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ISOCHRONOUS STRESS-STRAIN
CURVES FOR 2 1/4 Cr-1 Mo,
TYPE 304-304H, AND
TYPE 316-316H STEELS

TECHNICAL REPORT 2012 - PART I

PREPARED FOR

U S ATOMIC ENERGY COMMISSION
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BRAUN PROJECT 4122-W
UNITED NUCLEAR PROJECT 2351

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October 16, 1970

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Dear Mr Fry

ISOCHRONOUS STRESS-STRAIN CURVES
TECHNICAL REPORT 2012 PART I
LMFBR PIPING DESIGN GUIDE
AEC SAN FRANCISCO
PROJECT 4122-PW

Transmitted herewith are two copies of Part I, Technical Report 2012 covering the preparation of Isochronous Stress-Strain Curves for 2 1/4 Cr-1 Mo, Type 304-304H and Type 316-316H steels based on data currently available.

This is an interim report covering a portion of the work on Task 2012 for determining the time dependent behavior of materials. Work on this task will be continued to develop plans for experimental programs to obtain additional data. Evaluation of data, up-dating of the present curves, and preparation of relaxation strength versus time correlations will be developed when schedule and budget considerations have been settled.

Comments on this report are requested, and should be forwarded to C F Braun & Co prior to November 29, 1970.

Sincerely yours

Roger Detman
Project Manager

RFD IV

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H B Fry, Contracting Officer

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ISOCHRONOUS STRESS-STRAIN CURVES
FOR 2 1/4 Cr-1 Mo, TYPE 304-304H, AND
TYPE 316-316H STEELS

TECHNICAL REPORT 2012 - PART I

Prepared for US Atomic Energy Commission
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UNITED NUCLEAR CORPORATION
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Alhambra California

October 16, 1970

PRELIMINARY
FOR REVIEW ONLY

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1. INTRODUCTION

Strain is not independent of time in the creep range of temperature, as it is at lower temperature, but rather continues to occur with time. In principle, the continuing, time-dependent creep may be expected to lead to failure owing to excessive distortion, or alternatively, failure may result from the intervention of fracture (rupture). To preclude failure by excessive distortion or by rupture, the permissible working stress must be limited such that neither of these events will occur within the intended service life. Information concerning time-dependent strain also is required by the designer in connection with calculations relating to plastic instability and ratcheting.

A method of depicting the time-dependent strain behavior of materials that is convenient for the design engineer is in the form of plots showing the variation of stress with strain for fixed time; the resulting curves have come to be called isochronous stress-strain curves. This method of presentation was probably first used by McVetty in 1934,¹ and has since come to be widely used in the aerospace industries.

In the present report, consideration is given to possible methods of developing isochronous stress-strain curves appropriate for relatively long service life in pressure vessel and similar applications, and the conclusion is drawn that at the present time the only practicable approach is to compute them from creep intercept and creep rate data. Available data have been evaluated and isochronous stress-strain curves have been generated for times ranging between 10^3 and 5×10^5 hr for:

- $2\frac{1}{4}$ Cr-1 Mo steel at 1000, 1050, and 1100°F
- Type 304-304H stainless steel at 1000, 1100, and 1200°F
- Type 316-316H stainless steel at 1000, 1100, and 1200°F.

For reasons to be described, no distinction is drawn between the "regular" and "H" grades of 304 and 316. The data available for types 304L and 316L proved to be inadequate to permit generating isochronous curves for these grades.

2. METHODS OF GENERATING ISOCHRONOUS STRESS-STRAIN CURVES

Probably the most obvious and direct method of generating isochronous stress-strain curves is to take constant time sections through a family of creep curves (strain vs time), developed at different constant applied stresses at constant temperature. For several reasons, this procedure, unfortunately, proves not to be practicable for the present purposes. First, creep-time curves are not generally available in published literature, reflecting the fact that the ASME Code allowable stress criterion relating to creep is expressed in terms of the stress causing a secondary creep rate of 0.01% per 1000 hr, which, in turn, has meant that published creep data pertain largely to secondary creep rate. Second, the number of creep tests that have been made on any individual lot of material has commonly involved far too few different stress levels to provide an adequate family for taking constant time sections, even were the creep curves somehow to be made available. Finally, few creep tests have been continued beyond a few thousand hours, whereas the times that are of interest extend to beyond 100,000 hr.

