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No

THE COMBINED EFFECTS OF A SODIUM ENVIRONMENT AND EXTENDED LIFE ON TYPE 316 STAINLESS STEEL AND CROLOY 2-1/4 ALLOY STEEL DESIGN STRESSES

Report No BW 67-3

September, 1964

MASTER

to

U.S. Atomic Energy Commission
Chicago Operations Office
Lemont, Illinois

SODIUM-HEATED STEAM GENERATOR
DEVELOPMENT

AEC CONTRACT NO. AT (11-1) - 1280
B&W CONTRACT NO. 610 - 0067

THE BABCOCK & WILCOX CO.
BOILER DIVISION

Barberton, Ohio

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BY: R.C. Anstine

THE BABCOCK & WILCOX COMPANY
NUCLEAR & SPECIAL PRODUCTS
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BY: R.C. ANSTINE

ABSTRACT

To achieve an economical but safe design, the designer must have a good knowledge of the use limits of any material under consideration, including all environmental and extended life effects. In this Report, the writer has reviewed the available data and based on limited data, presents design stress curves for Type 316 stainless steel and Croloy 2 1/4 alloy steel in a sodium environment and for an operating life of 30 years. (See Figs. 4 and 5). It is the writer's recommendation that these design stress curves can be used for the safe design of sodium-heated steam generators and other sodium components until further data becomes available.

THE COMBINED EFFECTS OF A SODIUM ENVIRONMENT AND EXTENDED LIFE ON TYPE 316 STAINLESS STEEL AND CROLOY 2 1/4 ALLOY STEEL DESIGN STRESSES

R.C. ANSTINE

INTRODUCTION:

The designer of any equipment must utilize the materials of construction as economically as possible. This requires a good knowledge of the use limits for any material under consideration. To make the optimum selection of materials, the designer needs to know: (1) the design stress based on mechanical properties for each material under consideration, and (2) how these mechanical properties, and therefore the design stress, may change during the design life of the component. In addition, the designer needs to know the rate at which the material he originally provided is lost due to corrosion, erosion, or other processes.

To proceed with the design of the Sodium-Heated Steam Generator under this Contract, it was necessary to review all existing data and determine conservative design stresses for the temperatures expected in the steam generator. In setting these design stresses, the effect of the sodium environment on mechanical properties of the materials was taken into account as well as the extended life specified for the steam generator being designed under this Contract.

BACKGROUND - TEST PROGRAMS:

A critical problem in nuclear power plant design is the corrosive behavior of the liquids that are capable of efficient, high temperature transfer of the vast quantities of heat generated by fission.(1) Sodium is one of the liquid metals most extensively studied because it has excellent heat transfer qualities and has acceptable nuclear characteristics.(2) Sodium's high specific heat and low density make it economical to handle, and its capacity for heat removal per pound pumped is unmatched by any other liquid metal except lithium.

Early work on liquid sodium systems established that sodium attacked carbon steel in a dynamic system by removal of iron and alloying constituents, principally carbon.(3) The decarburization was severe enough to rule out the use of carbon steel at temperatures higher than 800 F. This explains why most all of the early work - late forties and early fifties - consisted mainly of programs using 300 series stainless steel and temperatures of less than 1000 F. However, during the middle and late fifties, extensive programs were conducted to develop ferritic alloy steels to replace austenitic stainless steels in sodium systems at temperatures up to 1000 F. Extensive work was done to determine if elements such as columbium, titanium, and vanadium would retard or eliminate decarburization of ferritic steels, allowing them to replace stainless steels.

During this period, studies were made of two-metal systems in sodium. These studies include the more common Croloy and stainless steels (Croloy 2 1/4 and Croloy 1 1/4, and Types 304 and 316 stainless steel) at temperatures up to 1100 F.

While these programs were in progress, nuclear power plants were being designed as one-metal systems of austenitic stainless steel with operating temperatures under 1000 F.

From the mid-forties to the present, test programs have been conducted to determine the feasibility, life, and mechanical properties of various materials in a sodium environment. These programs have established that a sodium environment has definite effects on the life and mechanical properties of the materials, but the extent and magnitude have yet to be determined. The programs have covered a wide range of many conditions, some of which are: surface finish, heat treating, load and temperature, static and dynamic systems, one- and two-metal systems, loop versus specimen size in a two-metal system, test duration. Because these tests were conducted under such varied conditions, it is difficult to draw sound conclusions or establish design limits for the material considered.

The U.S. Atomic Energy Commission (US AEC) has in progress a program to develop and design a 1000 MWe liquid sodium nuclear power plant. As part of this program, the Babcock & Wilcox Company has a Contract to develop and design the steam generators. The Specifications for the steam generators state that they are to be designed to the 1962 ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels and for an operating life of 30 years with an 80% load factor. Since the environment and the extended life of the unit does affect the mechanical properties of the materials of construction, using the 1962 ASME Boiler and Pressure Vessel Code design stresses does not result in a conservative design. The ASME Boiler and Pressure Vessel Code design stresses are given as maximums and it is the designer's responsibility to apply any reduction factors which may be the result of a special application such as this one.

