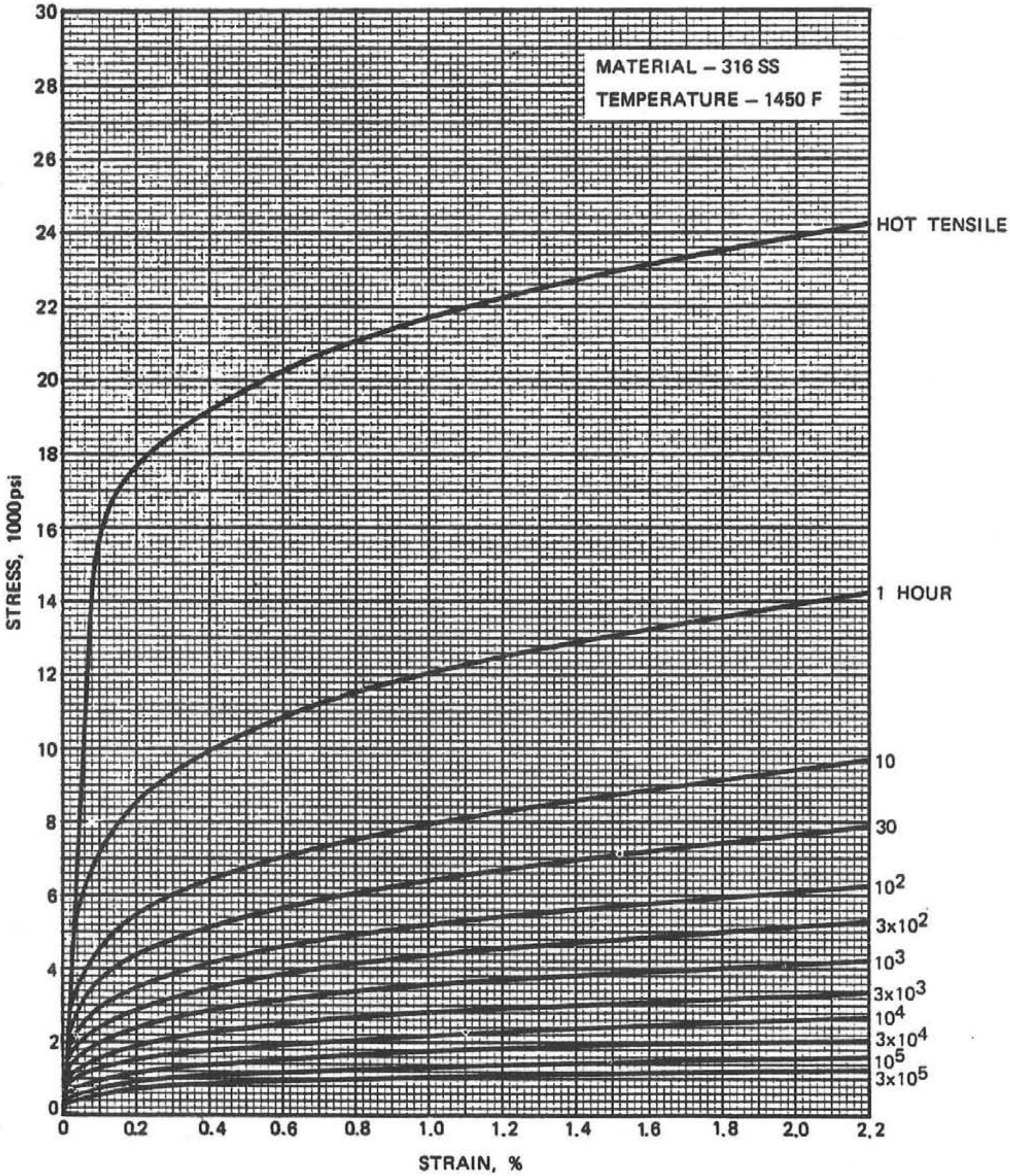

Fig. T–1800-B-14 Average isochronous stress-strain curves

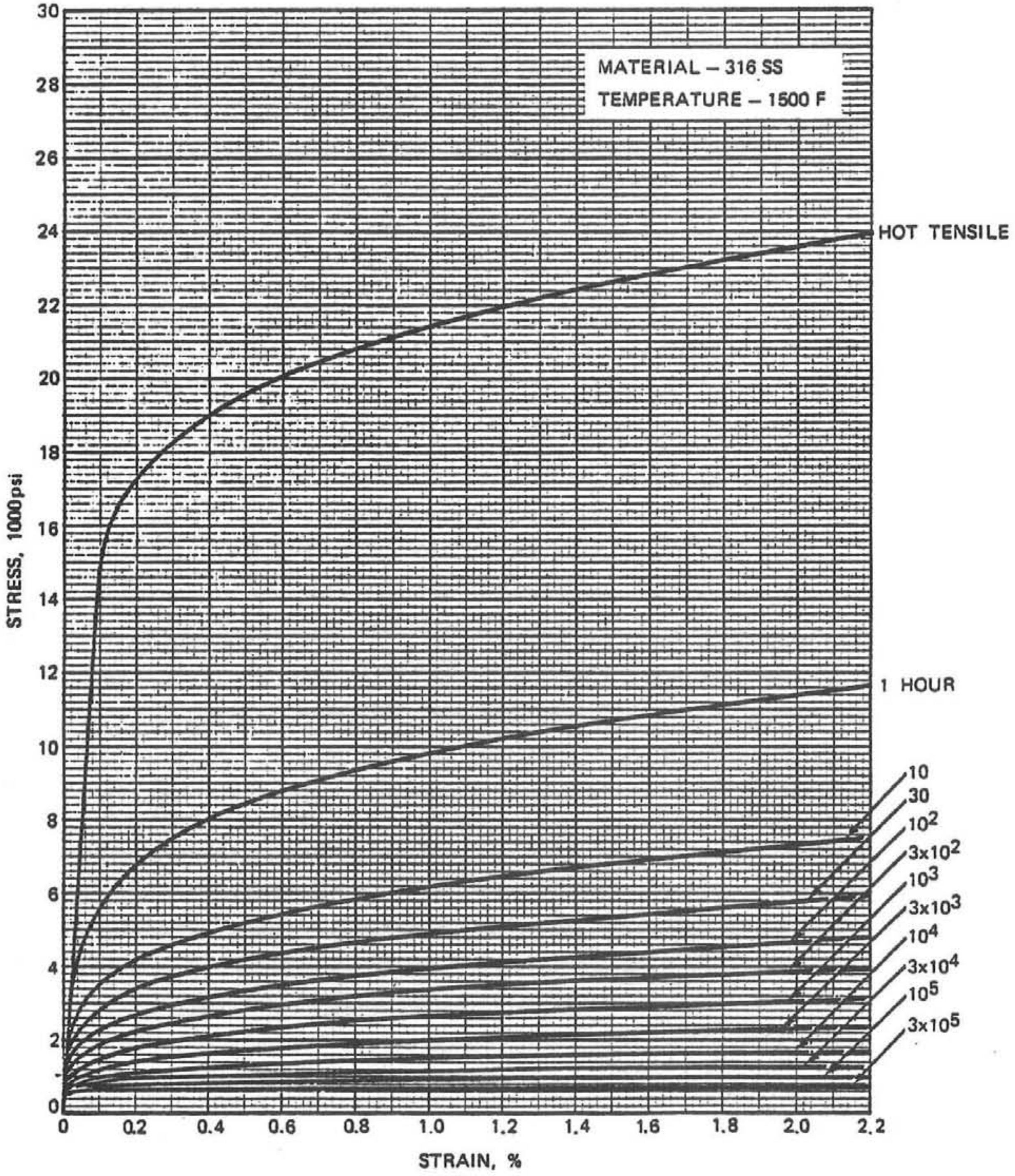

Fig. T–1800-B-15 Average isochronous stress-strain curves

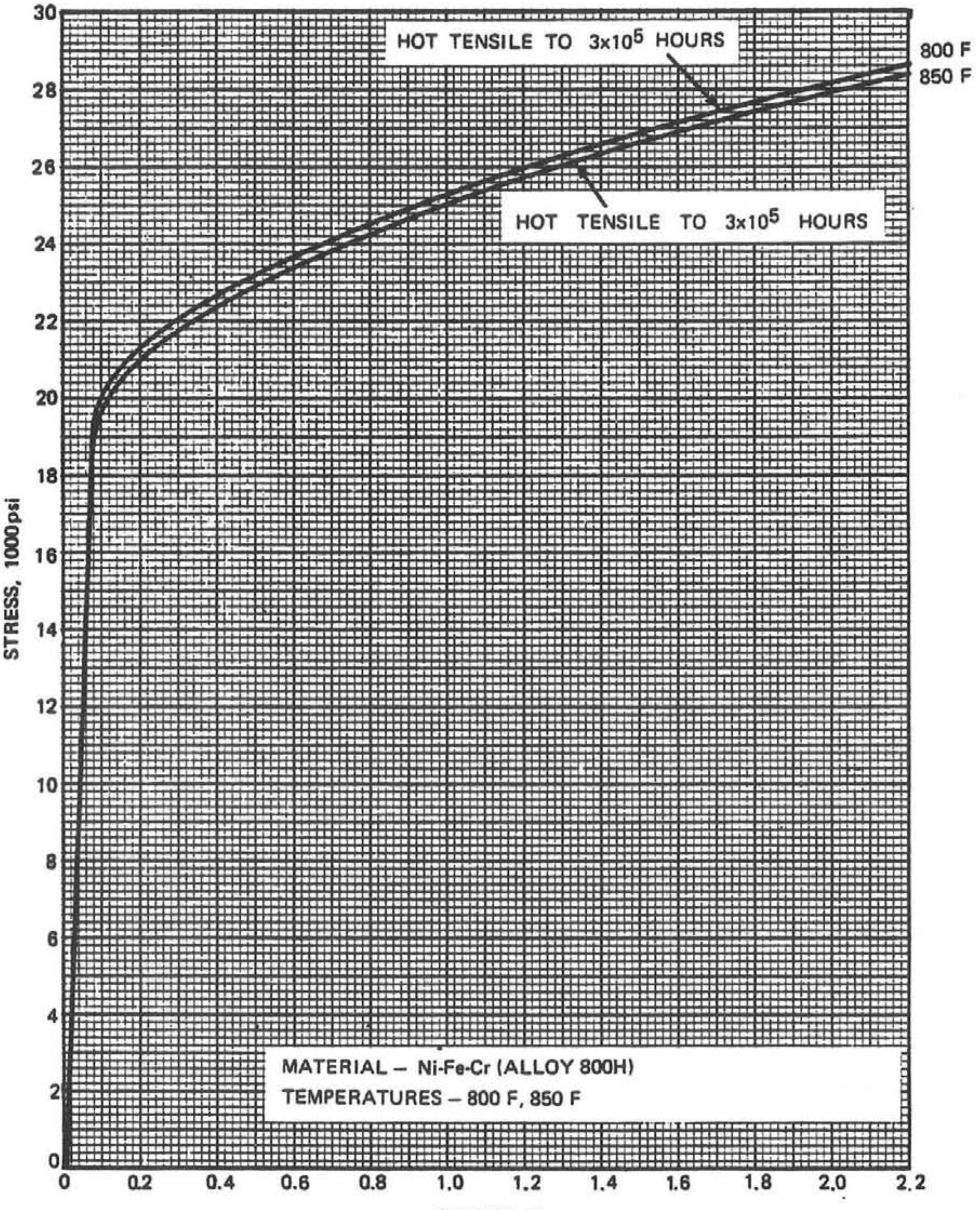

Fig. T–1800-C-1 Average isochronous stress-strain curves

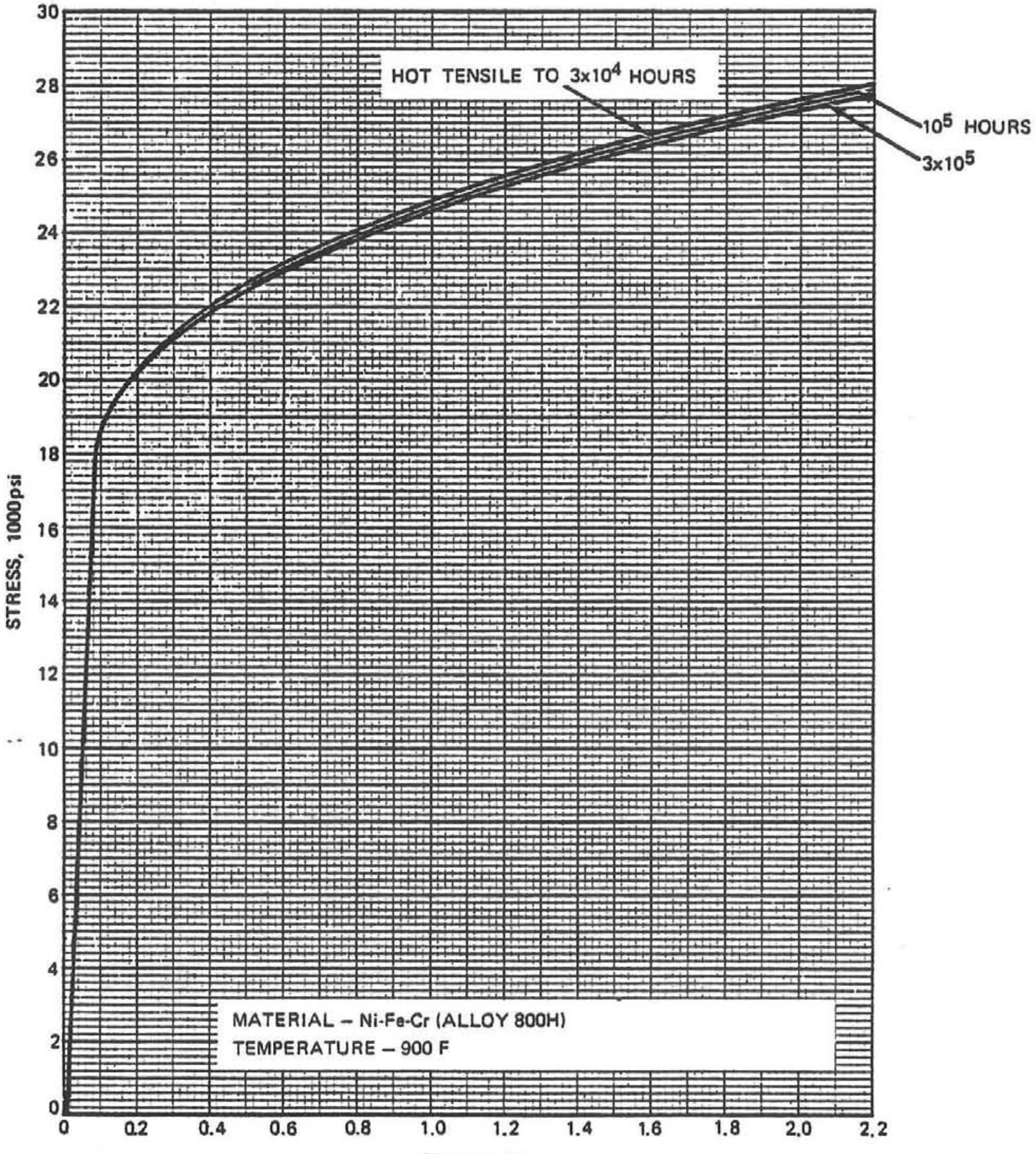

Fig. T–1800-C-2 Average isochronous stress-strain curves

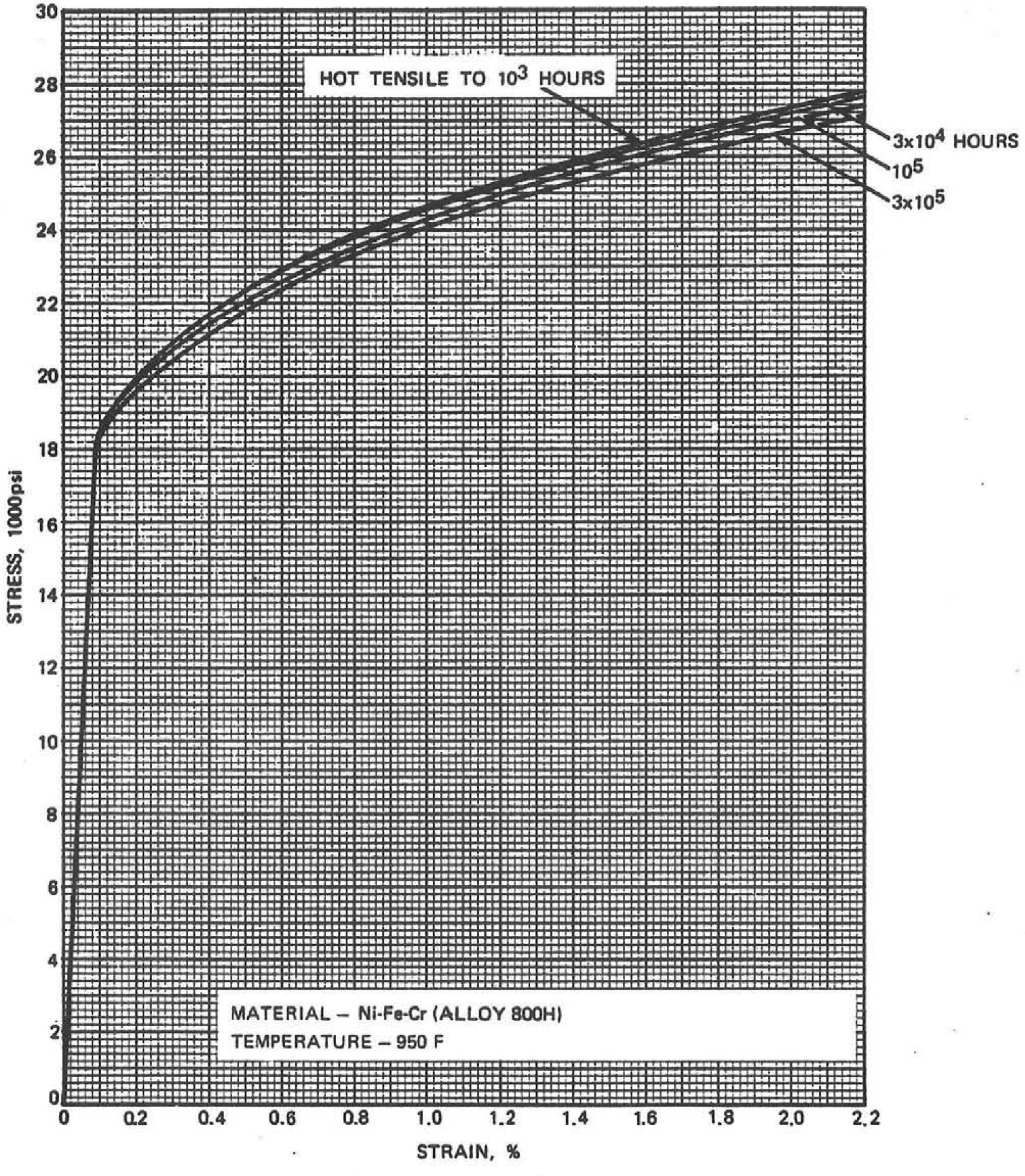

