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On elastic structural elements for Nuclear Reactors. A critical review

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On elastic structural elements for Nuclear Reactors. A critical review.

by

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Summary

The in-pile stress-relaxation behaviour of the materials usually employed for the elastic structural elements, in nuclear reactors, is critically reviewed and the results are compared with those obtained in commercial zirconium alloys irradiated under similar conditions.

Finally, it is shown that, under certain conditions, some zirconium alloys may be used as an alternative material for these structural elements.

Elastische Strukturelemente nuklearer Reaktoren
- Eine kritische Übersicht -

Zusammenfassung

Es wird eine kritische Übersicht des in-pile Spannungsrelaxationsverhaltens von Werkstoffen gegeben, die gewöhnlich als elastische Strukturmaterialien in nuklearen Reaktoren verwendet werden.

Ein Vergleich mit dem Verhalten kommerzieller Zirkonlegierungen - unter ähnlichen Bestrahlungsverhältnissen - zeigt, daß in bestimmten Fällen einige dieser Zirkonlegierungen als alternative Werkstoffe für elastische Strukturelemente in Frage kommen.

Introduction

Several elastic structural elements, mainly springs and spacers, are included in the fuel bundles of nuclear power plants. These elements are made with Inconel 718 and Stainless Steel (1.4980 = A 286 in the case of Atucha) and even if they show very good mechanical properties, under servicing conditions, have the disadvantage of a large neutron absorption reducing considerably the efficiency of the reactor. In fact, the cross-section for neutron absortion of these alloys is of the order of 30 times higher than that of the usual zirconium alloys.

It seems an interesting problem to look at the possibility of substituting,from the metallurgical point of view, these structural elements by similar ones but built with commercial available zirconium alloys.

If this is possible, from the point of view of the mechanical and corrosion properties, one has the additional advantage of a possible redesign of the fuel elements, reducing considerably fabrication costs. The exact economic advantage has to be evaluated but a rough estimate gives quatities that are important (at least 100.000 US-$, per year, only from the point of view of the burn-up; this value was estimated for Atucha).

It is the purpose of this report to review the mechanical properties of Stainless Steels,Inconel 718 and several zirconium base alloys, fundametally elastic properties and their degradation under service conditions (temperature and neutron irradiation).

Finally, the available data will be analyzed and some additional experiments will be suggested.

1. The problem of design

The elastic structural elements are made mainly in two shapes: springs with circular cross-section and sheets bent elastically. The maximum shearing stress in a spring of mean radius R, supporting a load P, is given by [1]

$$\sigma = 16 \text{ P R}/\pi \text{ d}^3 \qquad (1)$$

where d is the diameter of the cross-section of the coil, Fig. 1. For a sheet (beant beam) of rectangular cross-section, bent initially to a radius R_o and that after the application of the load changes to a radius R_1, the maximum shear stress applied to it is given by [2]

$$\sigma = \frac{1}{2} \text{ E t } (1/R_o - 1/R_1) \qquad (2)$$

where E is Young's modulus and t the thickness of the beam, Fig. 2. It must be pointed out that equations (1) and (2) are useful only for rough estimates and one should include additional effects such as the changes in temperature, irradiation growth, etc.

From equation (1) it is seen that the load supported by the spring is proportional to the stress applied to the material so that if this stress relaxes the supported load decreases in the same proportion. For the case of the bent beam, equation (2), if the stress relaxes R_1 will increases and consequently the load supported by the beam will be reduced.

Then, from the point of view of the use of the structural materials as elastic members the important mechanical property is the stress-relaxation (or the total creep strain) under servicing conditions. Once the load that must be sustained by the elastic element, and the limits between it can varies during service, has been established, the maximum stress applied to the material can be determined from equations (1) and (2) with the appropriate geometrical dimensions. From the stress-relaxation behaviour of the material, as a function of temperature and neutron dosis, it may be seen if this conditions are fulfilled. Then, the important property to be analyzed is the stress-relaxation behaviour under working conditions (temperature and neutron flux) since, as it will be shown, the behaviour of the unirradiated material is not representative of the situation in-pile. Finally, the approximate working conditions of the elastic elements in the Atucha reactor are given in table 1.