ASME BOILER AND PRESSURE VESSEL CODE REQUIREMENTS:

The mechanical properties used to establish the ASME Boiler and Pressure Vessel Code Design stresses are:

1. Ultimate Tensile Strength
2. Yield Strength
3. Creep Strength
4. Stress - Rupture Strength

Of these, creep and stress-rupture (creep-rupture) are of major concern, due to the temperature at which the steam generator operates. These two properties establish the majority of the design stresses.

Rupture tests supply information on hot ductility, surface stability, and metallurgical stability of the material.(4) These tests, in addition to determining the stress required to produce failure in a given time, supply information on the hot plasticity. The data curves are usually compared at a common time base (10^3, 10^4, 10^5 hours). The ASME Boiler Code uses 100,000 hours for its criterion (usually requiring extrapolation).

The creep strength of a material may be affected by a variety of factors, including composition, melting and deoxidation practices, grain size, and heat treatment. Aside from these influences, and depending on test temperature, load, and the rate of load application, creep or plastic flow takes place in a rather uniform manner.

By graphics and mathematics the rate of secondary creep is determined and plotted logarithmically to establish creep stress values for the rate of creep desired. The rate established as a criterion by the 1962 ASME

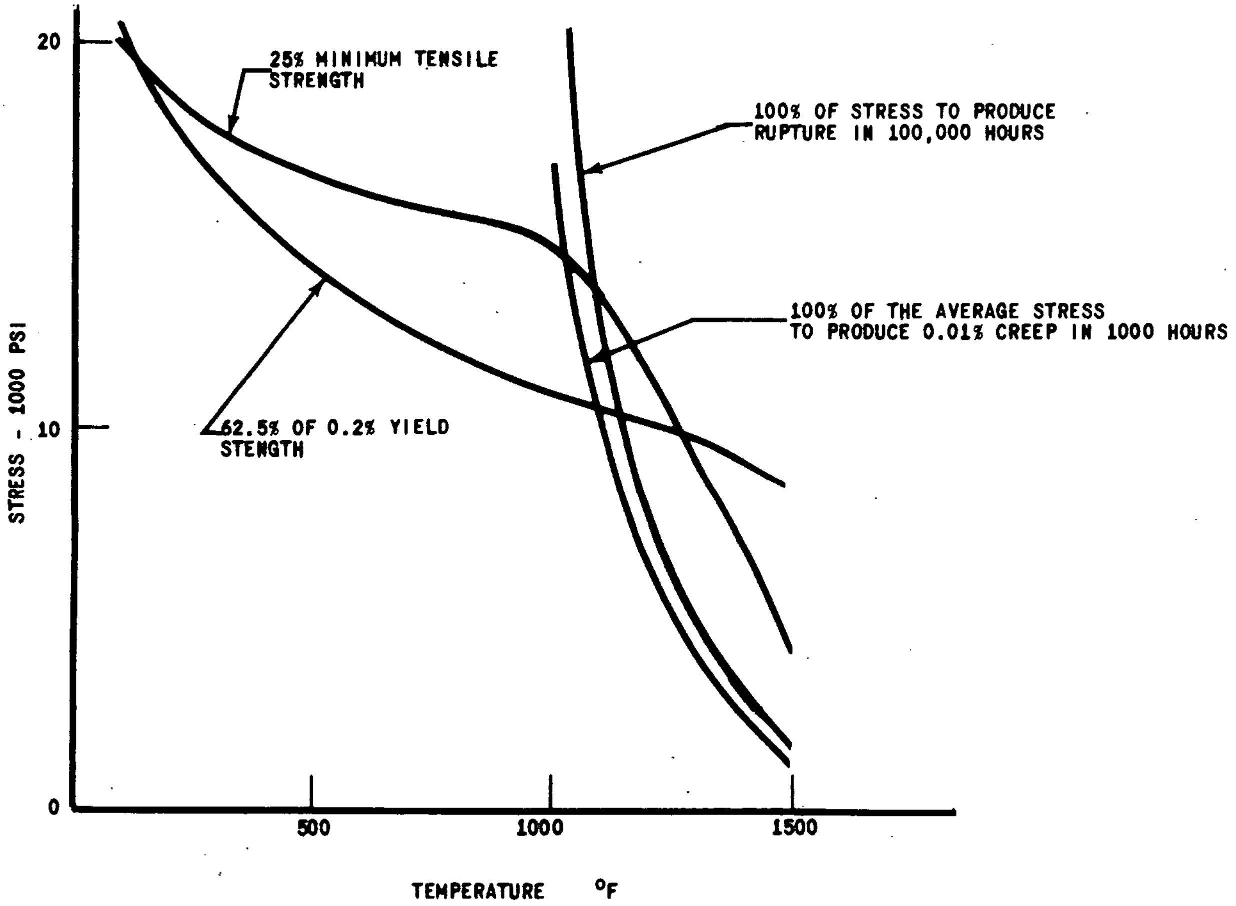
Boiler and Pressure Vessel Code is 1% in 100,000 hours frequently referred to as .01% in 1000 hours. This method is open to criticism as it discounts first-stage creep, and extrapolation to such an extremely long period of time may be inaccurate. However, it provides useful and comparative information for materials and is the current bases for design under the ASME Boiler and Pressure Vessel Code Rules.