Fig. T–1800-C-3 Average isochronous stress-strain curves

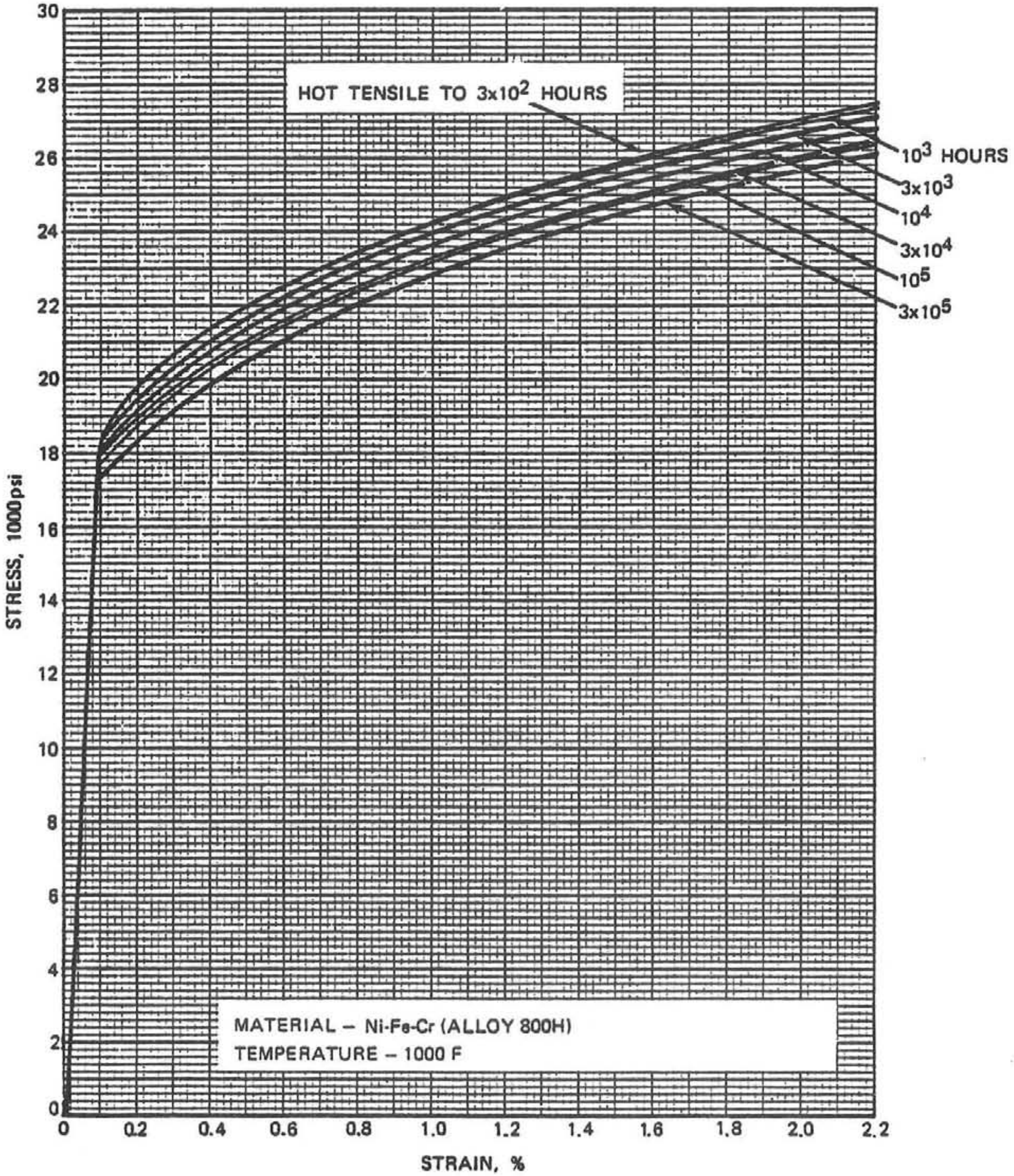

Fig. T–1800-C-4 Average isochronous stress-strain curves

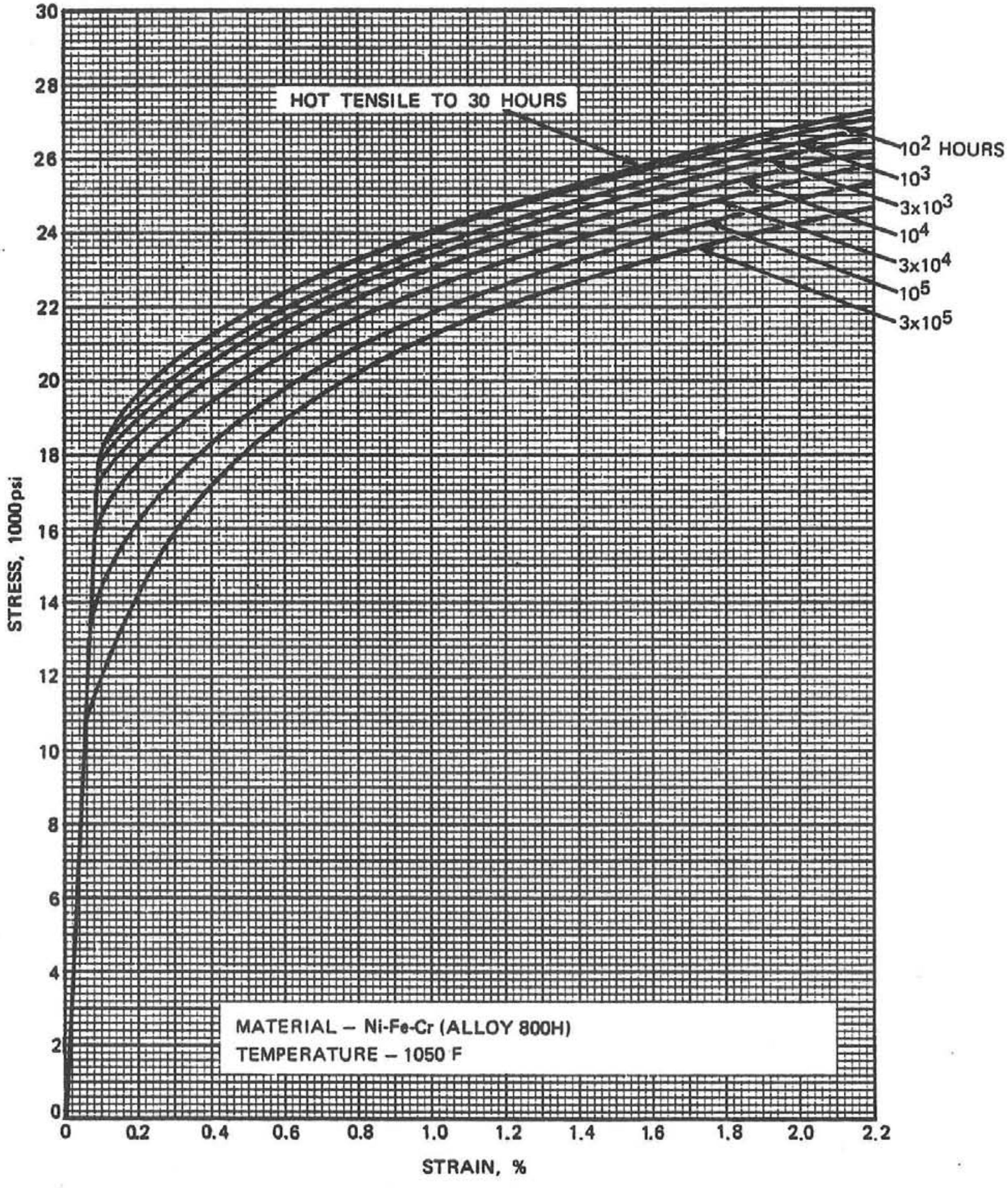

Fig. T–1800-C-5 Average isochronous stress-strain curves

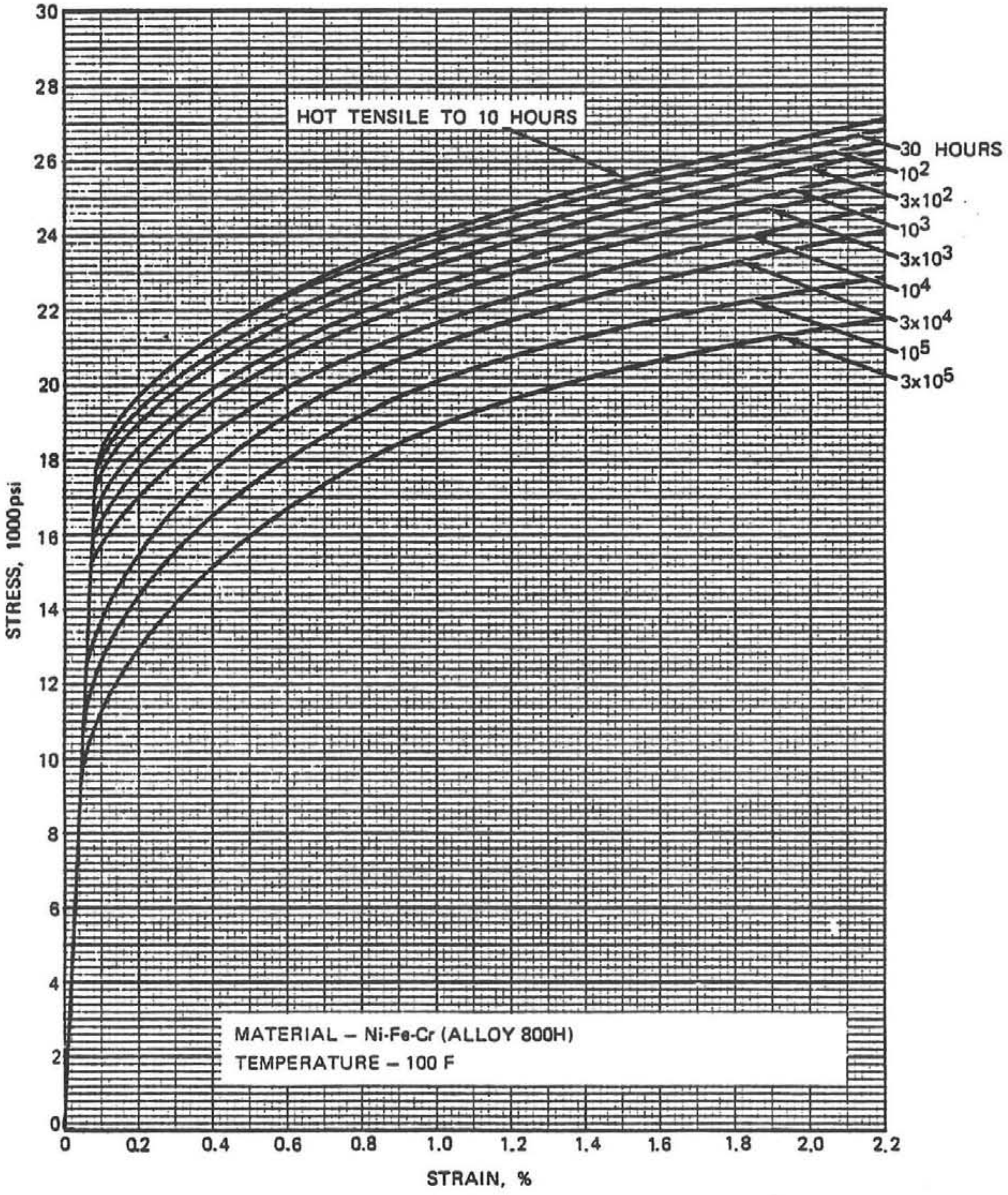

Fig. T–1800-C-6 Average isochronous stress-strain curves

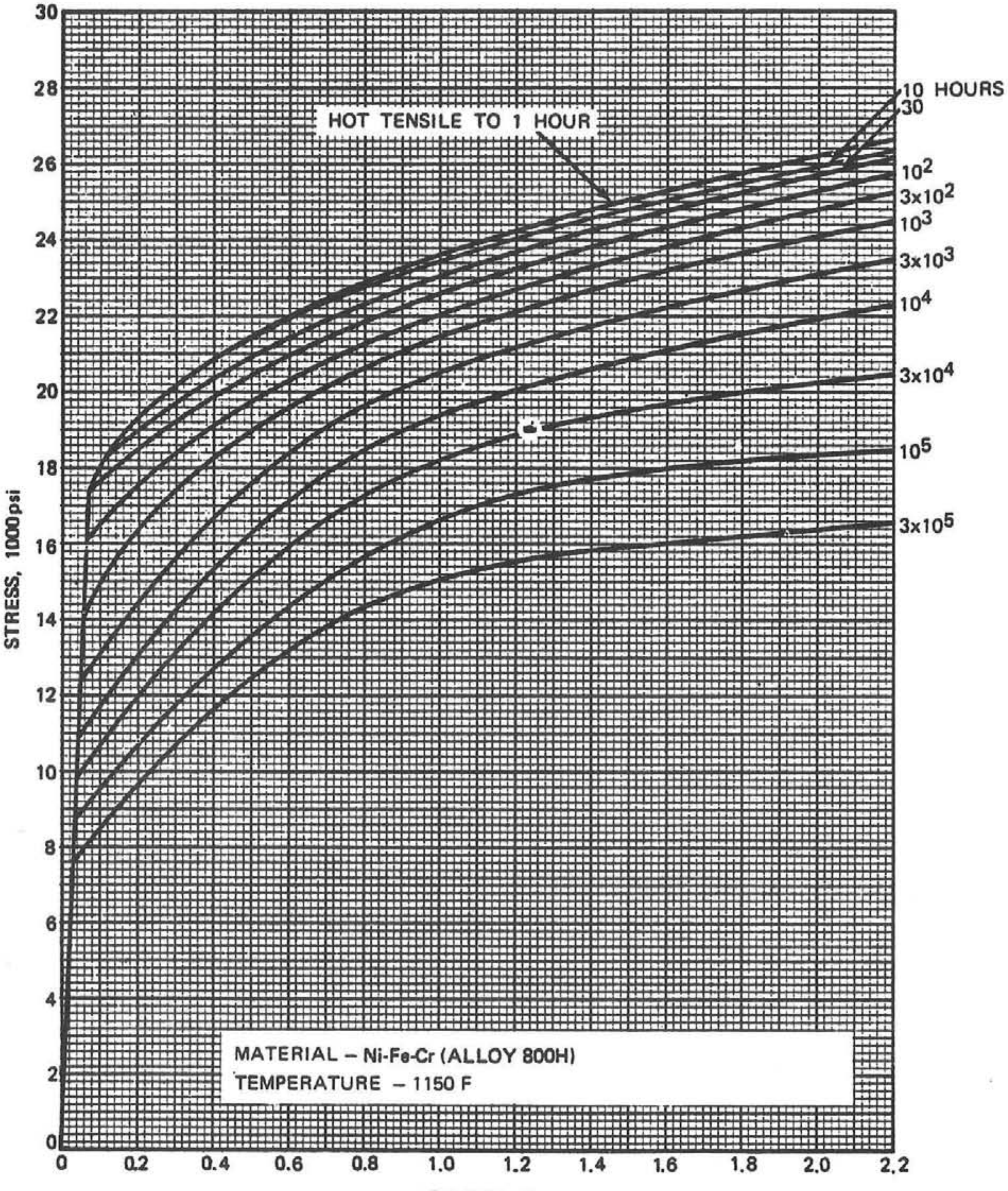

Fig. T—1800-C-7 Average isochronous stress-strain curves