A second possible approach to generating isochronous stress-strain curves, which does prove to be practicable, is to compute them from secondary creep rate and creep intercept data, within the limitation that creep shall not have entered the tertiary or accelerating period. This procedure may be expressed analytically in the following form:

$$C_t = C_0 + C_s t \quad (1)$$

in which C_t is the total strain at time t , C_0 is the intersection on the total strain axis of the secondary creep rate tangent, C_s is the secondary

creep rate, and where the time must not exceed that corresponding to the beginning of tertiary creep. What are required, then, are the dependences of C_S and C_0 upon stress, and a means for insuring that the computation is not carried into the tertiary stage of creep. Since it is not practicable to establish allowable stresses for individual lots of materials, but only for a class or grade of material as a whole, it would seem desirable to seek to develop an average isochronous stress-strain curve, based upon the average dependence of C_S upon stress, etc., rather than to attempt first to develop individual curves for individual lots of a particular grade and then average these. In fact, the latter approach is not feasible, because the amount of data available for an individual lot of a given class of material is seldom, if ever, adequate to the needs. Moreover, by this approach, advantage may be taken of the evaluations of secondary creep rate data that have been developed by the Metal Properties Council (MPC).^{2,3} Unfortunately, no similar assessment of the dependence of intercept upon stress is available, and would have to be developed.

A means for insuring that the computation is limited to times less than those corresponding to entry into tertiary creep is available. Leyda and Rowe⁴ studied in detail the relation between the beginning of tertiary creep and rupture for many materials of commercial interest, and observed that at a given temperature tertiary creep for a particular material sets in at a constant fraction F_S of the time for rupture. This fraction decreased with increasing temperature. Multiple lots were studied for a number of grades, including those of particular interest for nuclear applications; the results showed that it is possible to define an average value of F_S , exhibiting relatively modest scatter, defining the dependence of time-for-tertiary creep upon time-for-rupture for a class of material.

In the interval of primary creep, before secondary creep commences, the secondary creep rate-intercept procedure for computing isochronous stress-strain curves results in greater strains that would be actually experienced. At the present time, no method is known by which primary creep can be taken into account in developing isochronous curves by the creep rate-creep intercept approach, or even of assessing the extent of the error that may be introduced. In a very general way, it seems clear that the possible error increases with decreasing time, and decreasing strain. Some small comfort may be gained from the

fact that the error is always such as to result in more conservative design. Moreover, it seems unlikely that for strains on the order of 1% the error is significant at 100,000 hr and longer, which for long service applications would be of greatest interest, and probably is small for 10,000 hr.

In addition to the two methods for generating isochronous stress-strain curves already cited, some attention was given (initially) to the possibility that a generalized interrelation between rupture strength and creep strength, the latter defined in terms of the stress for a specific amount of strain, reported by Gill and Goldhoff,⁵ could be useful in developing isochronous curves. However, this approach was judged to be of limited value, owing (1) to the width of the scatter band, and (2) to the fact that the inter-dependence was reported only for a strain of 1%, and data were not available that would permit generating the rupture strength-creep strength dependence for other amounts of strain.

Brief consideration also was given to the possibility of employing multiterm analytical expressions relating strain to time, but the problem of assessing the several material constants of such expressions (necessitating extensive experimental study), even for an individual lot of material, let alone a grade, appears much too formidable to undertake within the schedule established for this effort.