The method used to establish design stresses from the mechanical properties data is found in Appendix P, paragraph UA-500 of Section VIII of the 1962 ASME Boiler and Pressure Vessel Code(5 & 6). Care must be exercised in selecting the appropriate factors since both Section I and Section VIII factors are given in this paragraph. The factors for tensile, yield, and creep strength are identical for both Section I and Section VIII while the factors for the stress-rupture differ and are as follows:

Section I: Sixty per cent of the average stress or eighty per cent of the minimum stress to produce rupture at the end of 100,000 hours.

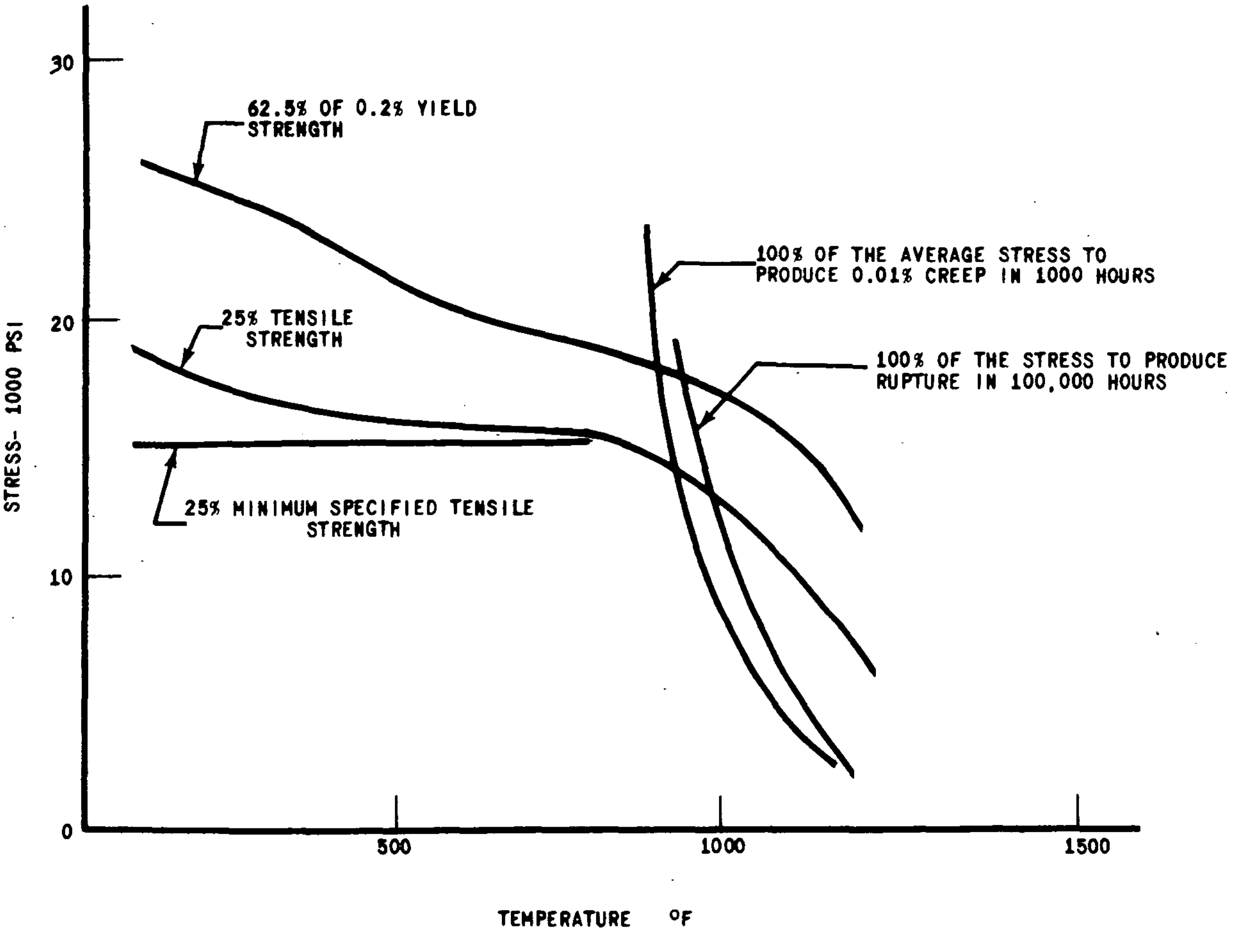
Section VIII: One hundred per cent of the stress to produce rupture at the end of 100,000 hours.