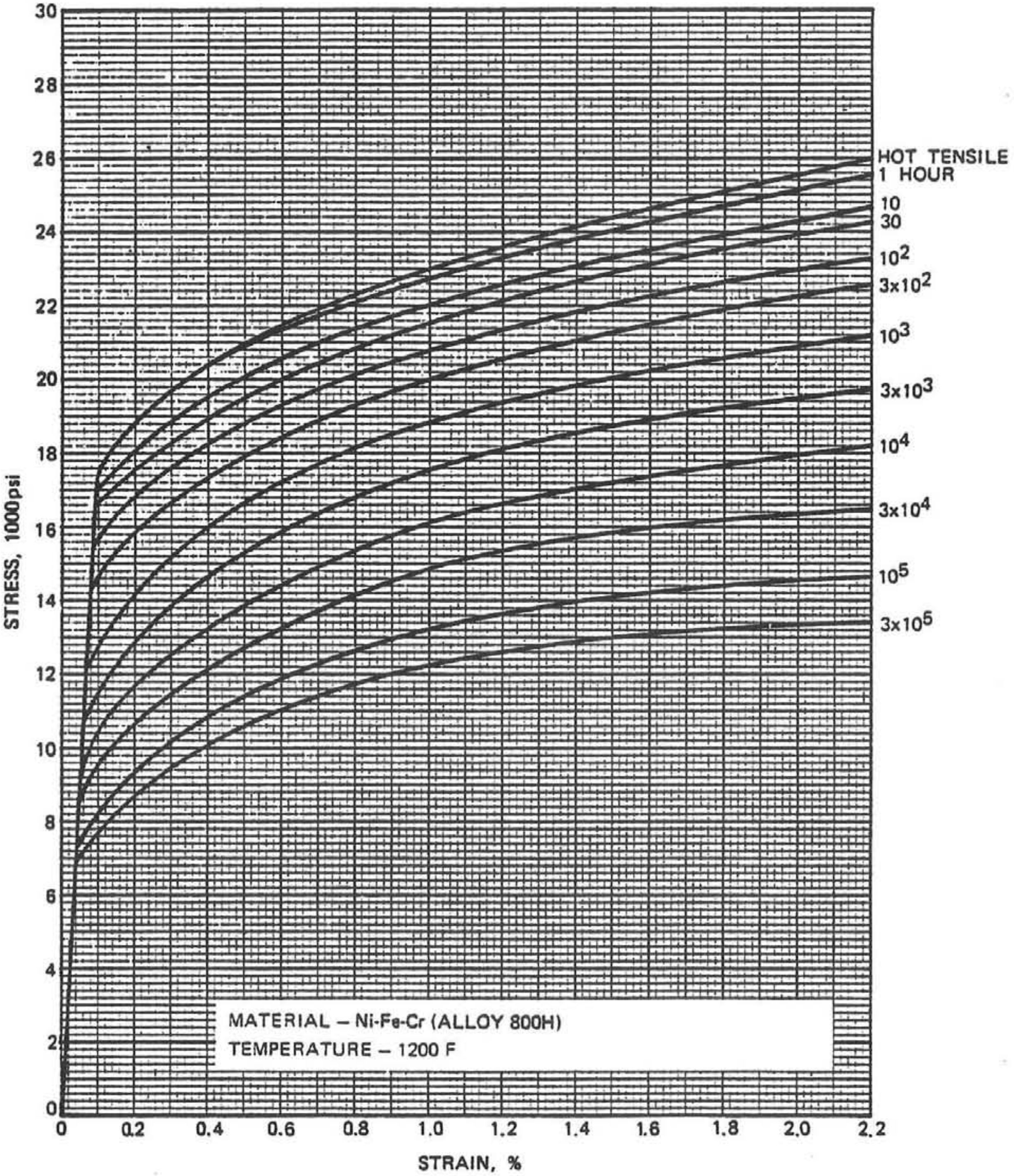

Fig. T–1800-C-8 Average isochronous stress-strain curves

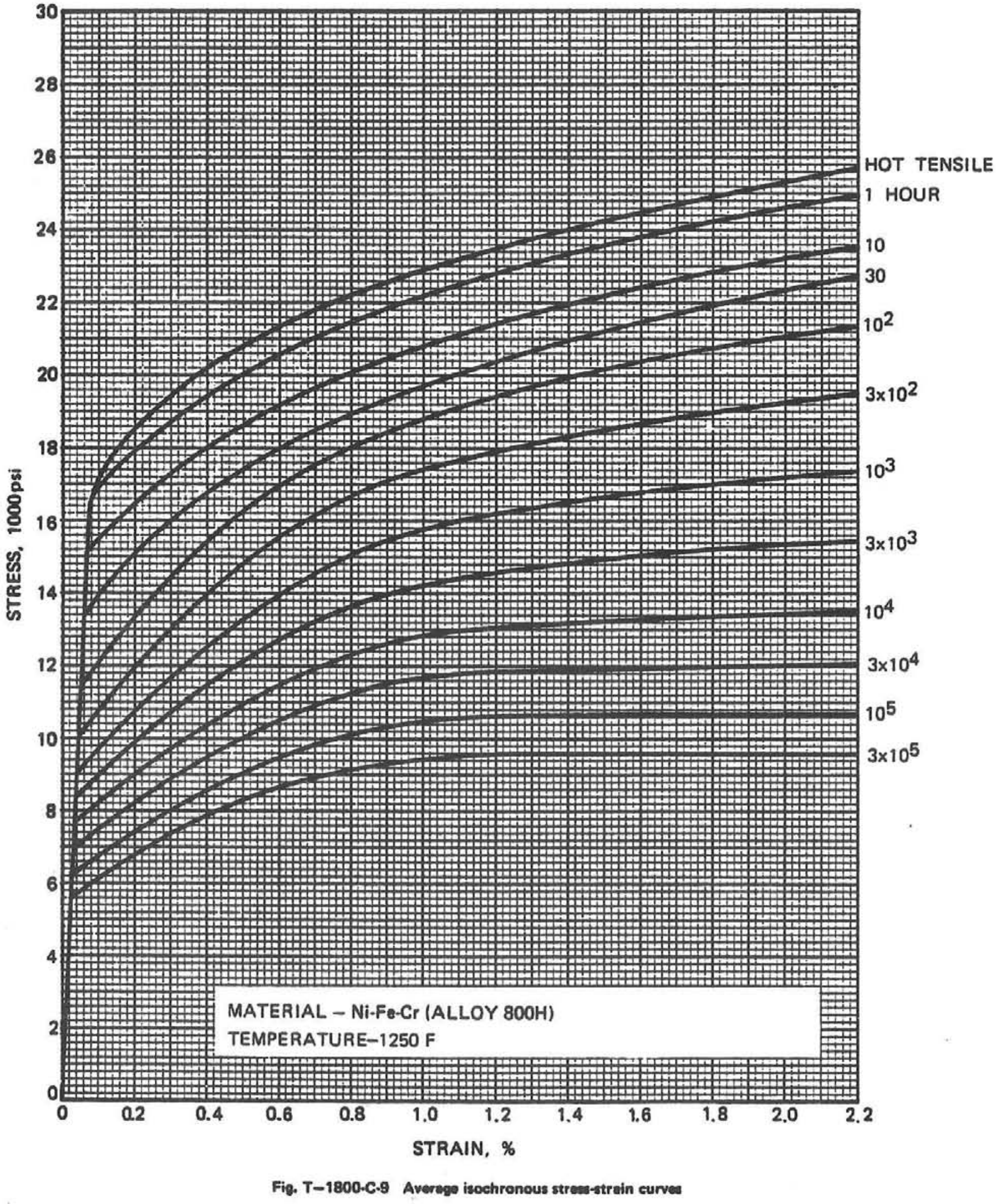

Fig. T–1800-C-9 Average isochronous stress-strain curves

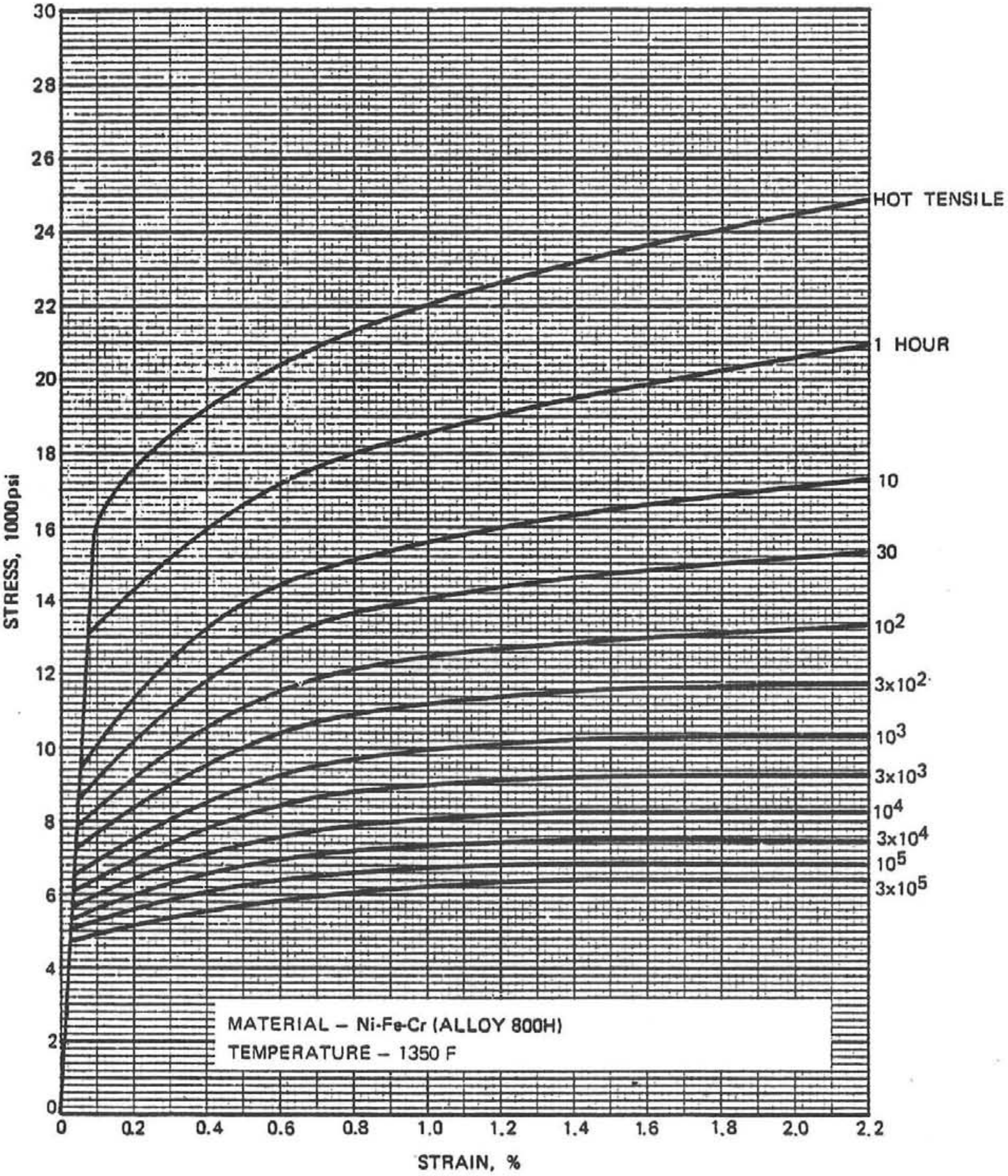

Fig. T–1800-C-10 Average isochronous stress-strain curves

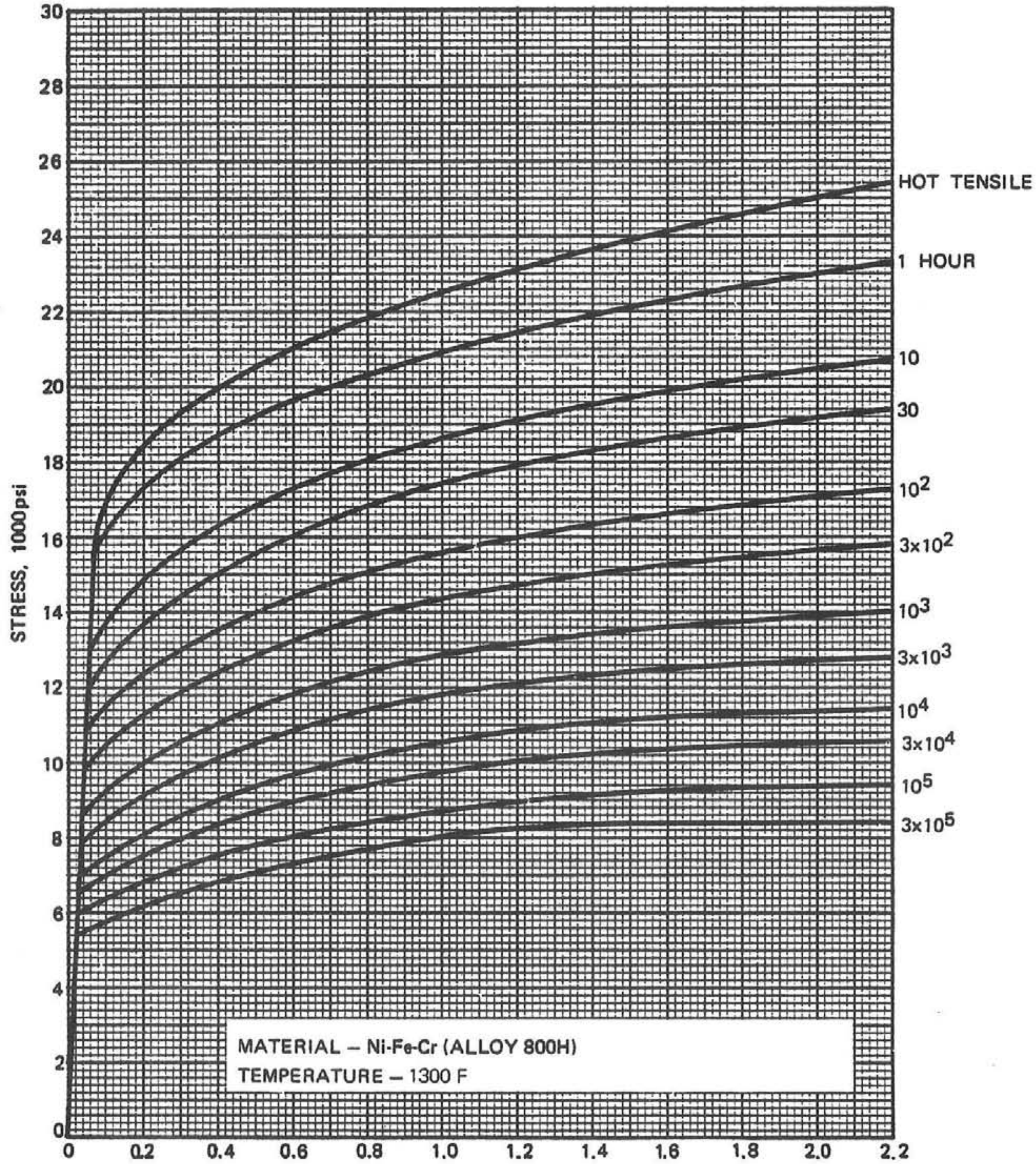

Fig. T–1300-C-11 Average isochronous stress-strain curves

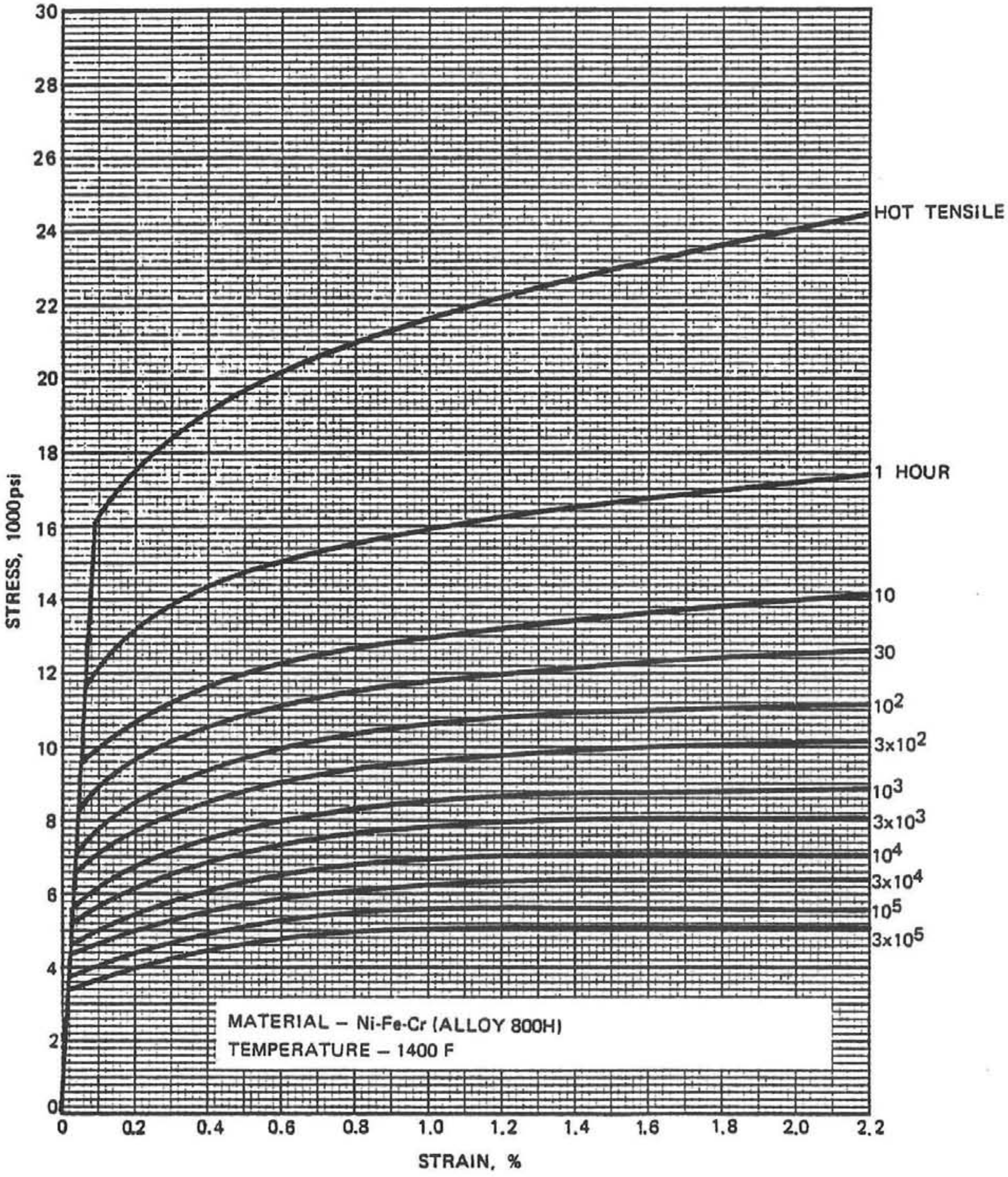

Fig. T–1800-C-12 Average isochronous stress-strain curves