Table 1:

Temperature	$T \simeq 573$ K	
Instantaneous flux	$\Phi_i \simeq 5 \times 10^{17}$ neutrons/m^2s	(E > 1 MeV)
Integrated flux	$\Phi_t \simeq 1 \times 10^{25}$ neutrons/m^2	(E > 1 MeV)
Total working time	$t \simeq 8.000$ h	

2. Stress-relaxation and creep behaviour

a) Inconel 718

It was not possible to obtain information on the stress-relaxation or creep behaviour of Inconel 718 under irradiation in conditions similar to those given in table 1. There is some information, given by Huntington alloys [3] on the relaxation of springs of unirradiated material. The data are shown in Fig. 3 and it may be seen that the stress-relaxation, for temperatures of the order of 573 K, is expected to be lower that 1 % in several thousand hours. Recent reports [4, 5] give information only on the influence of neutron irradiation on short term mechanical properties (mainly tensiles) for temperatures above about 673 K and neutron fluences up to 7.5×10^{26} n/m^2. It is stated in those reports that creep tests are in progress. The information given in the literature sometimes refers to the creep behaviour of the material and not to its stress-relaxation. In order to correlate numerically both data, the creep rate of the material, in terms of stress, time, etc., must be given [6].

In fact, if the creep rate, $\dot{\varepsilon}_p$, can be expressed as

$$\dot{\varepsilon}_p = A\sigma_o^n f(t) \qquad (3)$$

where σ_o is the applied stress, A is a constant related to the material and to the temperature f(t), is a function of the time t, then the plastic strain $\dot{\varepsilon}_p$ after a time t_o in a creep experiment would be

$$\varepsilon_p = A\sigma_o^n \int_o^{to} f(t)\, dt + C_1; \qquad C_1 = 0$$

During stress-relaxation, since $\dot{\varepsilon}_p = -\dot{\sigma}/E = A\sigma^n \; f(t)$, the stress, σ, after a time t_o will be

$$\int_{\sigma_o}^{\sigma} (d\sigma/\sigma^n) = - A\ E \int_{o}^{to} f(t)\ dt + C_2 = - E\ \varepsilon_p/\sigma_o^n$$

$$C_2 = 0$$

If n = 1, then

$$\ln\ (\sigma/\sigma_o) = - E\ \varepsilon_p/\sigma_o \text{ and } \sigma/\sigma_o = \exp\ (- E\ \varepsilon_p/\sigma_o)$$

so that the stress-relaxation $\Delta\sigma_{rel}$, after the time t_o is

$$\Delta\sigma_{rel} = 1 - (\sigma/\sigma_o) = 1 - \exp\ (- E\ \varepsilon_p/\sigma_o). \qquad (4)$$

If $n \neq 1$

$$\Delta\sigma_{rel} = 1 - [1 + (n-1)\ E\varepsilon_p/\sigma_o]^{1/(n-1)} \qquad (5)$$

It must be pointed out that "time-hardening" [7] was assumed, which is a reasonable assumption for the in-pile behaviour. In fact, the in-pile creep of some zirconium alloys [8] and stainless steels [9] seems to be described by an equation like (3).

When creep data are reported, the stress-relaxation will be estimated by equations (4) and (5) for several values of n. It should be reminded, however, that this will give only an idea of the order of magnitude of the stress-relaxation involved since, in addition, uniaxial conditions were assumed on deducing these equations [10, 11].

As an example, from the reported creep properties of Inconel 718 [3], shown in Fig. 4:

ε_p = 0,2 %; T = 866 K; t_o = 1,000 h; σ_o = 703 MPa the estimated stress-relaxation is

n	$\Delta\sigma_{rel}$ %
O	48
1	38
2	33.7
3	28.6.

These values are reasonable, when compared with those shown in Fig. 3 at lower stresses. The value for n = O is an overestimation.

b) Stainless Steels

b.1 SS 1.4980 (A-286)

No published data have been found for the in-pile creep and stress-relaxation behaviour of this steel. Some results for the tensile and creep properties, in unirradiated material, can be obtained from the supplier [12]. For example, at 873 K with σ_o = 360 MPa a strain of 0.2 % is obtained after 1,000 h.
No data are reported at lower temperatures.
With these values, the estimate stress-relaxation is

n	$\Delta\sigma_{rel}$ %
O	89
1	59
2	47
3	40

The stress-relaxation of this steel, for temperatures of 573 K and below, is expected to be slightly higher than that of Inconel 718.

b.2 Other stainless steels

Only few published data were found for the stress-relaxation of stainless steel, during irradiation.
J. W. Joseph, Jr. [13] reported some values of the stress-relaxation behaviour of SS type 304, under neutron irradiation. Round specimens under compression were used and the irradiation temperature was lower than 373 K. No stress-relaxation was observed in the unirradiated specimens tested at the same temperature. The results are shown in Fig. 5 and, as discussed in the

paper, the data at the higher stresses are in error due to the fact that the specimens were strained plastically.
In a later report by the same author and R. E. Schreiber [14] some stress-relaxation data for the same material are reported, but for measurements made in torsion with tubular specimens. Essentially the same results were obtained as for compression and they are shown in Fig. 6. The data shown in Fig. 5 are included for a comparison.