The stress values used are those based on a conservative average of the many reported tests conducted by producers and manufacturers. Figures 1 and 2 show pictorially the application of the factors to the reported test data for a 300 series austenitic stainless steel and a low chromium ferritic steel respectively. The design stress value for a particular temperature is defined as the lowest stress determined by applying the above factors to the test data.



TYPICAL 1962 ASME BOILER AND PRESSURE VESSEL CODE-
SECTION VIII REQUIREMENTS FOR ESTABLISHING A DESIGN
STRESS CURVE FOR A 300 SERIES AUSTENITIC STEEL

FIG. 1



TYPICAL 1962 ASME BOILER AND PRESSURE VESSEL CODE - SECTION VIII REQUIREMENTS FOR ESTABLISHING A DESIGN STRESS CURVE FOR A LOW CHROMIMUM FERRITIC STEEL

FIG. 2

MATERIALS SELECTION:

To have the lowest over-all cost for the steam generator, it is necessary to utilize the least expensive materials capable of satisfying the design conditions. Type 316 stainless steel was chosen for its superior strength at the higher temperatures and is an ASME Boiler Code approved material. Croloy 2 1/4 is a relatively inexpensive ferritic alloy steel with excellent mechanical properties to approximately 1000 F and is also a Code approved material. More environmental test data are available for these two materials than any other compositions.

To establish design limits for the above listed materials or for that matter any material in a sodium environment, the following effects must be considered:

1. Environment
   a. Non-Oxidizing
   b. Mass Transport
2. Extended Life Requirements

The effects of each of the above must be studied separately and applied to the basic mechanical properties of the material under consideration.

EFFECTS CONTROLLING DESIGN LIMITS:

Although a great amount of testing has been done in sodium and other environments, the long-time environmental effects on mechanical properties have not been established with certainty. To establish conservative design limits, it was necessary to re-examine the mechanical properties of the materials under consideration as they are affected by the above listed effects. A discussion of each, plus several other pertinent design limits not included in the design stress curves, is as follows:

ENVIRONMENT - NON-OXIDIZING

Considerable work has been done in non-oxidizing or neutral environments. Included in these neutral environments are gas, liquid metals, and vacuum. There is a remarkable amount of discrepancy in the data from each of these media, some of which may be due to equipment and system purity.

An effort was made to correlate the environmental effects of gas and vacuum systems to those of liquid metal systems to better understand and verify the effects of a liquid metal environment. Because there is a limited amount of data available for a sodium system, all available data must be evaluated.

The mechanical properties of the materials being tested in a sodium environment show the following trends:

1. Higher creep rates
2. Shorter rupture time
3. Longer fatigue life
4. Small reduction in elevated temperature yield and tensile strength.

The above items are rather general and vary from one material to another. The specific effects of the above items on each material will be covered later in this report.

ENVIRONMENT - MASS TRANSPORT

The second phenomenon of a liquid metal environment is mass transport. This is the movement of an element between dissimilar metals or between areas of different temperatures of like or dissimilar metals. An element that is being transported either in solution or as particulate matter may appear in the liquid as any one of several forms, namely:

1. Elemental (uncombined)
2. Oxides
3. Combined with sodium or sodium impurities
4. Combined with other material elements