Finally, a few data relating to time-dependent strain are available principally from European sources, but these are so limited that they are of possible correlative interest only. Furthermore, there is some evidence that the strengths of some materials, e.g., type 304 stainless steel and 2 $\frac{1}{4}$ Cr-1 Mo steel, produced outside the USA, may differ somewhat from the strengths of domestically produced material.

In summary, it appears that the only practicable approach to generating isochronous stress-strain curves at the present time is to compute them from secondary creep rate and creep intercept data.

3. DEPENDENCE OF SECONDARY CREEP RATE UPON STRESS

As indicated earlier, the data evaluations of MPC have assessed the average dependence of secondary creep rate upon stress. The data for stainless steel types 304 and 316 may be found in Reference 2, and data for 2 $\frac{1}{4}$ Cr-1 Mo steel in a draft report.³ It is unfortunately true that secondary creep rate data are seldom plentiful, as examination of the MPC evaluations will readily reveal, and the average values that have been reported are to be viewed only as best current assessments. Furthermore, the MPC evaluations have placed primary emphasis on the relatively slow secondary creep rates of interest in setting allowable stresses for long-life equipment, e.g., 0.01 and 0.1% per 1000 hr; whereas these are of interest in generating isochronous stress-strain curves, it is also necessary to know the stresses corresponding to creep rates as high as 10% per 1000 hr, if isochronous curves for times of 100 or 1000 hr are wanted, and as low as 0.0025% per 1000 hr if curves for 100,000 and 500,000 hr are wanted. Consequently, it has been necessary to assess for present purposes the dependence of secondary creep rate upon stress for both slower and faster rates. Finally, data for types 304 and 316 at 1000°F have proved particularly scarce. For all these reasons, a solicitation for possible additional data was made, and these data were integrated with the previously available data with a view to extending the previously defined average curves of stress vs secondary creep rate to faster as well as slower strain rates.

The stress vs secondary creep rate relations employed in generating the isochronous stress-strain curves are given in Figs. 1 and 2. In these graphs the stresses for secondary creep rates of 0.01 and 0.1% per 1000 hr correspond with the values defined by the MPC evaluations.^{2,3}

Fig. 1 — Variation of Secondary Creep Rate of 2¹/₄ Cr-1 Mo with Stress

Fig. 2 — Variation of Secondary Creep Rate of Types 304-304H and 316-316H with Stress

4. DEPENDENCE OF CREEP INTERCEPT UPON STRESS

Relatively few intercept data have been published, and no published assessments of these data, in the sense of the MPC evaluations of secondary creep rate data, are available. An effort has been made therefore to gather data from as many sources as possible, both published⁶⁻⁸ and unpublished. These data are summarized in individual plots in which the ordinate represents total strain, Figs. 3 through 5. The lower, dashed lines showing elastic strains were developed from published modulus of elasticity values.⁹ In a number of instances, it was not clear whether the reported intercept value represented total strain or only creep strains. In these instances, the reported strain has been plotted, except that if the reported value was less than the expected elastic strain, a correction for elastic strain was added. (Since it is essentially impossible to differentiate between the elastic and plastic strains during a creep test, except by an independent determination of the elastic modulus, it seems better, in general to develop intercept data in terms of total strain.) In some instances, intercept data were reported for "up-step" tests, in which successively higher loads are imposed at intervals; these intercept data have been omitted from the summary plots.

The extent of the scatter in intercept values evident in Figs. 3 through 5 seems unusually large. There are a number of possible causes for this scatter, in addition to the likelihood, already mentioned, that the reported values in some instances represent total strain and in others only creep strain. One of the most important of these relates to the likelihood that many of the values were taken before a true secondary creep rate was established. Gill and Goldhoff⁵ have shown that an apparent steady state may not represent a true secondary creep

rate, and that creep tests of much longer duration than are commonly performed are required to establish the true secondary rate. The intercept value derived from an individual creep test may be expected to increase steadily until the secondary rate is truly established.