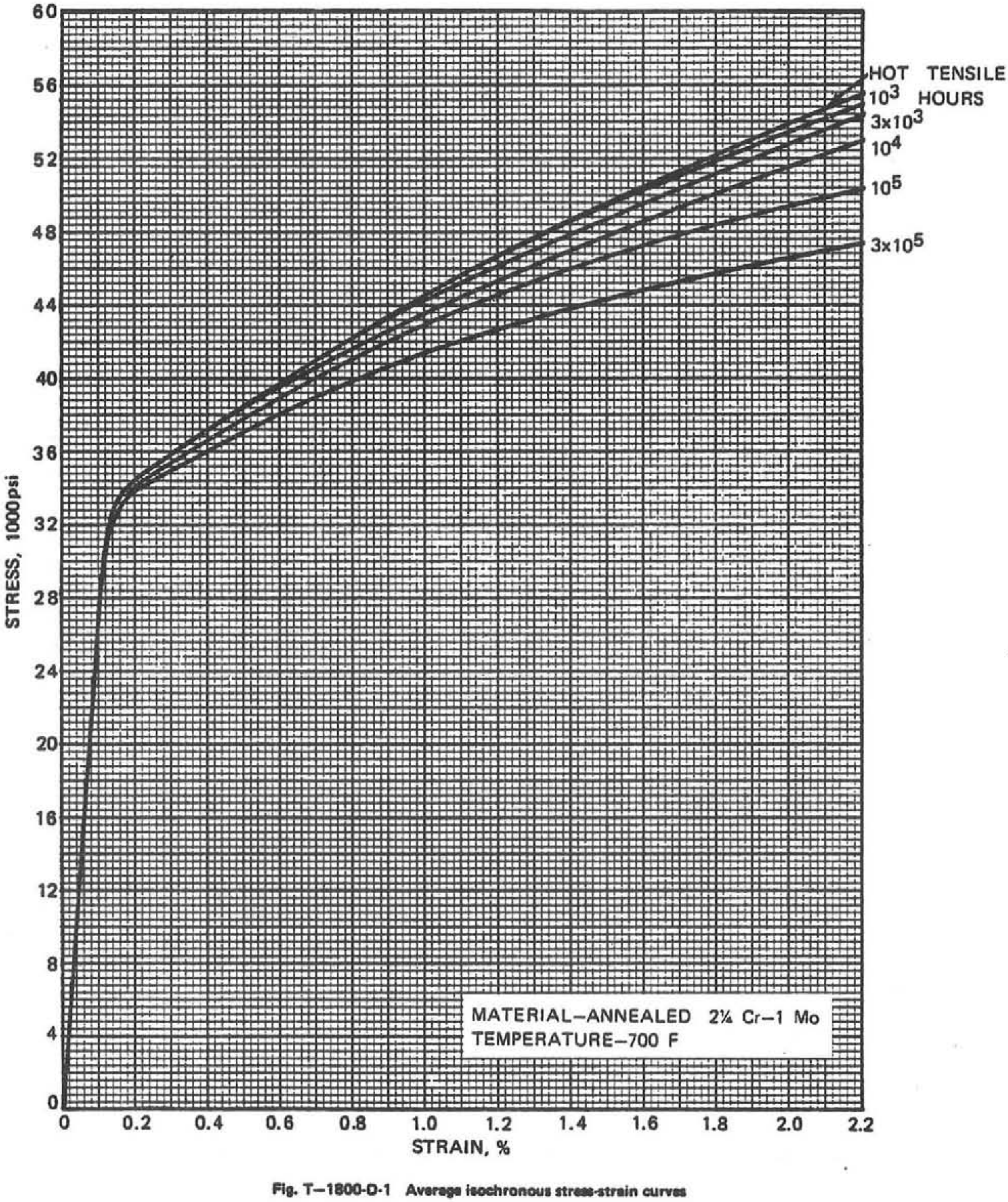

Fig. T–1800-D-1 Average isochronous stress-strain curves

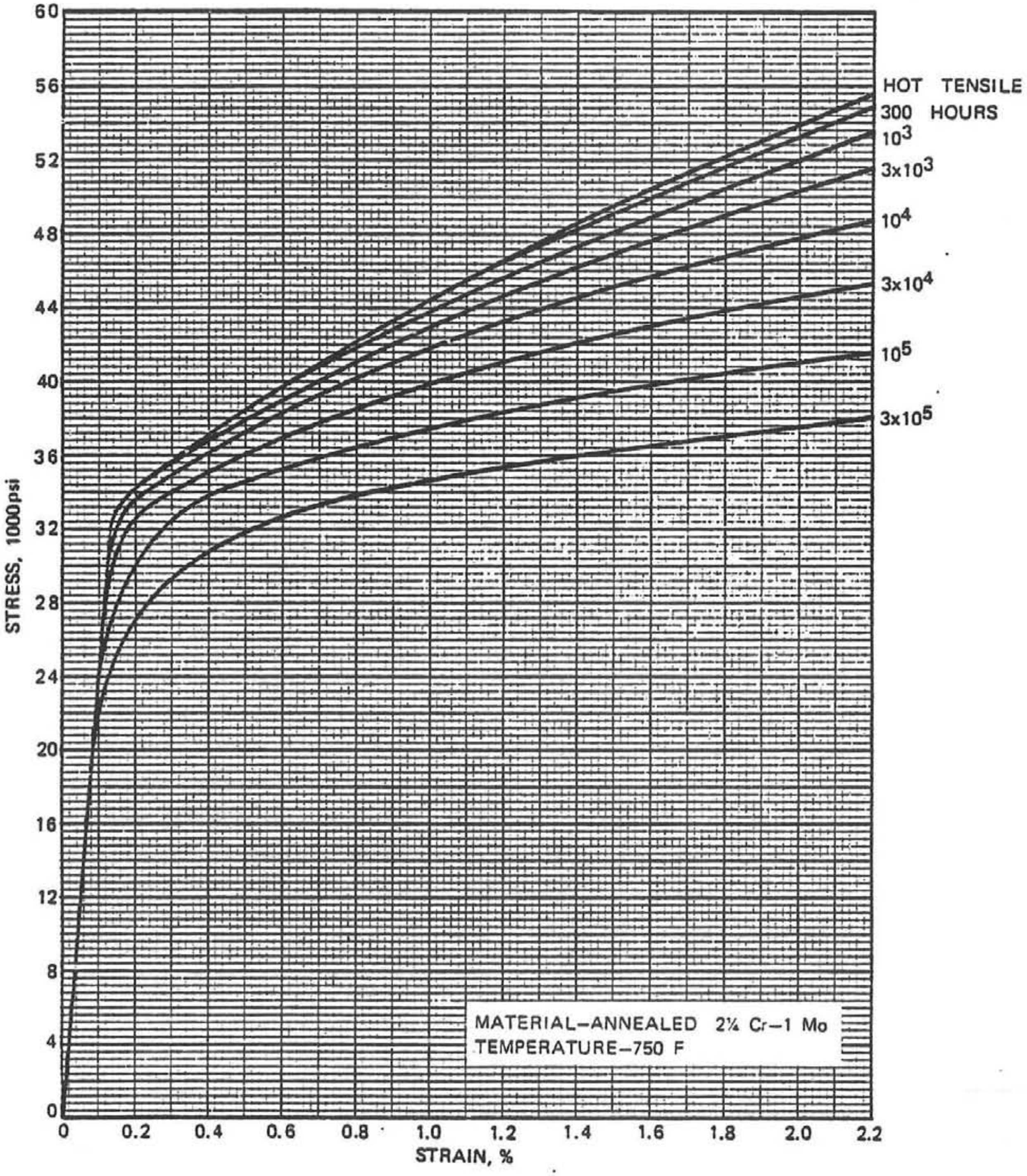

Fig. T–1800-D-2 Average isochronous stress-strain curves

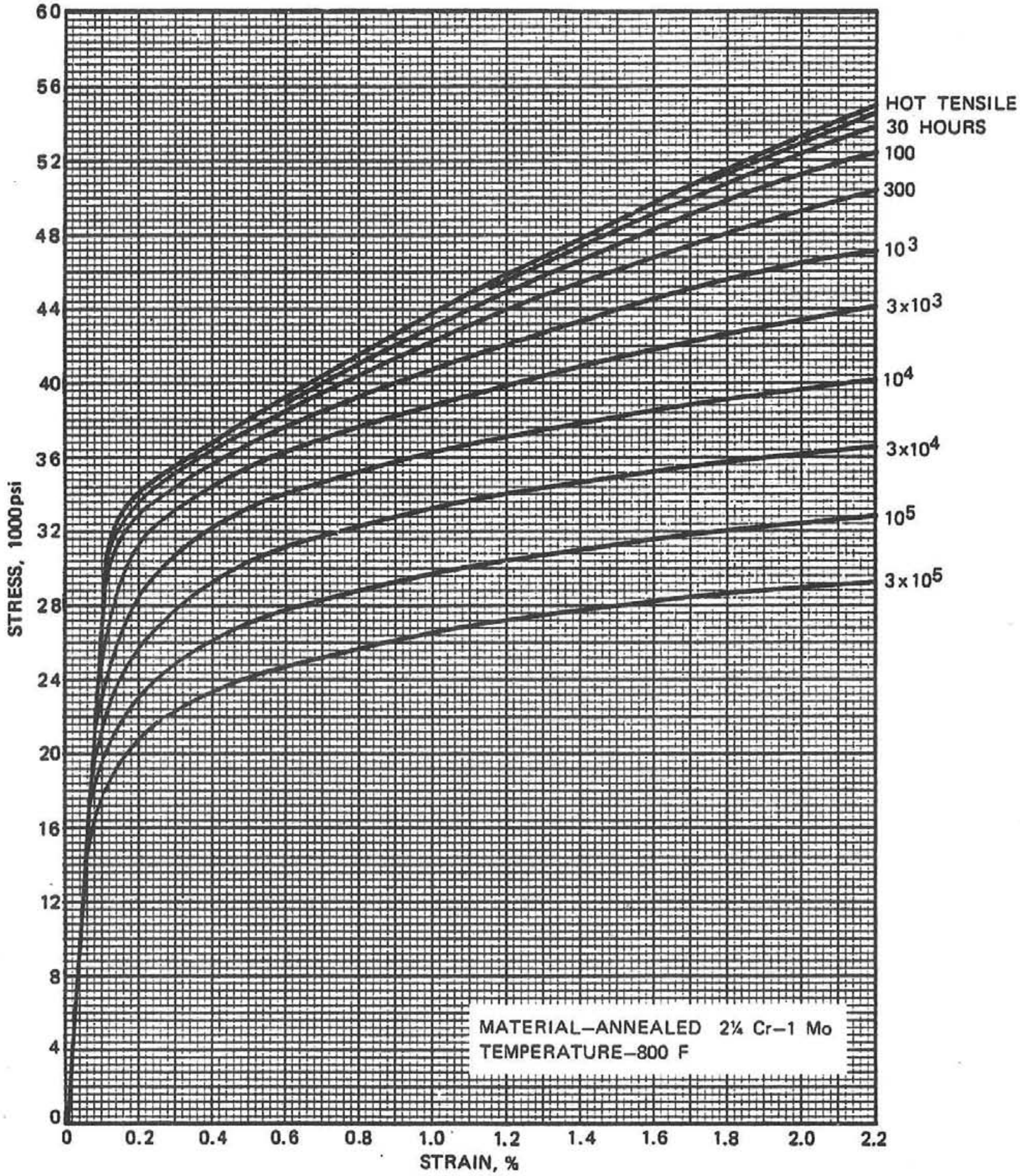

Fig. T–1800-D-3 Average isochronous stress-strain curves

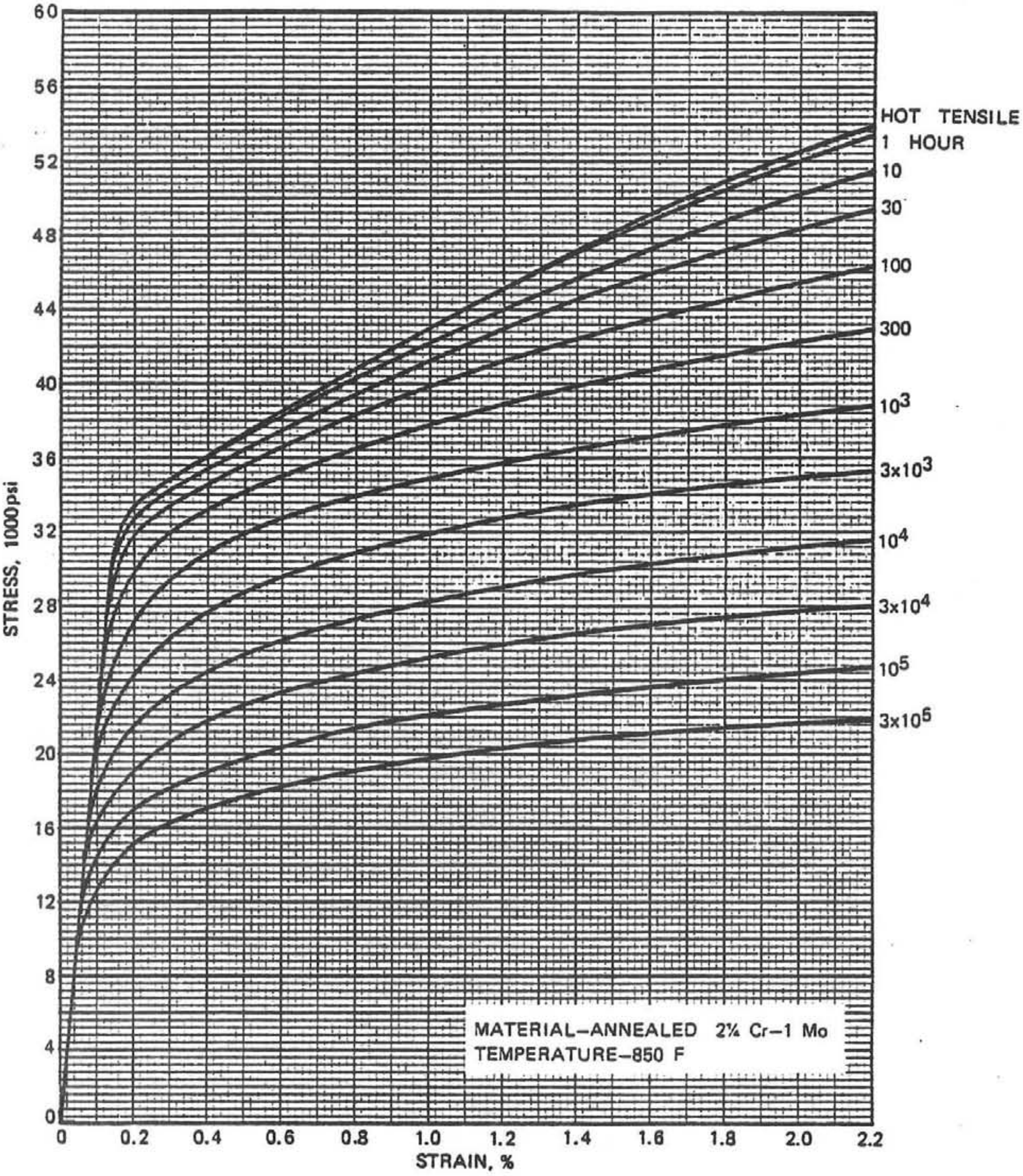

Fig. T—1800-D-4 Average isochronous stress-strain curves

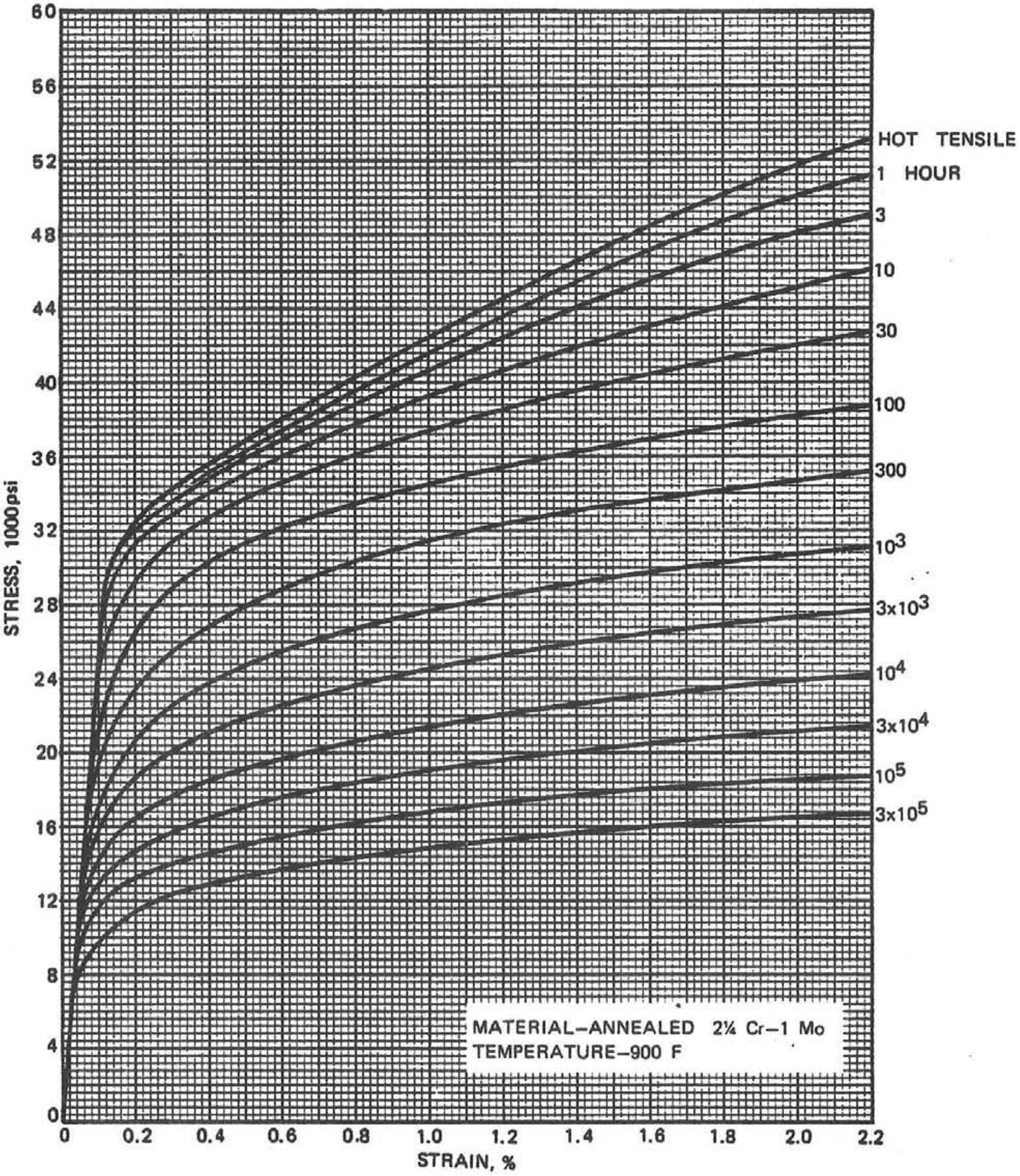