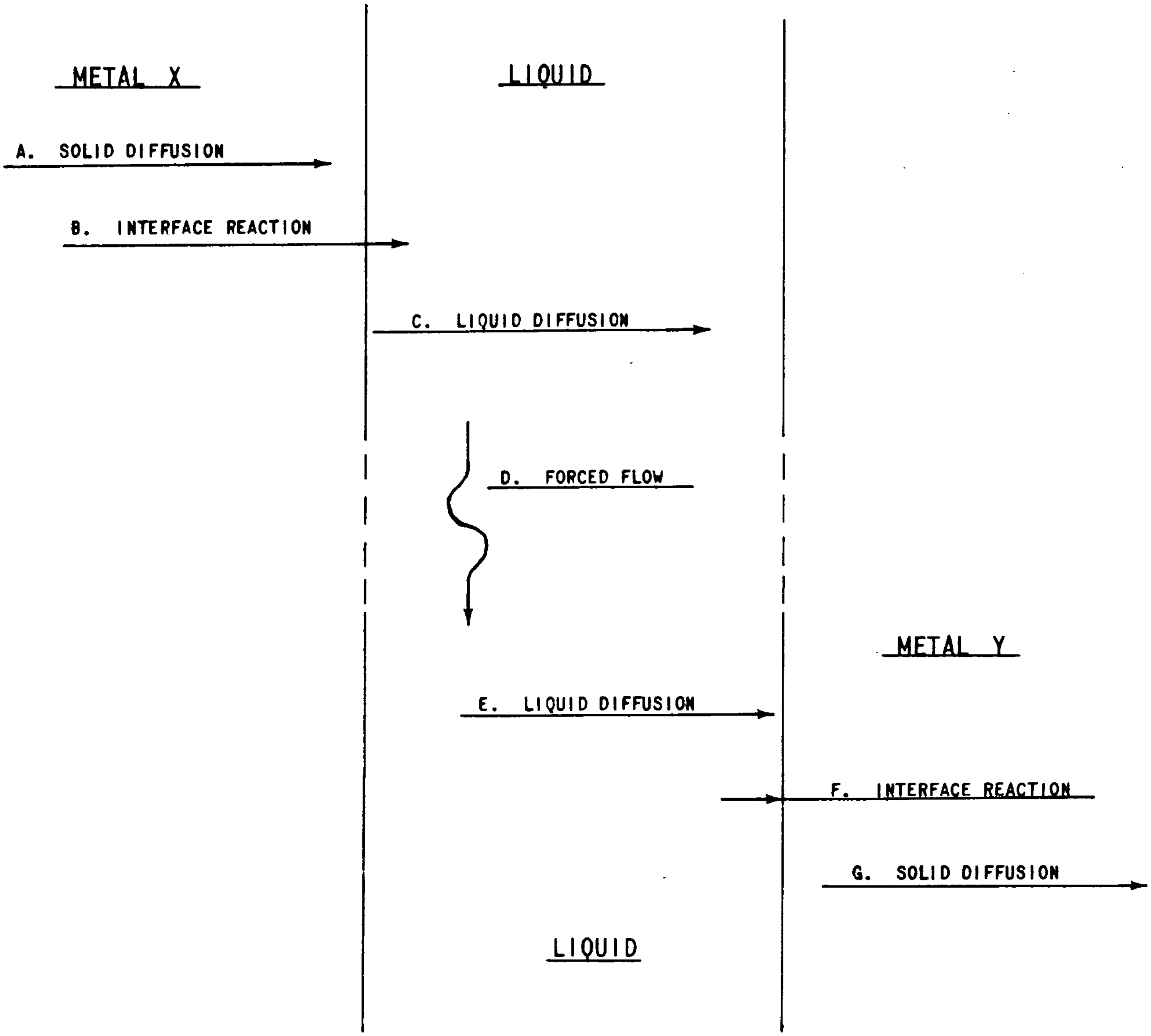
In analyzing the liquid for any element being transported, all forms must be taken into account.

A pictorial representation of mass transport is shown in Fig. 3 and described as follows:

A. The element as it is removed from the surface is replenished by other elements from within. This process is called solid-state diffusion, which is temperature and composition dependent.

B. The element, now at the solid-liquid interface, must transfer from the solid to liquid. This process is thought to be essentially a chemical reaction.

C. The element then diffuses through the stagnant boundary liquid into the flowing stream.



PICTORIAL REPRESENTATION OF MASS TRANSFER

FIG. 3

D. The element is carried from metal "X" to metal "Y" in the flowing stream.

Diffusion into metal "Y" follows steps E, F, and G, which are the same as, but in reverse order as, steps A, B, and C.

To determine whether one of the above described steps controls mass transport, or if the entire reaction is a combination of processes that can continue independent of the rest, a better understanding of mass transport is required. Once the process or processes are better understood, the over-all rate or rates can be determined.

EXTENDED LIFE

The ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels, which governs pressure vessel construction, uses 100,000 hours as its criterion for determining design stress values. The required life of the Sodium-Heated Steam Generator being designed under this Contract is 30 years with an 80% load factor or 210,000 full power hours. The approach to setting design limits, due to the extended life requirements, is to reduce the stress level to produce a creep rate of 1% in 210,000 hours. This results in a stress level approximately the same for both creep and stress rupture. Because of the long-time extrapolation, a questionable area which is covered earlier, this rather conservative limit was adopted for setting the design stresses.

FATIGUE

Although this is not a criterion included in the design curves, it is a property of major concern for any cyclic area of a design. Some have reported fatigue life to be several times longer for such an environment as compared to air. Improvement of this property is attributed to the non-oxidizing environment.