There are some reported results on the stress-relaxation of SS 302 and 347. These data are given in ref. [15] and it was not possible, up to now, to obtain the original papers. The data on the 302 steel are shown in Fig. 7 and were obtained at an irradiation temperature of 583 K under a flux > 10^{16} n/m^{2}s (> 1 MeV), in compression springs.
The results in SS 347 are shown in Fig. 8 and were obtained at an irradiation temperature of 333 K, in bending, for a stress of 53 MPa.

There are some data on the creep behaviour of SS 302 measured in springs, with a diameter of 9 mm and a wire diameter of 1.5 mm, under a stress of 407 MPa. These results, reported in [15], obtained at irradiation temperatures between 293 and 333 K are shown in Fig. 9. It is seen that the plastic strain is large, exceding the elastic strain, so that the stress-relaxation is expected to be high.
R. A. Wolfe and B. Z. Hyatt [16], reported some in-pile stress-relaxation data in Almar 362, a maranging stainless steel. The measurements were done at two nominal temperatures 333 and 586 K, by using the bent beam technique. The results are shown in Figs. 10 and 11. The authors did not give the initial stresses but the radii of curvature. These stresses were calculated from the radii taking E=190 GPa and the reported thickness. The stress relaxation can be calculated from the figures with the equation

$$\Delta\sigma_{rel} = 1 - R_o/R.$$

It may be seen that the stress-relaxation varies between 40 and 60 %, according to the temperature and the initial stress. The two type of specimens, A or B, differ in the initial cold-

working conditions and thermal treatments. The B specimens were stressed to values above the yield stress.
D. Mosedale et al [9, 17] and G. W. Lewthwaite and K. J. Proctor [18], reported several data on the in-pile creep of SS springs at stresses lower than 100 MPa. The data reported in [18] were taken in two austenitic stainless steels, FV 548 and ASI 316. The usual thermal treatments were given to the springs with a diameter of 12.7 mm and a wire diameter of 1 mm. The irradiation temperature was of the order of 373 K.
The results for the FV 548 springs are shown in Fig. 12. These data correspond to the irradiation creep since the thermal creep was subtracted out. The deflection, D, of the spring is given in terms of the initial elastic deflection, D_e.
The results for the ASI 316 springs are shown in Fig. 13. At the stresses used, no thermal creep was observed in these springs. The annealed spring crept transiently ($\sim$ 0.2 D_e) and considerably less than the cold-worked ones. An estimate of the stress-relaxation can be made, form the values given in Figs. 12 and 13, by using equation (4) and the reported deflections for the springs. The results are

σ_o	$\Delta\sigma_{rel}$ %	
43.3	58	Fig. 12
26.6	61	
41.8	41	Fig. 13

For the data reported in references [9] and [17] it was found that springs made from seven austenitic stainless steels crept far more in reactor, at temperatures of the order of 553 K, than in the laboratory at the same temperatures. The specimens were irradiated at a flux of the order of 3 x 10^{19} n/m^2 s (> 0.1 MeV).

There are several additional results reported in these papers and they will not be detailed. As an example, Fig. 14, taken from reference [17], shows a comparison between the irradiation induced creep in springs of ASI 316 and the thermal creep at a much higher temperature. It is seen that the irradiation induced creep is very high.

A stress-relaxation of the order of 30 % is obtained with equation (4) from the data of Fig. 14, in the irradiated specimen and after 4000 h.
Finally, K. D. Closs et al [19], reported some data on the in-pile creep of SS 1.4981, cold-worked 15 %. The measurements were taken in rods of 3 mm in diameter and 50 mm long.

The change in length as a function of the irradiation time is shown in Fig. 15 and it is independent of temperature for temperatures between 623 and 723 K. Using equation (4), with E = 180 GPa [12], a stress-relaxation of the order of 90 % is obtained, with the reported dimensions.

c) Zirconium alloys

Several data for the in-pile creep and stress-relaxation of zirconium alloys have been published in the literature [20-27] and only the most representative will be shown.
Fig. 16 (a) to (e), from reference [20], shows some results on the stress-relaxation of zircaloy-4 with different thermo-mechanical treatments and in Zr + 2.5 wt % Nb + 0.5 wt % Cu. It is seen that the irradiation increases the stress-relaxation at both temperatures. It must be pointed out that the stress-relaxation data in zirconium alloys, given in Figs. 16 to 19, were measured by the bent beam technique. Fig. 17, taken from reference [23], shows the stress-relaxation behaviour of zircaloy-2 specimens with different initial conditions, at various stresses. The specimens were prepared from pressure tubes in hoop (transverse) and longitudinal directions. The longitudinal specimens were cutted with the neutral axis either in the tangential (T) or in the radial (R) direction. These data were taken at temperatures of the order of 573 K and at a fast neutron flux (E > 1 MeV) of 2×10^{17} n/m^2 s. As for the data shown in Fig. 16, the in-pile stress-relaxation is higher than that observed in the unirradiated material. Similarly, Fig. 18, taken from reference [22], and Fig. 19, taken from reference [23], show the stress-relaxation behaviour of Zr-2.5 wt % Nb at similar temperatures and neutron exposures.