Fig. T–1800-D-5 Average isochronous stress-strain curves

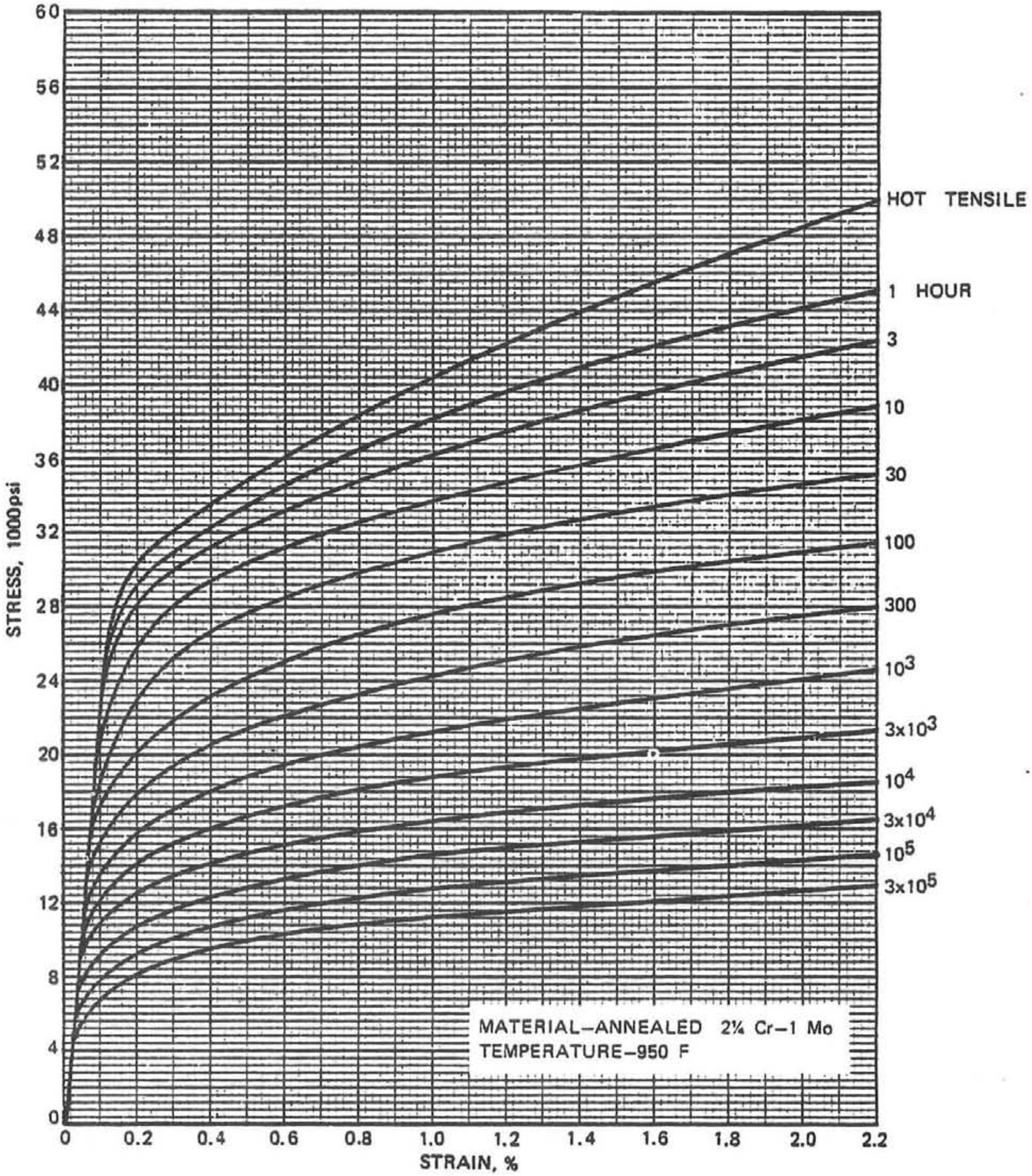

Fig. T–1800-D-6 Average isochronous stress-strain curves

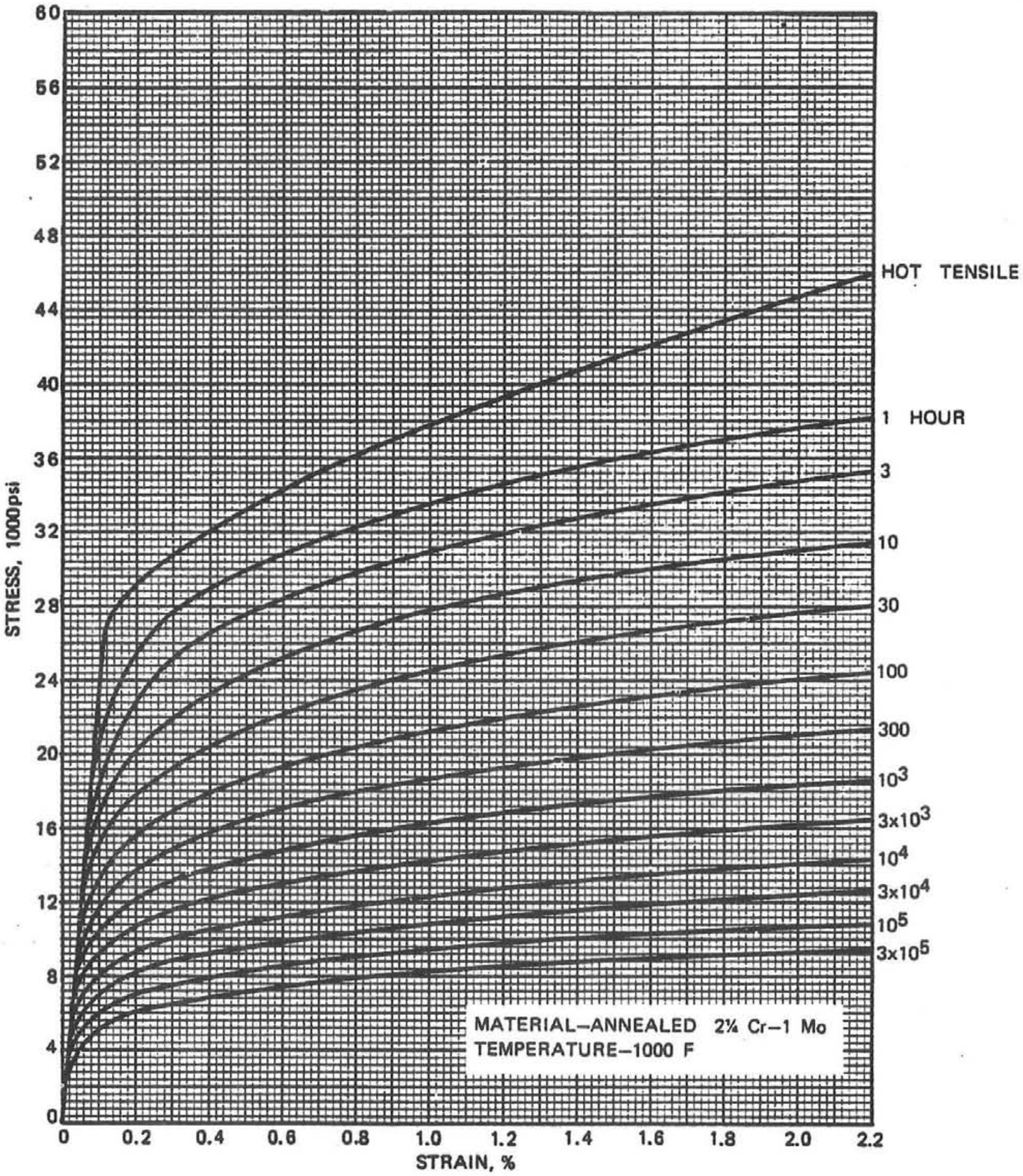

Fig. T–1800-D-7 Average isochronous stress-strain curves

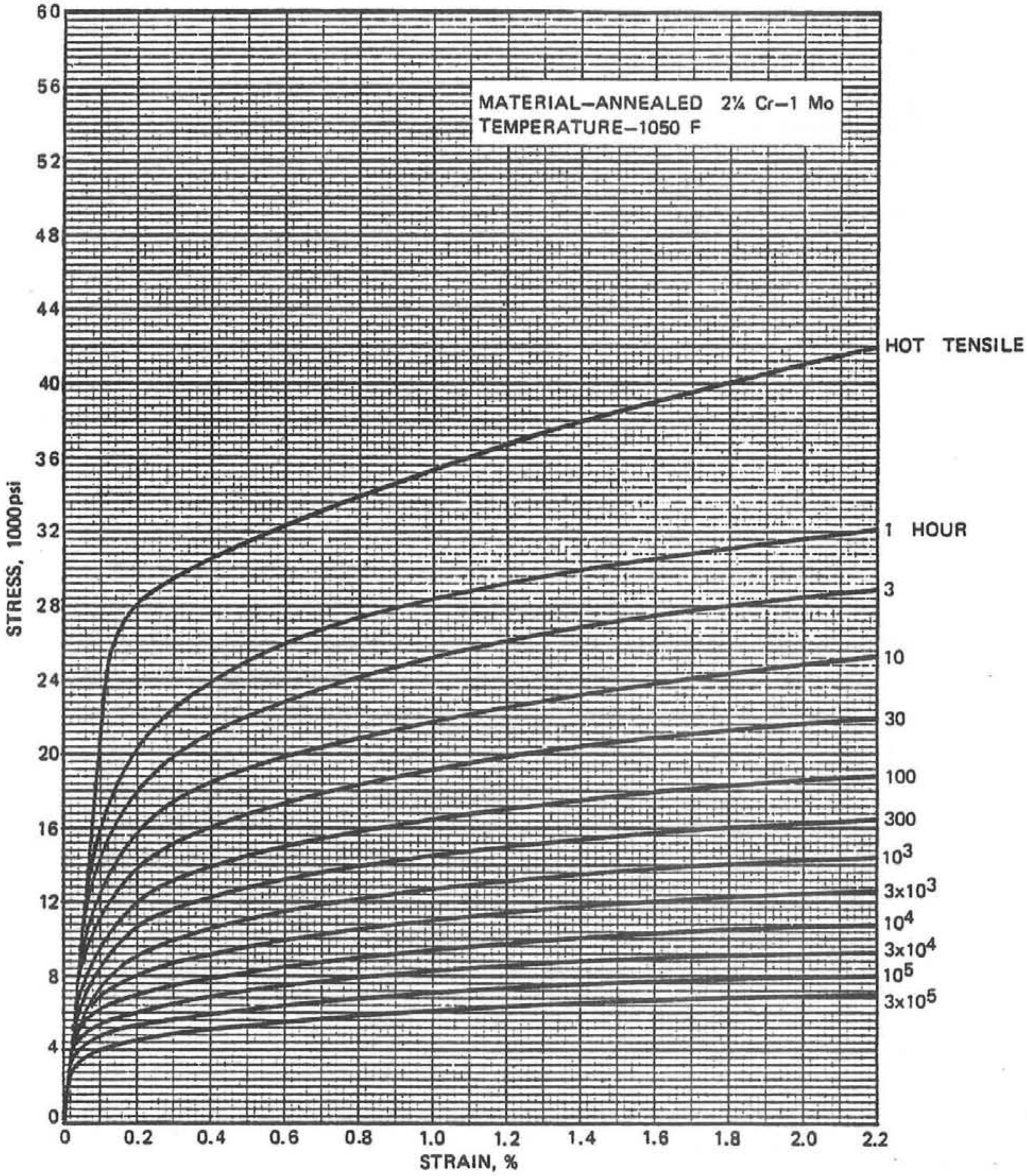

Fig. T–1800-D-8 Average isochronous stress-strain curves

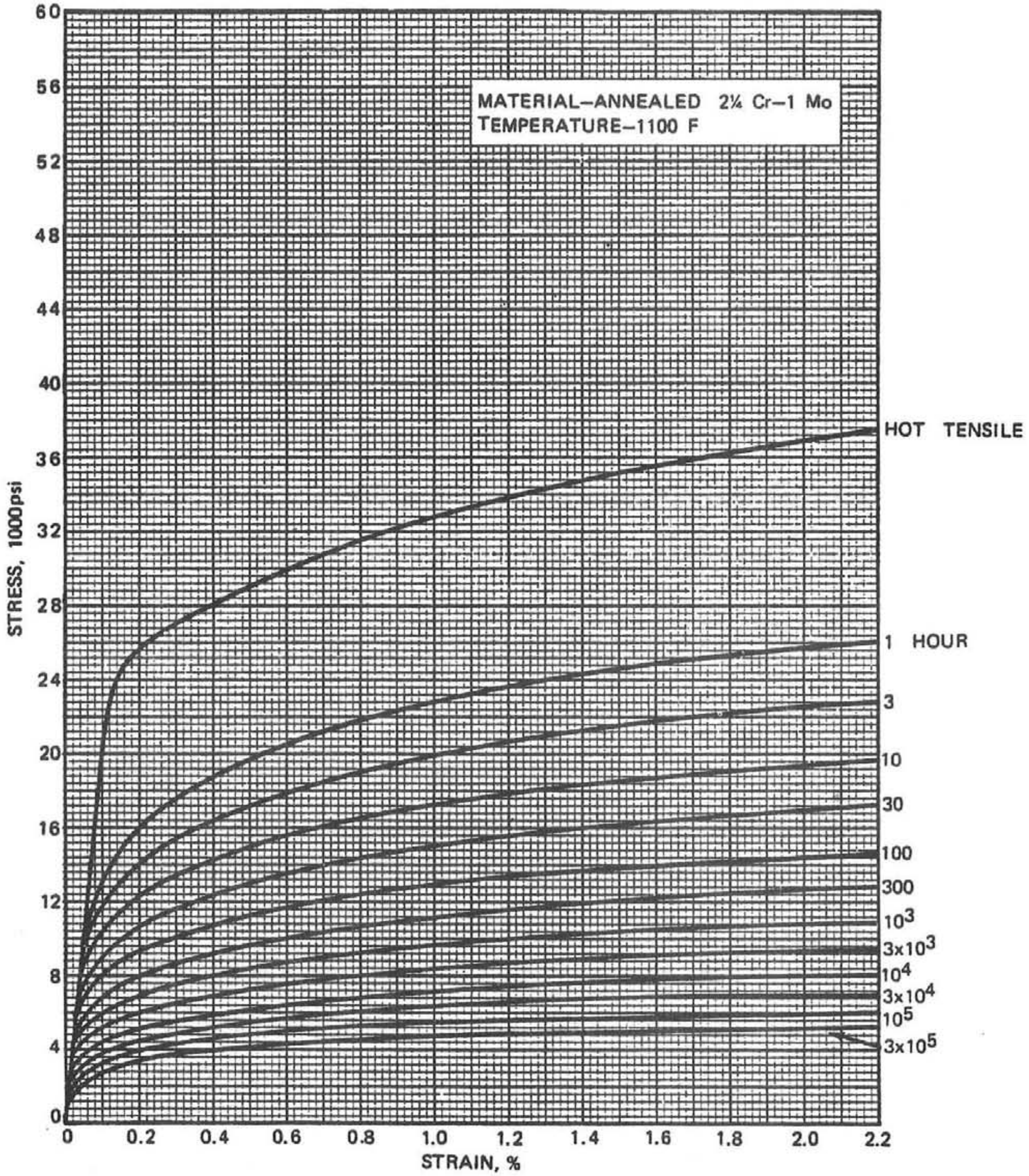

Fig. T–1800-D-9 Average isochronous stress-strain curves