Another possible cause for scatter of the intercept values derives from the fact that microstructural instability is widespread in materials of commercial interest, and the material behavior is sometimes sensitive to chemical composition and to initial structure. These microstructural changes may affect the inherent flow strength and also may result in dimensional changes independent of the applied stress, so that creep strain is a net result of several forces. It might be expected that intercept strains would be especially sensitive to such complex behavior. A correlary effect, appreciated generally by those performing creep tests, is that secondary creep rate measurements exhibit less variability than total strain measurements. The differences, of course, are aggravated by nonaxial loading, which is probably more common than is generally appreciated.

Finally, it is possible that some of the intercept values derive from tests in which strain was not measured directly from the specimen, but from one or another location along the load train. Although creep rates measured in such a way may be reasonable (since the load remains constant), the total strain may be quite erroneous owing to strains at the connections.

The importance of the scatter in intercept strains to the isochronous stress-strain curve will be discussed later in this report. The importance depends upon the portion of the spectrum that is of interest; fortunately, the intercept strain proves to be a relatively small fraction of the total strain in the region of 1% strain at 100,000 hr.

The curves shown in Figs. 3 through 5 were drawn visually to define what might be defined as "conservative averages."

Fig. 3(a) — Variation of Intercept Strain with Stress for 2 1/4 Cr-1 Mo Steel — 1000°F

Fig. 3(b) — Variation of Intercept Strain with Stress for 2 1/4 Cr-1 Mo Steel — 1050°F

Fig. 3(c) — Variation of Intercept Strain with Stress for 2 1/4 Cr-1 Mo Steel — 1100°F

Fig. 4(a) — Variation of Intercept Strain with Stress for Type 304-304H Steel — 1000°F

Fig. 4(b) — Variation of Intercept Strain with Stress for Type 304-304H Steel — 1100°F

Fig. 4(c) — Variation of Intercept Strain with Stress for Type 304-304H Steel — 1200°F

Fig. 5(a) — Variation of Intercept Strain with Stress for Type 316-316H Steel — 1000°F

Fig. 5(b) — Variation of Intercept Strain with Stress for Type 316-316H Steel — 1100°F

Fig. 5(c) — Variation of Intercept Strain with Stress for Type 316-316H Steel — 1200°F

5. BEGINNING OF TERTIARY CREEP

The values of the fraction, F_s , defining the ratio between the time for tertiary creep to begin and the time for rupture to occur that have been applied in the present report are taken (some by interpolation or extrapolation) from the paper by Leyda and Rowe,⁴ and are given in Table 1.

TABLE 1 — TIME FOR TERTIARY CREEP/TIME TO RUPTURE
VS TEMPERATURE

<u>Temp, °F</u>	<u>2¹/₄ Cr-1 Mo</u>	<u>304-304H</u>	<u>316-316H</u>
1000	0.459	0.52	0.52
1050	0.453	—	—
1100	0.447	0.50	0.525
1200	—	0.47	0.53

6. THE ISOCHRONOUS STRESS-STRAIN CURVES

Isochronous stress-strain curves are given for $2\frac{1}{4}$ Cr-1 Mo steel in Figs. 6(a), (b), (c), for 304-304H stainless steel in Figs. 7(a), (b), (c), and for 316-316H stainless steel in Figs. 8(a), (b), (c). Elastic strains and intercept strains have been superimposed on the plots.

The curves for $2\frac{1}{4}$ Cr-1 Mo apply for annealed material (or material normalized and tempered at relatively high temperatures); they do not apply for quenched and tempered nor for normalized and tempered materials such as those conforming to ASTM specifications A542 and A387. Data for temperatures less than 1000°F and higher than 1100°F were inadequate to warrant attempting to generate isochronous curves. As the temperature is increased above 1100°F, scaling tends to become excessive in oxidizing environments; consequently $2\frac{1}{4}$ Cr-1 Mo is seldom used at such temperatures.