Discussion and conclusions

Under the working conditions given in table 1, the Zr-2.5wt% Nb alloy shows the lowest stress-relaxations when compared with the rest of the commercial zirconium alloys (no data were found for Zr-1 wt% Nb). In fact, from Figs. 18 and 19(c) it is seen that this alloy relaxes 50 % or less if the appropriate thermo-mechanical treatments are used. These values are valid for stresses of the order of 200 MPa since the creep rate and consequently the stress-relaxation is expected to increase very rapidly at stresses above about 300 MPa [26].

It is clear that a stress-relaxation of the order of 50 % is too high when compared with the values expected, from out of pile measurements, for Inconel 718 (less than 1 %), Fig. 3, or SS 1.4980.

The question is: Are the out of pile data representative of the in-pile behaviour? Unfortunately, as pointed out before, it was not possible to obtain information on the in-pile creep or stress-relaxation of these materials. However, if the stress-relaxation of Inconel 718 and SS 1.4980 is affected by irradiation in a way similar to the reported steels, shown in Figs. 5 to 15, then their in-pile stress-relaxation is expected to become of the same order of magnitude as that found in Zr-2.5 wt% Nb.

It is evident that an important experiment would be to measure the elastic behaviour of the structural elements after servicing, i.e., when the fuel elements are changed. If the stress-relaxation is found to be of a few 10%, then these elements can be made of Zr-2.5 wt% Nb it the working stresses are of the order of 150 MPa. No corrosion problems are expected since this zirconium alloy shows excellent corrosion behaviour.

Finally, more experimental work is needed on the in-pile stress-relaxation of zirconium alloys, stainless steels and Inconel 718, since the out of pile data are not representative, specially at low temperatures. For example, the irradiation induced creep and stress-relaxation in stainless steels seem to decrease slightly with increasing temperatures [9,17,18]. This is an interesting problem, too, from the point of view of an understanding of the fundamental mechanisms of irradiation damage.

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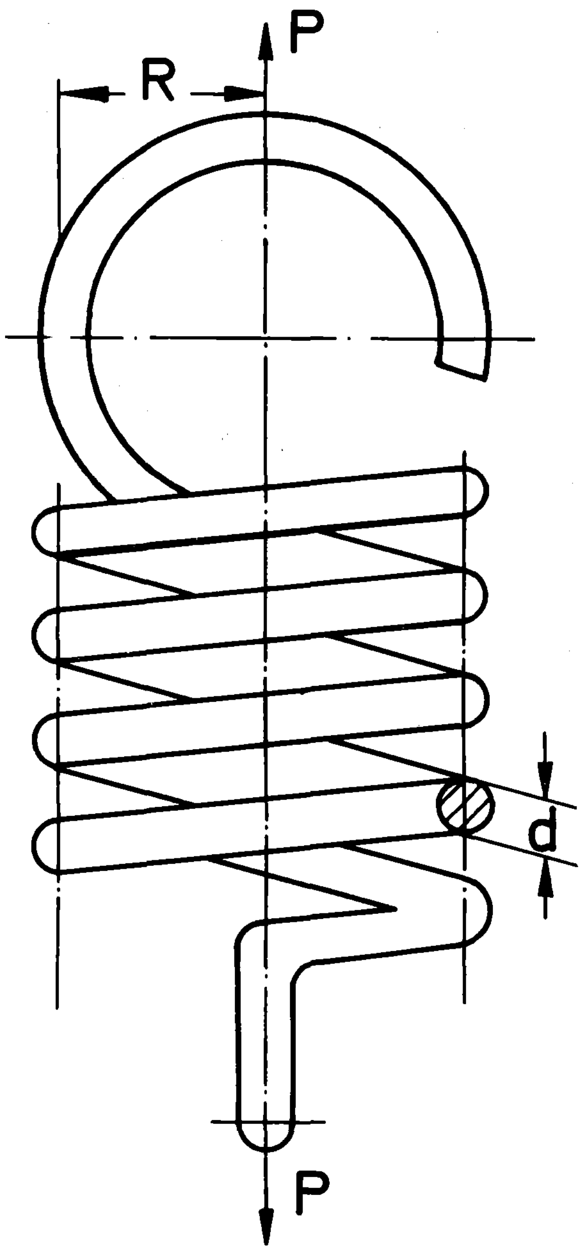