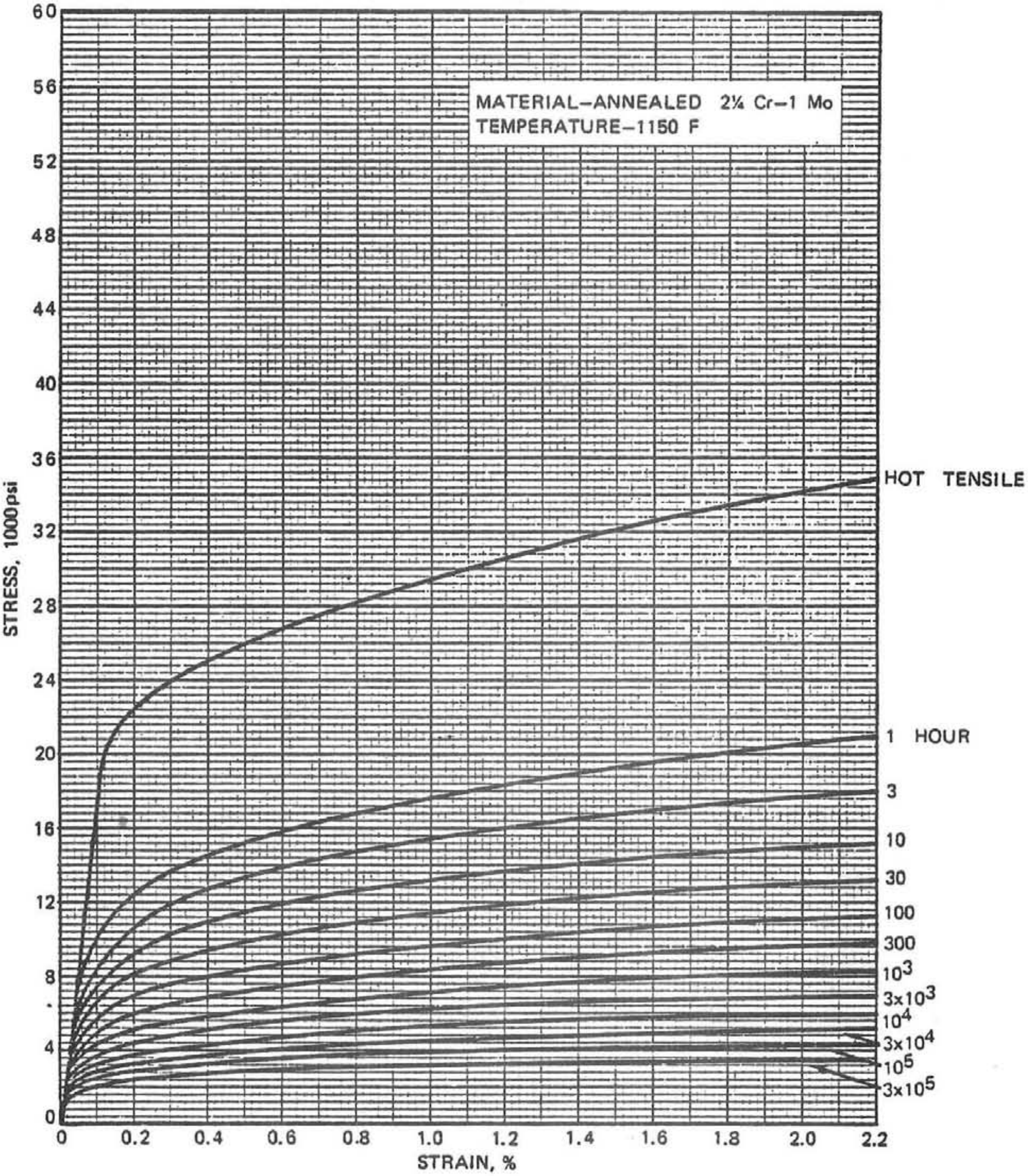

Fig. T–1800-D-10 Average isochronous stress-strain curves

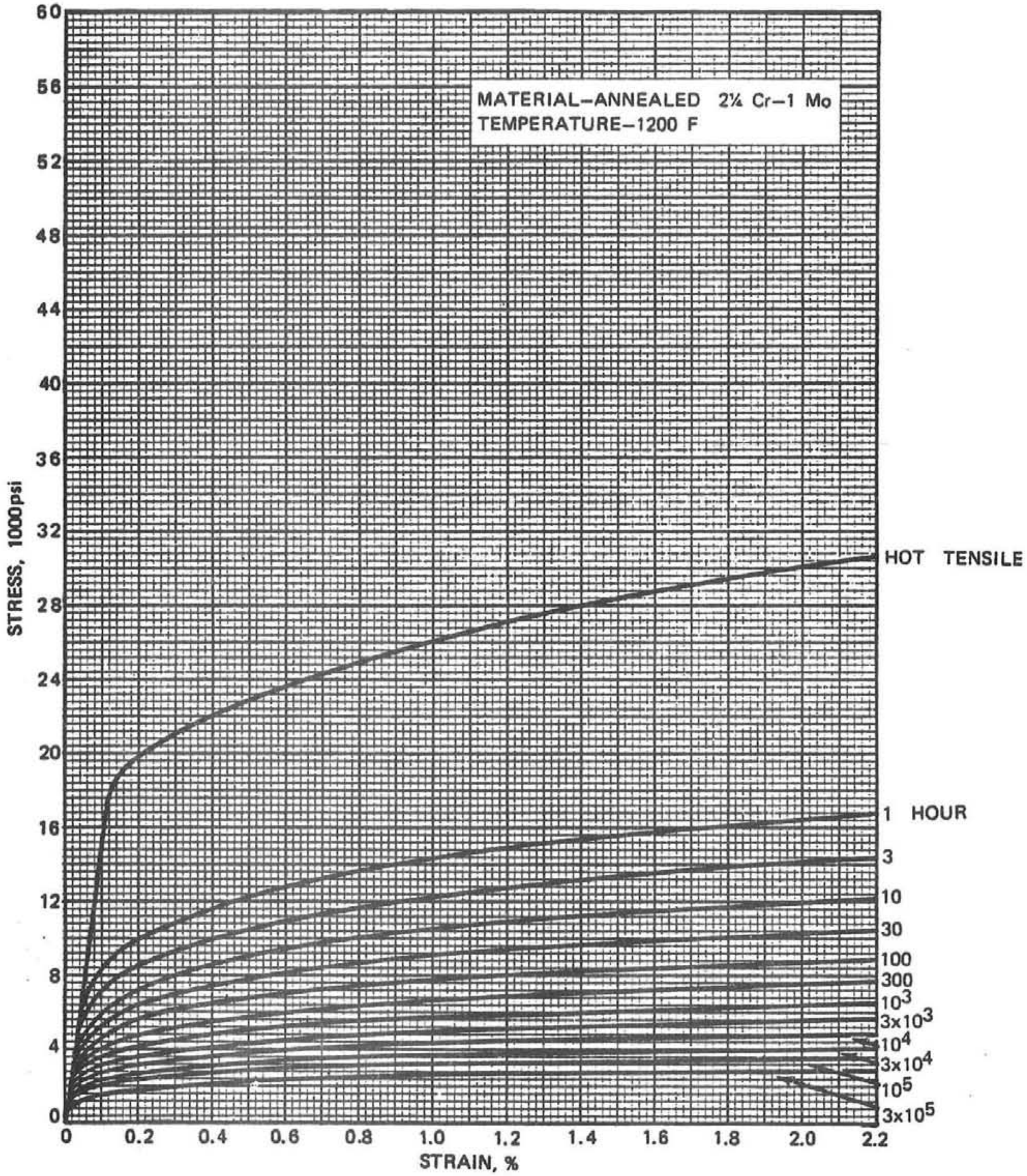

Fig. T–1800-D-11 Average isochronous stress-strain curves

SECTION 4
EXPLANATION

Section 4

EXPLANATION

The general philosophy and approach taken in preparing the Interim Design Standard was discussed in Section 2. This section provides a detailed paragraph-by-paragraph explanation of the Interim Design Standard.