THERMAL STRESS

Although low film resistance is desirable from heat transfer considerations, it presents a serious thermal stress problem.(7) As there is little thermal resistance in the liquid metal film, the temperature difference between the liquid metal temperature and the temperature existing on the other side of the wall must be accommodated in the vessel wall. Since temperature difference means differences in thermal expansion, stresses are created in the metal that are proportional to the temperature differentials. The maximum thermal stress decreases with increasing thermal conductivity of the structural material and increases with increasing surface and heat transfer coefficient. Therefore, the use of liquid metals in heat-transfer systems results in higher thermal stresses in the structural material than occur in the conventional steam-water system, because the major temperature drop is taken in the vessel walls.

In determining the loading to be considered in designing a vessel, the ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels, states in paragraph UG-22 that the effects of temperature gradients on maximum stress should be included. In setting design stress values, only static properties are considered. Since there is little film resistance in a liquid-metal heat transfer system, it is important to recognize the magnitude of the stress that might be encountered. Because the greatest thermal stress normally exists under transient conditions, the number of these cycles should be defined.

ESTABLISHING DESIGN STRESSES:

Developing design stress curves for the materials under consideration, namely Type 316 stainless steel and Croloy 2 1/4 alloy steel, all environmental and extended life effects, as applied to the mechanical properties, must be determined and combined. As stated earlier, there are three effects to be considered; namely, non-oxidizing environment, mass transport, and extended life.

The bases for establishing the design stresses are the same as used by the 1962 ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels with the exception of time. The most recent data available(8) were used to arrive at the basic 100,000 hour curves for creep and stress to rupture. These curves were then extrapolated to 210,000 hours to allow for the extended life of the unit.

Mine Safety Appliance Research Corporation (MSA)(9) has done considerable mechanical property testing at 1200 F of Type 316 stainless steel and at 1100 F of Croloy 2 1/4 alloy steel. Other applicable data, most of which is unpublished, has been used to establish the design curves shown on Fig. 4

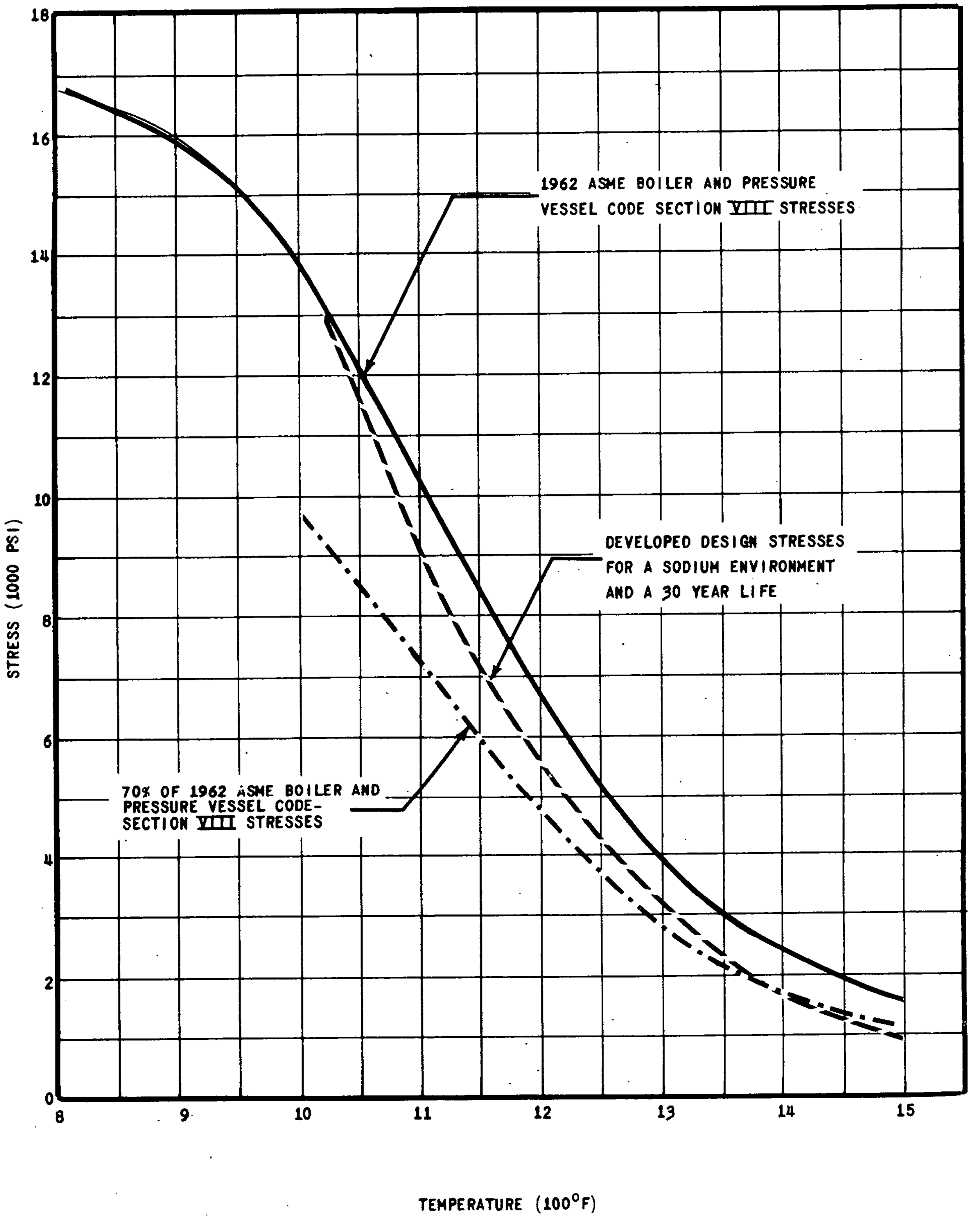
for Type 316 stainless steel and Fig. 5 for Croloy 2 1/4 alloy steel. These stress curves were developed by applying the following factors, similar to the ASME Boiler Code factors, to the stress values reduced by the extended life and environmental considerations for each of the materials:

1. 100% of the average stress to produce 1% creep in 210,000 hours.
2. 100% of the stress to produce rupture in 210,000 hours.

Fig. 4, for Type 316 stainless steel, includes all of the factors for extended life (210,000 hours) and the non-oxidizing environment effect. The extended life does not affect the design stresses until approximately 1150 F. This effect reaches 10% between 1200 and 1250 F and a maximum of 33% at 1400 F. The non-oxidizing environment effect, which was reported by MSA Research Corporation, shows a 20% reduction of creep strength at 210,000 hours. Applying this affect to the creep curve, it now becomes the controlling factor at approximately 1050 F.

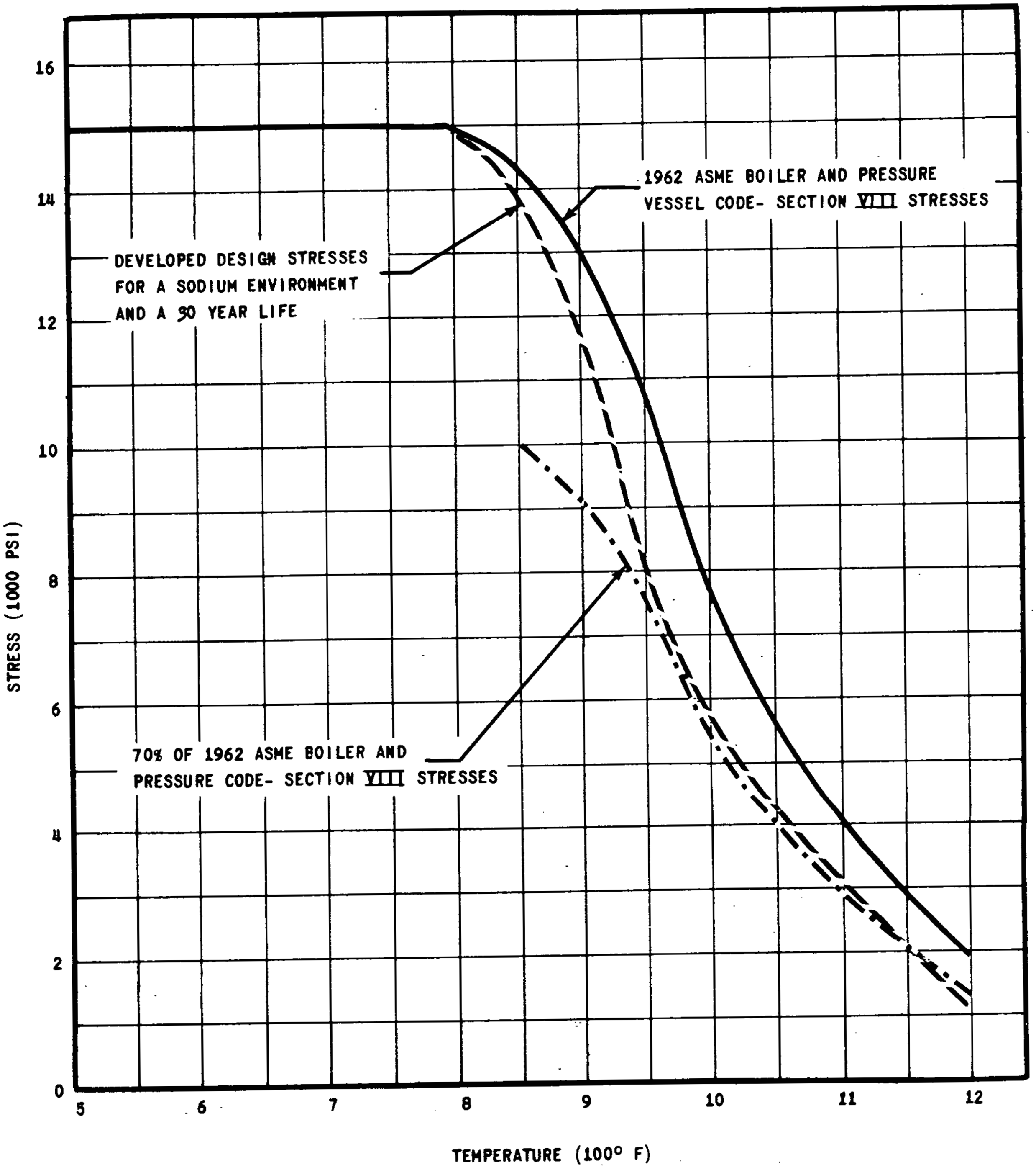
Not included in the design stress curve are the effects of carburization and nickel and chrome transport. Although carburization tends to strengthen, it also tends to embrittle the material.