The austenitic stainless steel curves also represent annealed material, and would not be applicable to cold-worked material. No distinction is made between the "regular" and "H" grades. The specifications for the H grades of 304 and 316 permit lower annealing temperatures and higher carbon than do the specifications for the regular grades. Although there is no lower limit on specified carbon for the regular grades, the ASME Code stress tables impose, by footnote, an effective minimum of 0.04% (which is required for the H grades) for service temperatures over 1000°F. Hence the regular grades would appear to be encompassed within the requirements of the H grades.

A search was made for data for grades 304L and 316L, but the quantity of data available proved inadequate to warrant attempting to generate isochronous stress-strain curves.

Dashed portions at either end of the strain range of some of the isochronous curves have been estimated. At lower strains, the dashed portions represent regions corresponding to secondary creep rates less than 0.0025% per 1000 hr, which is the lowest rate to which the stress vs rate plots (Figs. 1 and 2) were extended. At higher strains, the dashed portions represent the intrusion of tertiary creep, as established by applying the Leyda-Rowe F_S factors.⁴ This estimate was made by computing the time for rupture corresponding to the beginning of tertiary creep in 10,000 hr, 100,000 hr, etc., and then from the MPC evaluations for the stress dependence of time for rupture,^{2,3} establishing the corresponding stress. This stress then was taken as identifying the beginning of tertiary creep on the isochronous stress-strain curves. The dashed portions of the isochronous curves are "guesstimates."

The stress-intercept curves drawn on the isochronous stress-strain plots will aid in assessing the possible error deriving from the extensive scatter in the intercept data. Taking 1% strain at 100,000 hr as a reference point of important concern, it is of interest to note that the intercept strain is a relatively negligible fraction of the total. Hence the exact positioning of the stress-intercept curve is not particularly important for this portion of the family of isochronous stress-strain curves. However, as the strain or the time is decreased, the intercept strain becomes an increasingly important fraction of the total strain, and, in fact, for the shorter time at the lower temperatures, the isochronous curve tends toward coincidence with the intercept curve. Although the trend to coincidence is influenced by the uncertainty in defining the position of the intercept curve, the basic reason for the trend is that the method employed for computing the isochronous curve breaks down at shorter time because primary creep is ignored. If primary creep were taken into account, the true strain would be progressively less than the computed strain as the time is decreased, and, in fact, would become less than the intercept strain. Unfortunately, no method is available at present to introduce a correction for primary creep strain and there is no way of knowing when the computation procedure begins to break down. It seems certain that 100-hr isochronous stress-strain curves, computed by the procedure employed, would have little resemblance to reality, and it seems probable that a significant error would be involved in many of the 1000-hr curves; consequently, curves have not been included for times less than 1000 hr. Some small comfort may be gained from the fact that failure to correct for primary strain results in a conservative design.

It is not possible at this time to assess quantitatively the possible errors in the isochronous curves that have been generated. Some of the causes for scatter have been discussed in earlier portions of this report. To a large extent, extensive scatter of results is inherent in the sensitivity of creep properties to composition and structure, and in the difficulties of experimental measurement of these properties. Nor, can complete interconsistency between the isochronous stress-strain curves and related properties, e.g., time for rupture, be expected. The MPC evaluations of creep strength and of rupture strength were carried out independently on separate data populations which were always far from plentiful and in many instances perhaps not fully representative of the grade. Thus, the portion of an isochronous stress-strain curve may be found to lie slightly above rather than below the rupture stress for the same time, as would be required. Because there is no way to assess the uncertainties, it is believed better to accept such an inconsistency than to attempt to adjust the end results.

As indicated earlier, it has not seemed possible to generate minimum isochronous stress-strain curves directly, and the curves that are offered in Figs. 6, 7, and 8 represent averages. The only practicable way of estimating a minimum curve would appear to be to take an arbitrary fraction of the average, and a reasonable value for this fraction, based upon the general character of creep data, is suggested to be 80%.