Fig. 1

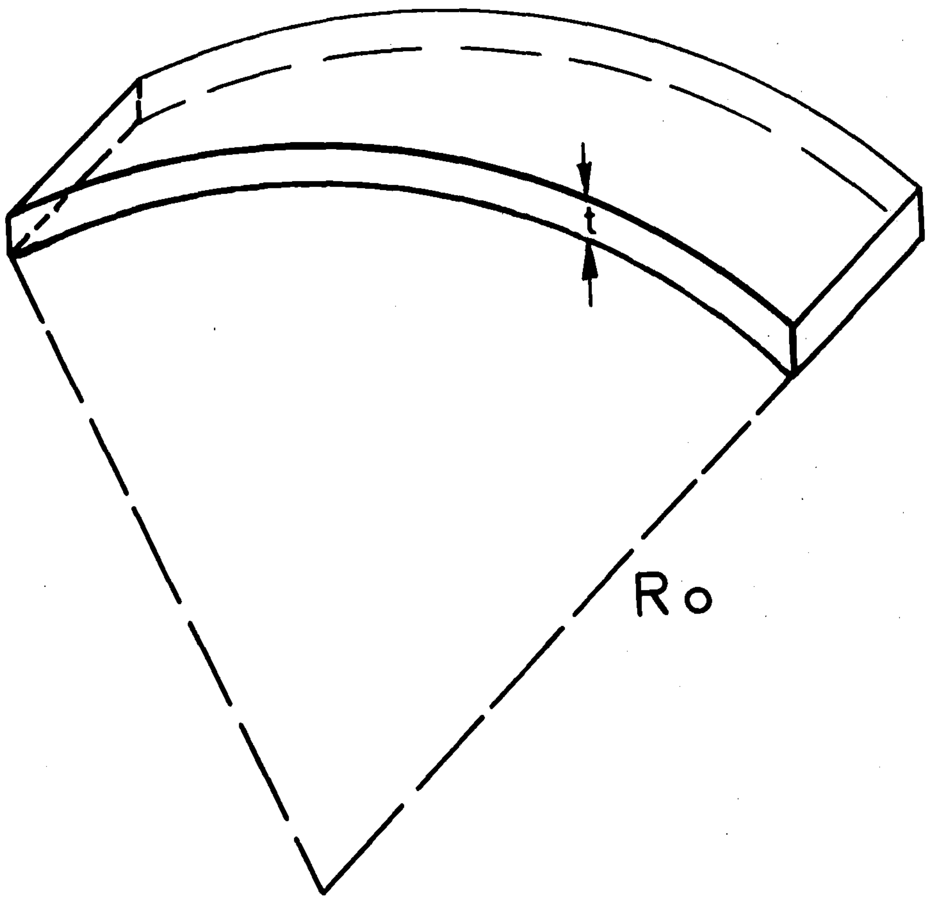

Fig. 2

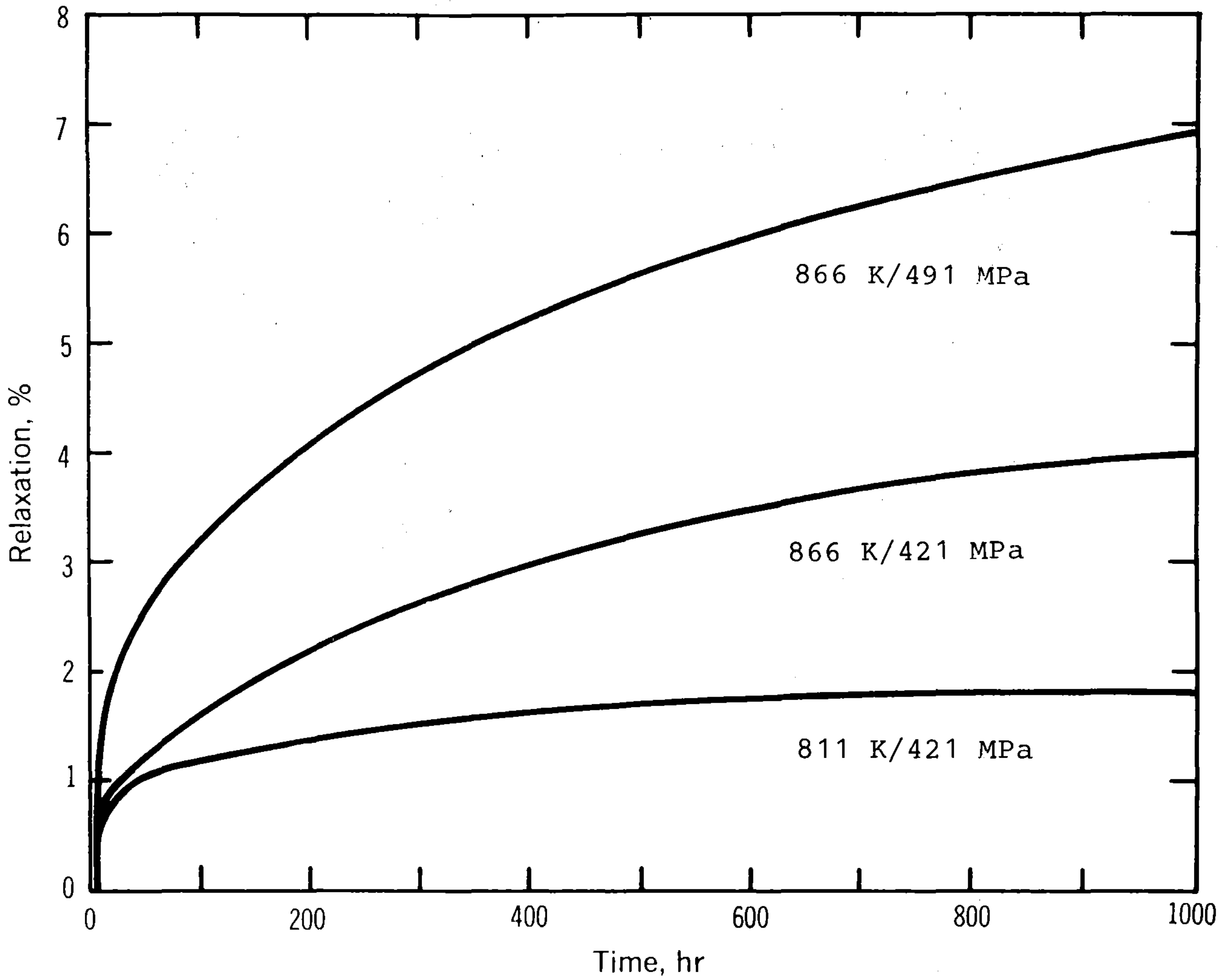

Fig. 3: Relaxation of helical coil springs made from 3.76 mm - diameter cold-drawn Nr. 1 Temper wire. (Springs annealed 1255 K/1h and aged 991 K/8h. F.C. to 894 K, hold at 894 K for total aging time of 18 h). Data taken from Ref. (3).