SCOPE: The scope of the Interim Design Standard is limited to pressure vessel and piping components of the central receiver solar thermal power systems of the water/steam type. With a few alterations and additions this standard may be made applicable to distributed systems and advanced solar power systems. Design criteria for nonmetallic materials such as ceramics would require a major study and a new design standard. Pressure parts associated with rotating or reciprocating mechanical devices such as pumps, compressors, turbines, generators, and engines are excluded. Components having an internal pressure not exceeding 15 lb/in^2g (103 kPa) or in excess of 3000 lb/in^2 (30,670 kPa) are also excluded. These exemptions are consistent with the Section VIII-Division 1 and Section I approaches.

NUMBERING SYSTEM: The numbering system follows the general pattern of Section III and Code Cases 1592 and 1481.

-3100 GENERAL REQUIREMENTS FOR DESIGN. The general pattern of Code Case 1481 for nuclear Class 2 and 3 components was followed. The style of presentation used in Section VIII-Division 1 is different from that of Section VIII-Division 2. Rather than choose either of those, the most recently developed and most convenient style of Code Case 1481 is utilized herein.

-3111 (b) Identical to -3111 (c) of Code Case 1481. A general statement of this type is useful and essential until specific rules to guard against low energy fracture are adopted.

-3111 (c) Similar to -3111 (e) of Code Case 1481. Certificate holders are those who are authorized by ASME to use Code Symbols for marking items which have been constructed and inspected in compliance with the ASME Solar Energy Standard.

-3112 DESIGN REPORT AND CERTIFICATION. The design and reporting requirements of the Code range from almost none in Section I to the detailed stress report in Section III. Section VIII-Division 2 procedure requires a Manufacturer's Design Report (Page 12 in Section VIII-Division 2) which includes calculations and drawings necessary to show Code compliance. Section VIII-Division 1 requires a Manufacturer's Data Report (UG-120 and Appendix W). The approach selected for the Interim Design Standard is:

- Use Section VIII-Division 1 procedures if Division 1 is used for component design.
- Use Section VIII-Division 2 procedures if Division 2 is used for component design. Division 2 procedures should also be required for those components for which explicit computations relating to fatigue, creep-fatigue, or buckling are made.

-3200 DESIGN RULES (VESSEL). The numbering system parallels that of Section III. The components of Section III pertaining to design are:

-3200 Design by Analysis (Vessels)
-3300 Design by Rule (Vessels)
-3400 Valves
-3500 Pumps
-3600 Piping

The Interim Design Standard is mainly concerned with vessels and piping. Hence the sequence selected is:

-3200 Design Rules (Vessels)
-3300 Piping

-3220 BASE DESIGN RULES. Section VIII-Division 1 has been selected as the basis of design for solar power plant components. Section III was not selected because:

- Section III was developed for nuclear power plant components.
- Class 1 rules are generally very restrictive and expensive to use.
- Solar power plant components do not call for such a high level of reliability as required for Class 1 nuclear components.
- Class 2 or 3 nuclear components may be more similar to solar power plant components.
- Subcreep* temperature Class 2 and 3 rules are similar to those in Section VIII.

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*Subcreep temperature is defined as any temperature value at which the design stress intensity is given in Section VIII-Division 2 of ASME Boiler and Pressure Vessel Code.

- Elevated temperature Class 2 and 3 rules are used as a guide to develop rules for solar components at elevated temperature service.
- Requirements relating to materials, fabrication, inspection, testing, and pressure-relief devices of Section III are very stringent and may result in heavy economic penalties when used for solar power plants.

Reasons why Section I was not selected:

- Section I is applicable only for boilers in which steam or other vapor is generated at a pressure of more than 15 lb/in^2g, and high-temperature water boilers (>250°F; >160 lb/in^2g).
- Technically, Section I may be applicable to the receiver components of a solar power plant in which steam is generated directly within the receiver.
- All components of a Distributed Collector Solar (DCS) system would fall outside the jurisdiction of Section I. This is so because the receiver of a DCS system may use fluid (organic oil) which is not vaporized and may also operate at pressures lower than 15 lb/in^2g.
- The central receiver solar power system in which liquid sodium or molten salt is heated in the receiver would also be outside the jurisdiction of Section I.
- Section I is highly dependent on experience with steam and hot water boilers at the specific conditions covered and thus many of the specialized rules may not be applicable for solar components.

Since the applicability of Sections I and III is limited, a logical and consistent set of rules for solar components must be based on Section VIII-Division 1.

-3220 (a) In addition to Section VIII-Division 1 rules, additional requirements are needed for solar components for which certain failure modes, not explicitly considered in Section VIII-Division 1, are important and may affect the design. These additional requirements are given separately in -3250.

-3220 (b) Since Section VIII-Division 1 design rules have been judged to be the most suitable for solar power plant components, it is recommended that the requirements of Section VIII-Division 1 relating to materials, fabrication, inspection, testing, and pressure relief devices also apply.

-3220 (c) Modified from UG-5(c) [Page 11] of Section VIII-Division 1. Approval for new solar materials should be obtained from the Solar Code Committee instead of the Section VIII Committee.

-3220 (d) Snow loads, shipping loads, and vibrations are not included in the list of loads given in Section VIII-Division 1. These are included in the Interim Design Standard.

-3230 ALTERNATIVE DESIGN RULES. Section VIII-Division 2 is an alternative to Division 1 based on 'Design by Analysis' for service at temperatures in the subcreep regime. Division 2 permits a reduction in the wall thicknesses of many pressure components and hence it is considered advisable to retain this alternative in the Interim Design Standard.

-3230 (c) Similar to a statement in A-100 (a) of Section VIII-Division 2. This is a useful clarification.

-3230 (d) Modified from AM-100 (d) [p. 19] of Section VIII-Division 2. Approval for new solar materials should be obtained from the Solar Code Committee instead of the Section VIII Committee.

-3250 ADDITIONAL REQUIREMENTS. Section VIII-Division 1 design rules do not explicitly guard against the following failure modes which may be important in the design of some solar power plant components.

- Excessive plastic deformation
- High strain-low cycle fatigue
- Stress rupture/creep deformation (inelastic)

Also, Section VIII-Division 1 rules do not consider the effects of the following loads adequately.

- Seismic load
- Thermal loads (sustained)
- Thermal and mechanical loads (cyclic).

In order to account for these loads and failure modes, a set of additional rules are prescribed.

-3251 FATIGUE EVALUATION (SUBCREEP EVALUATION). An explicit fatigue evaluation is necessary for some solar power plant components. This section is contains two parts. The first part lists those components for which no fatigue evaluation is required and Section VIII-Division 1 rules are considered adequate. The second part relates to the fatigue evaluation rules which must be met for the remaining components. Section VIII-Division 2 fatigue rules are recommended for explicit fatigue evaluation at low temperatures.

-3251.1 FATIGUE EVALUATION NOT REQUIRED. Presently, only those receiver components not directly exposed to the solar heat flux have been identified to have small enough cyclic stresses that a fatigue evaluation may not be required. More components may be added to the list as more experience with solar components is gained.

-3251.1 (b) This statement allows the owner to reduce the design cost if he has determined that a particular component would be safe and effective without fatigue evaluation.

-3251.2 (b) and (c) These are repetitions of two significant statements given in AD-160 of Section VIII-Division 2. They are not essential but extremely helpful because they list the specific articles and appendices where the rules are given in Section VIII-Division 2.

-3252 CREEP-FATIGUE EVALUATION. For elevated temperature service, solar components must be protected from time-dependent failure modes. In Section VIII-Division 1 the pressure stresses are limited to an allowable stress, S. This stress, S, at elevated temperature is determined from the following time-dependent considerations:

- 67 percent of average rupture strength at 10^5 h
- 80 percent of minimum rupture strength at 10^5 h

- 100 percent of average stress for a creep rate of 0.1%/1000 h.

This does account for the creep effects caused by steady-state pressure stresses. However, the creep-fatigue and ratcheting effects caused by cyclic pressure (or mechanical loads) and thermal stresses are completely ignored in Section VIII-Division 1. For some solar components these effects may be very important. Code Case 1592, for Class 1 nuclear components, requires explicit creep-fatigue and ratcheting evaluations. Code Case 1481, for Class 2 and 3 nuclear components, provides exemption rules to the creep-fatigue evaluation. For solar components, the following rules are selected:

a. Explicit ratcheting evaluation is not required.
b. For certain components, explicit creep-fatigue evaluation is not required.
c. Exemption rules to creep-fatigue evaluation are provided. Use Code Case 1481 as a guide.
d. An explicit creep-fatigue evaluation is required for any component which does not belong to (b) and cannot meet the exemption in (c).

Ratcheting is a failure mode which causes excessive deformation and may impair the functional requirement of a component. In solar components,this is not a very important consideration. The only major failure that must be guarded against is rupture/leakage. Creep-fatigue is the corresponding failure mode. Creep-fatigue limits in the nuclear Code may be too conservative for use in solar component design because of the higher reliability and safety requirements of nuclear power plant components.

-3252.1 CREEP-FATIGUE EVALUATION NOT REQUIRED. A component for which the cyclic stresses are low may be exempted from creep fatigue evaluation. Presently, only those receiver components not directly exposed to the solar flux are included in the exemption list. More components may be added as more experience with solar systems is gained. A statement providing some flexibility to the owner is also provided.

-3252.2 RULES TO DETERMINE NEED FOR CREEP-FATIGUE ANALYSIS. The creep-fatigue exemption rules are based on Appendix A of Code Case 1481. This is the only code which contains a set of exemption rules to creep-fatigue evaluation. The following are the differences between the Appendix A, Code Case 1481 rules, and the rules in -3252.2:

- Code Case 1481 provides three sets of exemption criteria. The first is related to analytical evaluation and is used as a basis for rules in -3252.2. The second set is related to experimental evaluation. These exemption criteria are not directly applicable to solar applications. Further study is required before a suitable experiment base exemption is developed for solar components. The third set is already included in -3252.1 (b).

- The definition of a significant load cycle in Appendix A of Code Case 1481 is related to the allowable stress values of Code Case 1592. These are S_m, S_t, and S_{mt}. However, the base design rules for solar components use Section VIII-Division 1, in which the allowable stress, S, is used. Therefore, the definitions in 1.1, Appendix A of Code Case 1481 have been modified so that Section VIII-Division 1 may be utilized without adversely affecting the rules. These details are described as follows:

  - Appendix A, 1.1 (a) of Code Case 1481 considers a load cycle significant if "the range of the elastically calculated primary stress is greater than 125 percent of the maximum allowable primary stress," i.e., $\Delta P_m > 1.25 S_m$, for elevated temperatures $S \leq S_m$. Therefore, S_m can be conservatively changed to S. This change is adopted in -3252.2 (a).

- Appendix A, 1.1 (b) and (c) of Code Case 1481 consider a load cycle significant if the range of the elastically calculated secondary stress is greater than 50 percent of:

  (1) $3S_m$ when the maximum wall-averaged temperature is equal to or below the temperature at which $S_m = S_t$.

  (2) $3S_{mt}$ when the maximum wall-averaged temperature is above the temperature which $S_m = S_t$.

  S_t for the above may be determined either for the specified service life or 10^5 h.

  For case (1), the condition remains unchanged if 3S is used instead of $3S_m$ because $S \equiv S_m$ at those temperatures where this case applies.

  For case (2), $3S_{mt} \equiv 3S_t$. S_t is a time-dependent property whereas S is determined from time-dependent considerations at 10^5 h. Logically, S_t at 10^5 h should be equal to S but the properties listed in Code Case 1592 show that S_t at 10^5 h < S. This is because S_t is determined from minimum properties whereas S is determined from average properties. For solar components, S is adequate because it would eliminate the use of additional properties such as S_t and S_{mt}, make a more convenient rule, and use a material property (S) which is more consistent with the reliability and safety requirements of solar components. Thus, the two statements of 1.1 (b) and (c) in Appendix A are modified to a single requirement of -3252.2 (b).

- Appendix A, 1.1 (d) of Code Case 1481 considers a load cycle significant if the range of the elastically calculated peak stress is greater than twice the allowable stress amplitude at 10^6 cycles. The allowable stress amplitude is computed by multiplying the allowable strain amplitude obtained from the elastic design fatigue curves of Code Case 1592, (Figure T-1430-1) by Young's Modulus.

  The same statement is made in -3252.2 (d) except that the allowable stress amplitudes must be taken from the fatigue curves attached to the code. These fatigue curves [Figures -3252.2(a) and -3252.2(b)] are extensions of Section VIII-Division 2 fatigue curves to elevated temperature range. These curves were developed by the Working Group on Creep Analysis of the ASME Boiler and Pressure Vessel Code Committees. The approach is more consistent with that of Section VIII-Division 2.

-3252.3 CREEP-FATIGUE ANALYSIS. For those solar components which cannot meet the exemption rules, explicit creep-fatigue evaluation must be performed. Code Case 1592 is the only code that provides a set of creep-fatigue evaluation rules and hence they are utilized herein with some modifications. These modifications are explained and justified below.

- The number of design allowable cycles, N_D, in Code Case 1592 (T-1411, p. 167) are determined from design fatigue curves (Figures T-1420-1 and T-1430-1). The curves in Figure T-1430-1 include the effects of slow strain rates and are used for elastic analysis. For solar components only the design fatigue curves of Figure T-1420-1 are included and the curves Figure T-1430-1 are discarded for several reasons. The creep-fatigue evaluation is of major importance for components which are subjected to high thermal stresses, e.g., the receiver components exposed to direct radiation. In those cases, the computed strain range is approximately the same whether determined from an elastic analysis or an inelastic analysis. Furthermore, the large factors of safety incorporated in the fatigue curves of Figure T-1420-1 are sufficient to account for any underestimate in the strain ranges if computed elastically.

- The allowable time, T_d, in T-1411 of Code Case 1592 is determined from stress-to-rupture curves at a stress value equal to the calculated stress (or effective stress) divided by the factor K' (Table T-1411-1). For the solar components [-3252.3 (a)], this factor K' is assumed to be 1. This eliminates some of the conservatism adopted in Code Case 1592 for nuclear components.

- The procedure to calculate the equivalent strain range as described in -3252.3 (b) is technically identical to T-1413 of Code Case 1592; however, the presentation is modified somewhat for convenience.

- The following sections of Code Case 1592 have not been included in -3252.3.

  - T-1430 - Limits Using Elastic Analysis. These limits are too restrictive and therefore not suitable for solar components.

  - T-1432 - Fatigue Damage Evaluation. This section could be utilized for solar components if studied and evaluated thoroughly. Some modifications may be needed in order to make it suitable for solar application.
  - T-1434 - Calculation of Strain-Range for Piping. Not applicable.
  - T-1435 - Alternate Creep-Fatigue Evaluation. Not Applicable.

- The procedure to compute creep damage in T-1433 has been modified considerably. The main thrust of these modifications is to simplify the creep-damage evaluation and to decrease the level of conservatism built into the rules for nuclear components.
  - The loading condition classifications, normal, upset, emergency, and faulted, have been excluded. This is consistent with the Section VIII-based philosophy of the Interim Design Standard.
  - For elastic analysis, 1.25 Sy is used for solar components as in T-1433 for nuclear components.
  - For elastic and inelastic analysis, instead of 'stress intensity', the maximum principal tensile stress has been chosen as the criterion for determining creep damage for Type 304 and 316 stainless steels. This is a significant departure from Code Case 1592, which assumes that stress intensity or shear stress governs the creep rupture damage. This assumption would mean that compressive stresses cause as much creep-rupture damage as tensile stresses. This is contrary to available experimental evidence, at least for materials such as Type 316 and 304 stainless steels.[2-5]

Table 4 shows some test data taken from Reference 1 and pertains to Type 316. While this data is not conclusive with regard to multiaxial effects, it does indicate that:

- Compressive holds are no more damaging than zero holds.
- The creep-rupture criteria of nuclear Code based on stress intensity or effective stress, which in effect treats compression and tension as equally damaging, is too conservative and hence unsuitable for solar applications.