Fig. 6(a) — Isochronous Stress-Strain Curves for 2 1/4 Cr-1 Mo Steel - 1000°F

Fig. 6(b) — Isochronous Stress-Strain Curves for 2 1/4 Cr-1 Mo Steel — 1050°F

Fig. 6(c) — Isochronous Stress-Strain Curves for 2¹/₄ Cr-1 Mo Steel — 1100 °F

Fig. 7(a) — Isochronous Stress-Strain Curves for 304-304H Steel — 1000°F

Fig. 7(b) — Isochronous Stress-Strain Curves for 304-304H Steel — 1100°F

Fig. 7(c) — Isochronous Stress Strain Curves for 304-304H Steel — 1200°F

Fig. 8(a) — Isochronous Stress-Strain Curves for 316-316H Steel — 1000°F

Fig. 8(b) — Isochronous Stress-Strain Curves for 316-316H Steel — 1100°F

Fig. 8(c) — Isochronous Stress-Strain Curves for 316-316H Steel — 1200°F

7. ISOCHRONOUS STRESS-STRAIN SIMILARITY

Rabotnov^{10,11} found that isochronous curves are often similar, and consequently their equation could be written:

$$\sigma = \phi(\epsilon) \eta(t) \quad (2)$$

Eq. 2 is based on the assumption that stress can be related to deformation and time through the product of two functions which are independent functions of strain and time, respectively. If the function η is defined such that $\eta(0) = 1$, then $\phi(\epsilon)$ is theoretically the instantaneous deformation curve.

Rabotnov found that a fairly good approximation to the function $\eta(t)$ is given by:

$$\eta(t) = \frac{1}{1 + at^\beta} \quad (3)$$

Using this relation, Eq. 2 can be written as:

$$\sigma = \frac{\phi(\epsilon)}{1 + at^\beta} \quad (4)$$

with $\phi(\epsilon)$, a , and β as unknowns. These unknowns may be evaluated by assuming a value of β , and determining the best values of $\phi(\epsilon)$ and “ a ” by a least-squares evaluation of the σ and t data obtained from the isochronous curves.

An initial test of the applicability of this approach in representing

the isochronous curves developed in this study was made using the isochronous stress-strain curves for 304-304H steel at 1200°F shown on Fig. 7(c). Values of β between 0.28 and 0.36 were investigated based on Rabotnov's suggestion that a value of 0.3 is usually appropriate for steel. Table 2 shows some of the results of this investigation.

TABLE 2 — COMPUTED CONSTANTS FOR EQ. 4

Total Strain, %	$a \times 10^2$		$\phi(\epsilon) \times 10^{-4}$ psi	
	$\beta = 0.30$	$\beta = 0.33$	$\beta = 0.30$	$\beta = 0.33$
0.25	3.8108	1.7722	1.1518	1.0874
0.50	4.9739	2.2075	1.5658	1.4439
1.00	4.6860	2.0702	1.7692	1.6348
1.50	4.4675	1.9874	1.8760	1.7389
2.00	4.3035	1.9197	1.9369	1.7996
2.50	4.3977	1.9488	2.0392	1.8895
3.00	4.2270	1.8807	2.0445	1.8975
3.50	4.0548	1.8130	2.0497	1.9102
4.00	4.0478	1.8094	2.0834	1.9416
	$\bar{a} = 4.3299$	$\bar{a} = 1.9350$		

This screening study indicated a number of items which should be explored further. It was found that the calculated value of "a" showed some strain dependence. Values of β of 0.28 or less are required for $\phi(\epsilon)$ to approach actual tensile test data, however, decreasing β increases the computed variance in $\bar{a}$.

Fig. 9 shows a comparison between the isochronous stress-strain curves for 304-304H stainless steel [Fig. 7(c)] at 1200°F and computed values using $\bar{a} = 0.0433$, and $\beta = 0.3$. As can be seen, the agreement is reasonable, providing a tentative indication that similitude does exist between the isochronous curves.

Fig. 9 — Comparison of Isochronous Stress-Strain Curves of Fig. 7(c) and Values Computed from Eq. 4

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