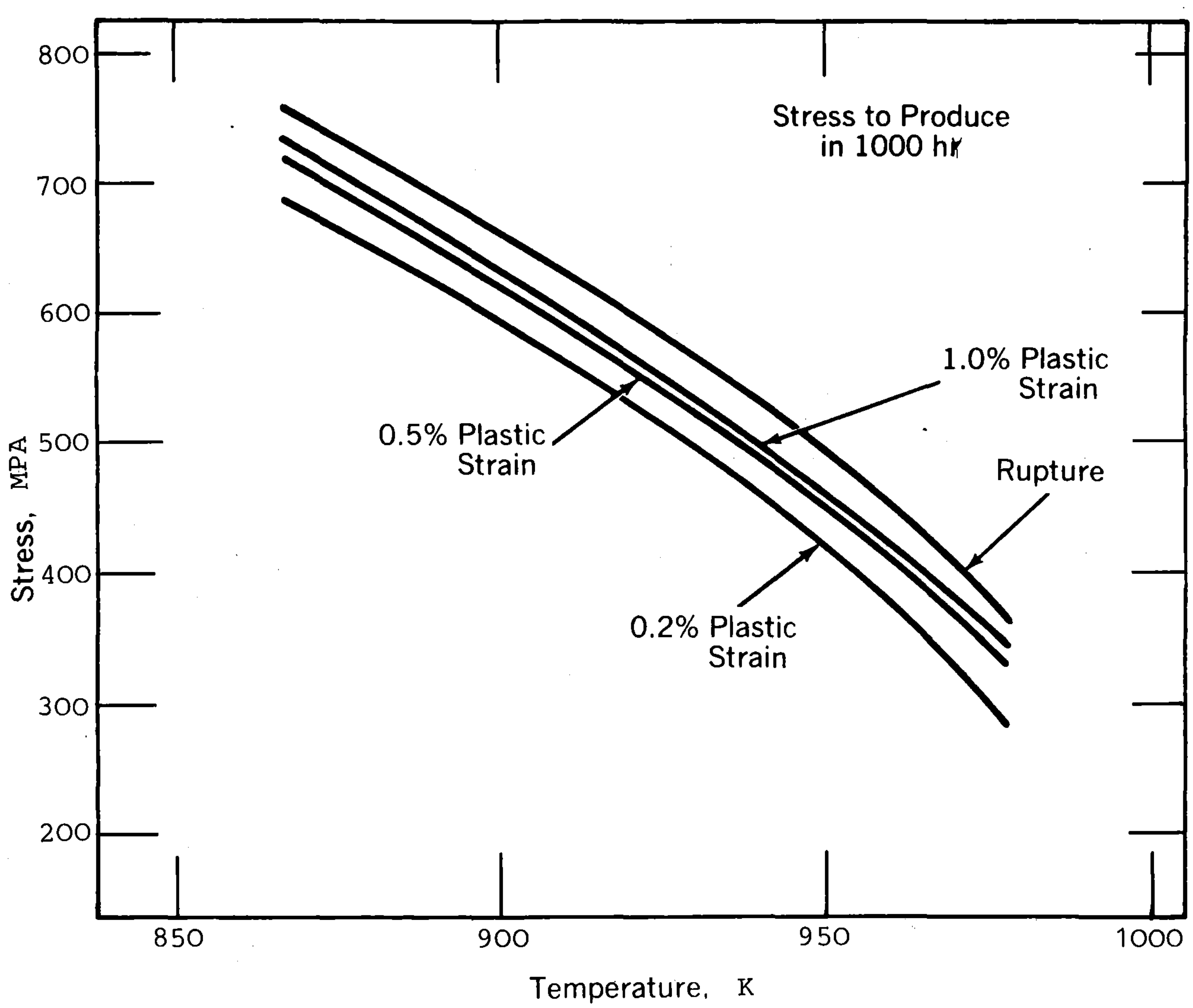

Fig. 4: Creep-rupture properties (1000 h) of hot-rolled, 15.88 mm - diameter bar (1255 K/1h, W.Q. and aged 991 K/8h, F.C. to 894 K, hold at 894 K for total aging time of 18 h). Data taken from Ref. (3).