Fig. 5 for Croloy 2 1/4 alloy steel, includes all of the factors for extended life (210,000 hours) and a trend of most of the environmental effects. The effects of extended life start to control the design stress at approximately 925 F. The non-oxidizing environment effects are from data reported by MSA Research Corporation. This data, when extrapolated to 210,000 hours, gives better environmental results for creep and stress - rupture than in air.



DEVELOPED DESIGN STRESSES FOR TYPE 316
STAINLESS STEEL IN A SODIUM ENVIRONMENT
AND A 30 YEAR LIFE

FIG. 4



DEVELOPED DESIGN STRESSES FOR CROLOY $2\frac{1}{4}$ ALLOY STEEL IN A SODIUM ENVIRONMENT AND A 30 YEAR LIFE

FIG. 5

Decarburization is factored in from data(8) obtained from several very low carbon tests. The environmental effect, for which there is no data available, is the migration of nickel and chrome to the Croloy 2 1/4 alloy steel.

Figs. 4 and 5 each show three curves. The first is a plot of the 1962 ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels design stresses, which is used as a basis for these studies. The second curve is a plot of 70% of the 1962 ASME Boiler and Pressure Vessel Code Design stress curve. These stress values were used in the early stages of the design study since no design stress curves were available. The third curve is a plot including all of the environmental and extended life effects, as outlined in the above paragraphs, for each of the materials.

It is the writer's opinion that the design stress curves are rather conservative and enable the designer to safely proceed with the design of the steam generator. The problem of mass transport when applied to this particular plant design may not be as severe as one might think. First of all, carbon transport (decarburization-carburization) is rather limited since only the carbon in the sodium and that of approximately one-third of Croloy 2 1/4 is available due to temperature limitations. Factored into the Croloy 2 1/4 alloy steel design curve are the effects of decarburization. Anything less than complete decarburization should support higher design stresses, which would make the design curve more conservative. Carburization tends to enhance the mechanical properties included in the design curve for Type 316 stainless steel but introduces an aging effect and a shortening of fatigue life which must be factored into a design.

As designers, The Babcock & Wilcox Company believes the best way to obtain the necessary data and substantiate much of the preceding work is to model as closely as possible the operating conditions of the full-size unit in a laboratory set up.(10) Such a loop is in operation, and the results of the first 1000 hours operation will soon be available. At the completion of the scheduled operational life, the loop will be disassembled and sectioned to determine and verify mass transport rates and mechanical properties of the various environment conditions. As this and other additional data become available, the presented design stress curves can be re-evaluated.

CONCLUSIONS:

It is fairly evident what happens to the materials under consideration in a sodium environment, but the extent and resulting effect on the mechanical properties caused by these environmental reactions is still in a state of question. A considerable amount of research is being done but the number of conditions to be studied does not make this a simple, straightforward task.

Care must be exercised in selecting the materials of construction. At present, there are a limited number of materials available to the designer. The two materials discussed in this report do not present severe fabrication problems since they are rather popular materials of construction. There is enough environmental data available for each material from which new design stress curves have been plotted.

(See Figs. 4 and 5). Although a great amount of testing has been done in a sodium environment, it still is not possible to establish the long-term effects on the mechanical properties with certainty. Data are required to accurately predict the environmental effects throughout the life of the unit. This increased knowledge of the environmental effects will permit a more intelligent application of materials.

RECOMMENDATIONS:

1. It is recommended, based on the data available at this time, that the design stress curves presented herein should be used in the design of sodium components.
2. The mechanical properties should be established for several temperature levels with longer testing periods.
3. A better understanding of the long-term environmental effects and to what extent they affect the mechanical properties should be established.
4. Mechanical properties of other materials of construction should be determined for use in a sodium system.

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