Table 4 Fatigue Data for Type 316 Stainless Steel*

Test Temperature °F (°C)	Total Strain Range (%)	Total Strain Rate (1/sec)	Hold Time† (min)	Cycles to Failure
1202 (650)	1.00	.0040	0.0	1122
	1.02	.0041	1.0T	460
	1.00	.0040	1.0C	1690
	1.00	.0040	1.0S	1020
	1.97	.0040	0.0	459
	1.95	.0040	6.0T	86
	1.92	.0040	6.0C	386
	1.90	.0040	6.0S	414
1100 (593)	1.00	.0040	0.0	2213
	1.00	.0040	0.6T	1170
	1.00	.0040	0.6C	2134
	1.00	.0040	0.0	2213
	1.00	.0040	6.0T	393
	1.00	.0040	6.0C	1938
1050 (566)	1.98	.0040	0.0	564
	1.96	.0040	6.0T	163
	2.07	.0040	6.0C	665
	2.05	.0040	6.0S	562

*Solution annealed.
†T (Tensile hold time)
C (Compressive hold time)
S (Symmetric hold time).

Similar evidence exists for Type 304 stainless steel. Not enough test data is available for Incoloy 800 and other materials. The developers of Code Case 1592 did recognize the validity of the above arguments, but because of the lack of conclusive evidence regarding multiaxial effects, they decided to be conservative and treat compression and tension the same. This may be appropriate for nuclear applications where safety and high reliability are of paramount importance. For solar systems of the water/steam type, there are no safety questions of this nature and hence such conservatism is not warranted. Hence, after considerable thinking, this new criteria was chosen. Additional tests are needed in order to generate creep rupture and creep-fatigue data so that this criteria may be refined and set on firmer footing. For materials other than 304 and 316 stainless steel the Interim Design Standard requires that effective stress be used for creep-damage evaluation until new material data and criteria are developed.

- -3252.3(c) is identical to T-1420(a) of Code Case 1592 (p. 168). It provides a mathematical procedure to compute cumulative creep damage during a time period in which the stress may not be constant.

-3260 BUCKLING INSTABILITY LOADS. Section VIII-Division 1 buckling limits are given in UG-23, UG-28, UG-29, UG-33, and Appendix V. Section VIII-Division 2 buckling limits are given in Article D-3 (pp. 157-162) and Appendix 2. The limits in both Divisions of

Section VIII are about the same and apply only to specific geometrical configurations under specific loading conditions. These include:

- Cylindrical shells (with and without stiffening rings) under external pressure.
- Cylindrical shells (with and without stiffening rings) under axial compression.
- Spherical shells under external pressure
- Formed heads with pressure on convex side.

Section VIII does not guard against:

- Strain-controlled buckling
- Time-dependent buckling.

Section VIII philosophy is essentially followed for the specific buckling rules for solar power system components. As in Section VIII, strain-controlled and time-dependent buckling are not mandatory requirements. Section VIII (either Division 1 or Division 2) may be used for time-independent load-controlled buckling. For geometric configuration and loading conditions which are not treated in Section VIII, the buckling limits are provided. This makes the rules in the Interim Design Standard more complete and consistent with Section VIII philosophy. These additional rules have been taken primarily from Code Case 1481. Although not mandatory, strain-controlled buckling rules have been included for convenience of the potential user.

-3261 (b)	Definitions. Identical to -3131.2 of Code Case 1481.
-3261 (c)	Identical to -3131.3 of Code Case 1481. Provides guidelines for cases in which interaction between load-controlled and strain-controlled buckling may occur.
-3261 (d)	Condensed version of -3131.4 of Code Case 1481.
-3261 (e) and (f)	Explained previously.
Table 3262.1	The limits are different from those in Code Case 1481 in that the limits on service loadings have been excluded. This was done simply to make those rules consistent with the philosophy of Section VIII.
-3300	DESIGN RULES (Piping). Solar piping may undergo cyclic loading due to diurnal variations which solar plants must withstand. Section I and Section VIII-Division 1 do not give any explicit consideration to cyclic loads. Therefore, ANSI B31.1 and B31.3 are recommended for the design of solar piping systems. Both ANSI B31.1 and B31.3 adequately consider the effect of cyclic loading.
Appendix A	Definitions. Definitions of terms used in the Interim Design Standard are given. Most are taken from Code Case 1592.
Appendix T	Average Isochronous Strain Curves. These curves are taken from Code Case 1592.

SECTION 5
TEST AND DEVELOPMENT NEEDS

Section 5

TEST AND DEVELOPMENT NEEDS

The Interim Design Standard is based on Section VIII of the Boiler and Pressure Vessel Code. It includes modified portions of other Sections of the Code in order to prevent failure modes that directly concern solar applications but not most Section VIII applications. In most cases the modifications were taken from Sections of the Code governing nuclear components. Thus the levels of reliability are much more stringent than needed for solar applications. An attempt was made in developing the Interim Design Standard to reach a reasonable compromise between the lack of adequate requirements of Section VIII and the overly conservative rules governing nuclear applications to obtain a uniform level of reliability that is appropriate to solar needs. The major changes relate to component applications at temperatures where creep is a factor. Some of the important changes are:

- Creep Damage. At temperatures for which creep is a factor, there is now a requirement that creep damage be considered. In the "nuclear codes" this damage is based on the effective stress or stress intensity during hold time. In the Interim Design Standard the creep damage is based on the maximum principal tensile stress. The justification for this is shown in uniaxial data for 304 and 316 stainless steel. This criterion is much less conservative and simpler to apply than the nuclear Code criterion and is of great importance to the practicality of solar component design. In addition, an arbitrary factor of 1.1 on creep damage which appears in the nuclear codes has been reduced to 1.0.
- Fatigue Damage. The nuclear Code requirement has been eased somewhat by permitting the general use of the curves for inelastic analysis at "elevated temperatures."

- Creep Fatigue Evaluation. Various exemptions have been specified and the exemption rules in Code Case 1481 have been modified for solar applications.

- Ratcheting and Creep Ratcheting. No additional requirements for ratcheting or creep ratcheting evaluation have been placed in the Interim Design Standard. Thus the evaluations that are made in the nuclear codes are deemed unnecessary. One related area is weld material. The nuclear codes deal with this by allowing only one half the allowable strain limits for weld material as for base material when calculations use data for base material.

- Buckling Instability. Since the rules for buckling in Section VIII apply only to specific configurations and loading, additional limits are provided which are applicable to general configurations and loading conditions. The additional requirements of the evaluation of creep buckling and strain-controlled buckling that appear in the elevated temperature nuclear Code are not mandatory.

The test and development needs are considered to fit into one or more of three types.

Type 1	Substantiation of the basis of the Interim Design Standard and/or the reduction of unnecessary conservatism in the Interim Design Standard.
Type 2	Simplification of the application of the Interim Design Standard.
Type 3	Expansion of the coverage of the standard to include additional materials and applications.

The test and development needs are summarized below.

5.1 TESTS RELATED TO CREEP-FATIGUE CRITERIA

Since creep fatigue is an important failure mode in solar components, tests are needed to verify or modify the creep-fatigue criteria and to generate design data. The following tests are recommended.

5.1.1 Elevated Temperature Fatigue Data (Type 3)

For temperatures in the subcreep regime, fatigue curves are available in ASME Code Section VIII-Division 2. However, acceptable fatigue curves at elevated temperatures are available only for three materials--Type 304 and 316 stainless steels and Incoloy 800H (Code Case 1592). For other candidate materials such as Incoloy 800, Inconels, and Haynes 188, fatigue data and design curves at elevated temperatures are needed.

5.1.2 Creep-Rupture Data (Type 3)

Code Case 1592 gives creep rupture times for four materials: Type 304 and 316 stainless steels, Incoloy 800H, and 2-1/4%Cr-1%Mo. For other candidate materials such as Incoloy 800, Inconels, and Haynes 188, tensile creep-rupture data are needed.

5.1.3 Cyclic Compressive Hold-Time Tests (Type 1)

The Interim Design Standard chooses the maximum principal tensile stress as the criterion for creep damage. The use of the maximum principal tensile stress criteria is generally less conservative than the choice of the stress intensity or the effective stress that is used in Code Case 1592. The applications in nuclear systems have not suffered unduly under this rule because most of their applications exhibit high tensile stresses. However, solar applications generally exhibit high compressive stresses in critical areas.

There is some justification for the use of this criterion. This justification is material dependent and has been obtained with uniaxial specimens. There is a limited amount of data mainly for Type 316 and 304 stainless steels.

Cyclic compressive as well as tensile hold-time tests are recommended for other candidate materials.

5.1.4 Multiaxial Creep-Fatigue Tests (Type 1)

Multiaxiality effects on creep-fatigue damage are an important consideration in solar applications. Multiaxial tests are generally complex and expensive. As a minimum, biaxial creep-fatigue tests are recommended. Argonne National Laboratory (ANL) is currently conducting such tests on Type 316 stainless steel tubes. Multiaxial tests using other candidate materials are necessary.

5.1.5 Structural Tests on Solar Receiver Tubes or Panels (Type 1)

Tests on solar receiver tubes under nonaxisymmetric flux conditions would be useful for evaluating the validity of the criteria proposed in the Interim Design Standard. These tests may be performed in a solar test facility or under simulated conditions with infrared heating. It may be noted that these tests would take into account the effects of bending which are excluded from the ANL tests.

5.2 RATCHETING TESTS (TYPE 1)

The Interim Design Standard does not give any specific requirements to prevent excessive thermal or creep ratcheting. This is different from the nuclear Code, which contains requirements for ratcheting analysis and limiting the ratcheting strain. The assumption for the Interim Design Standard is that the requirements to prevent ductile and creep rupture, the $3S_m$ limit (if Section VIII-Division 2 is used) and the creep fatigue limit will preclude excessive ratcheting. This assumption, however, needs to be verified by ratcheting tests that simulate solar conditions.

5.3 DEVELOPMENT OF EXEMPTIONS FROM CREEP-FATIGUE ANALYSIS TO MEET THE REQUIREMENTS OF THE INTERIM DESIGN STANDARD (TYPE 2)

The Interim Design Standard requires that for most components, either a creep-fatigue evaluation must be made or it must be demonstrated that there are few enough significant load cycles to make an analysis unnecessary. These rules for load significance were chosen to be only slightly less conservative than similar rules in the elevated-temperature nuclear Code. The following two studies could be very helpful in reducing the analysis and structural costs.

- Specific cases should be developed for components, loading conditions, and materials that can be safely exempt from creep-fatigue analysis.
- The exemption rules based on the significant cycles should be studied and analyses of many designs should be made. Less conservative rules can be developed if justified.

5.4 REVIEW OF THERMAL AND CREEP RATCHETING REQUIREMENTS IN THE INTERIM DESIGN STANDARD (TYPE 1)

The limits of the validity of the approach taken in the Interim Design Standard regarding thermal and creep ratcheting should be explored. This may be done by the analysis of typical and extreme cases on a cylindrical tube. For the appropriate materials, the results for a possible range of solar loading conditions and pertinent materials properties should be studied. If cases can be found which meet the ductile rupture and creep-fatigue criteria but still exhibit excessive thermal or creep ratcheting, the solar standards would have to be revised.

5.5 DESIGN AND ANALYSIS CURVES (TYPE 2)

There is a need for direction and simplification in the use of solar standards as well as a need to simplify the process of optimization of solar systems in compliance with the solar standards. The most immediate need relates to design curves for tubes subjected to radiant solar heating.

5.5.1 Tube Analysis Curves

The solar receiver tubes require complex analyses in order to meet the solar standard specifications. These tubes frequently operate at elevated temperatures and are subjected to nonaxisymmetric radiant heating. They are subjected to a much larger number of significant heating and cooling cycles than the tubes in nuclear or fossil fuel power systems.

The analyses of these tubes frequently involve very expensive computer programs. The use of a specialized computer program to develop a series of design curves is proposed. For example, with given tube material, diameter, thickness, internal pressure, heat flux, bulk temperature, and film coefficient, one can obtain the maximum metal temperature, thermal gradient, stresses, and strains.

5.5.2 Design Curves

Another important set of curves can be developed for the use of the system designer. He sets up a system with appropriate assumptions and would like to maximize the heat flux. One constraint is the maximum heat flux in a tube allowed by the solar standards. These limitations include prevention of ductile rupture and creep fatigue. Thus, given the tube material, diameter, thickness, internal pressure, bulk temperature, film coefficient, and the criteria of the solar standards, the maximum allowable heat flux would be determined.

5.6 ANALYTICAL AND EXPERIMENTAL STUDIES ON METALLIC SOLAR STRUCTURES (TYPE 1)

Development of data related to material strength (tensile, yield, creep rate, fatigue characteristics, etc.) is only one aspect of the problem of constructing safe structures. These materials data are obtained from the chosen working parameters and are usually an arbitrary point of measurement. These data must then be related to the complex shapes and loading conditions of actual structures by means of analysis. The allowable materials and dimensions of the structure are then determined by the limitations imposed by solar standards. There are many difficult areas concerning solar applications which need more study. Three specific items are discussed below.

5.6.1 Effects of Material Property Variations on Multiaxial Analysis (Type 1)

Even though there generally exists a large scatter in materials data, some definite value or values are chosen for design and analysis. These are called "book" values. The material properties of actual structures vary. However, for the usual design in the elastic range, the important parameters vary little. It is simple to use an appropriate factor for safe design.

For inelastic (plastic and creep) behavior, the material data scatter is large. The effect on safe design of variations in the actual material properties and dimensions is not intuitively obvious. In some cases, the choice of a particular value for a parameter would be conservative for one possible failure mode but not for another. This is particularly true in the two possible failure modes of creep and fatigue damage which are of great importance in solar receiver applications.

It is useful to study the effects of the variation of materials parameters with typical problems encountered in solar receivers. The effects of this variation may be related to the limits defined in the solar standards. It may then be appropriate to assign limits of material properties for use in solar applications.

5.6.2 The Effects of Weld Material on Elevated Temperature Long-Time Behavior (Type 1)

Analyses of structures with elastic-plastic-creep behavior require the entire "stress-strain-time" material property data. The material property values for weld material and the heat effective zone as compared to those for base material can be very different. This weld material is usually chosen mainly for its adequacy in terms of ductability and may have some properties that are substantially different from those of the base material. Central receivers generally--and in particular the 10-MWe central receiver--have panel assemblies that are constructed of tubes placed side by side and joined by full-length longitudinal-seam welds. At elevated temperature design, many of the properties of the weld and base materials will determine the adequacy of the design. In a manufacturer's analysis, only the book values of the base material are used.

It is useful to study basic tensile and beam specimens of base metal, weld metal, and combined specimens, under creep. It is also necessary to study the compatibility of the base and weld metal properties to guard against specific failure modes (i.e. creep fatigue) that are required by the solar standard. In order to do this, tensile and large beam specimens can be used to test base metal, weld metal, and combined specimens. Existing large creep-bending machines can be used for accurate evaluation of the creep properties. Bending specimens can then be tested in a large creep-fatigue bending setup to determine creep-fatigue behavior.

5.6.3 Experimental and Analytical Evaluation of Attachments and Joining Methods (Type 2)

Failure frequently occurs at joints in which the stress levels are high. This is especially true of the fatigue and creep fatigue modes of failure which are of great significance in solar applications.

There are a number of experimental studies that are important. Some of these are:

- The attachments of tubes to headers under the loads imposed on solar receivers.
- Lug and hanger attachments to tubes.
- The stresses due to applied thermal loads in welded panels in which there may be different weld and base metal material properties. The effect on the ends of adjacent rows of hot and cool tubes and the effect of the local stresses due to the longitudinal weld may be studied.

5.7 MONITORING OF METAL BEHAVIOR

Excessive permanent distortion of components of a solar installation is to be avoided. It is difficult to measure this distortion because of the wiring and long-term nature of the measurement. It is especially difficult at elevated temperature because strain gages and similar techniques are very questionable over the long term. However, there is one effective method of measuring permanent metal growth in which the measurements are made only at ambient temperature at periods of shutdown. The method, known as image transfer, requires no foreign material on the part of attachment of wires.

It would be of value to develop some laboratory data directed towards solar applications and to apply the technique to various solar installations. A comparison with measurements made by means of other techniques would also be of great value.

SECTION 6

REFERENCES

Section 6

REFERENCES

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