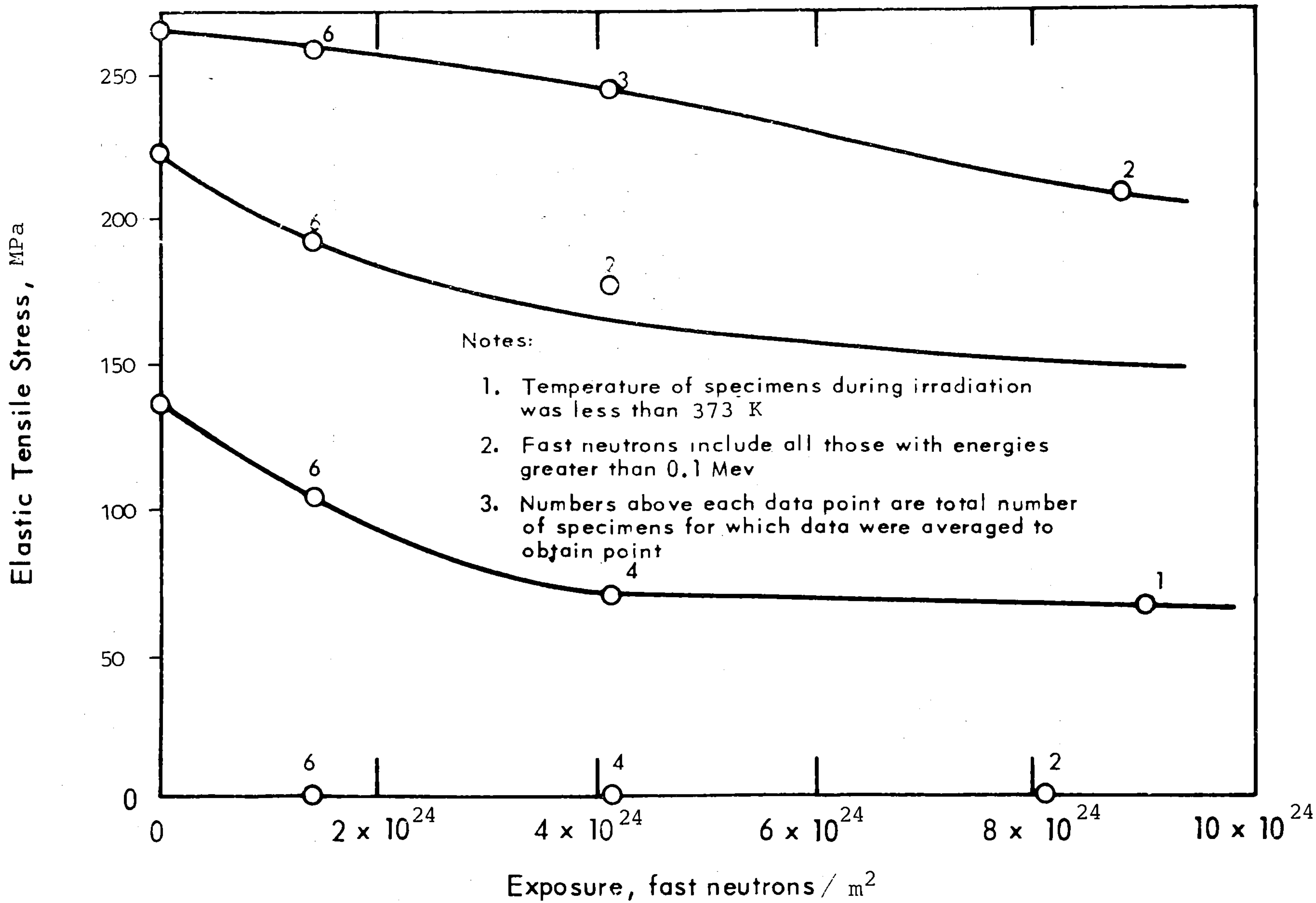

Fig. 5: Stress relaxation in type 304 Stainless Steel during irradiation. Data taken from Ref. (13).

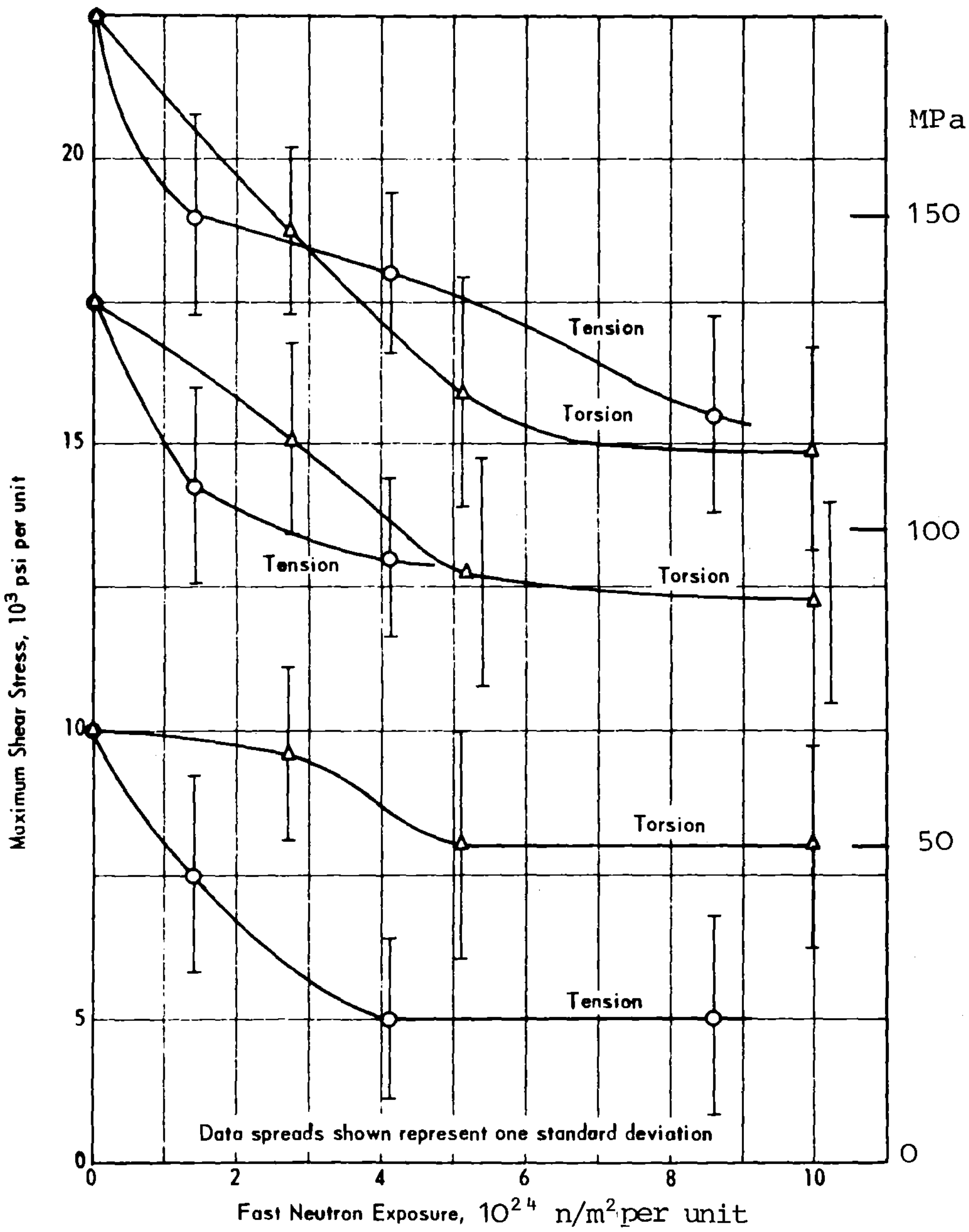

Fig. 6: Comparison of shear stress-relaxations in tensile and torsional specimens of 304 Stainless Steel. Data taken from Ref. (14).

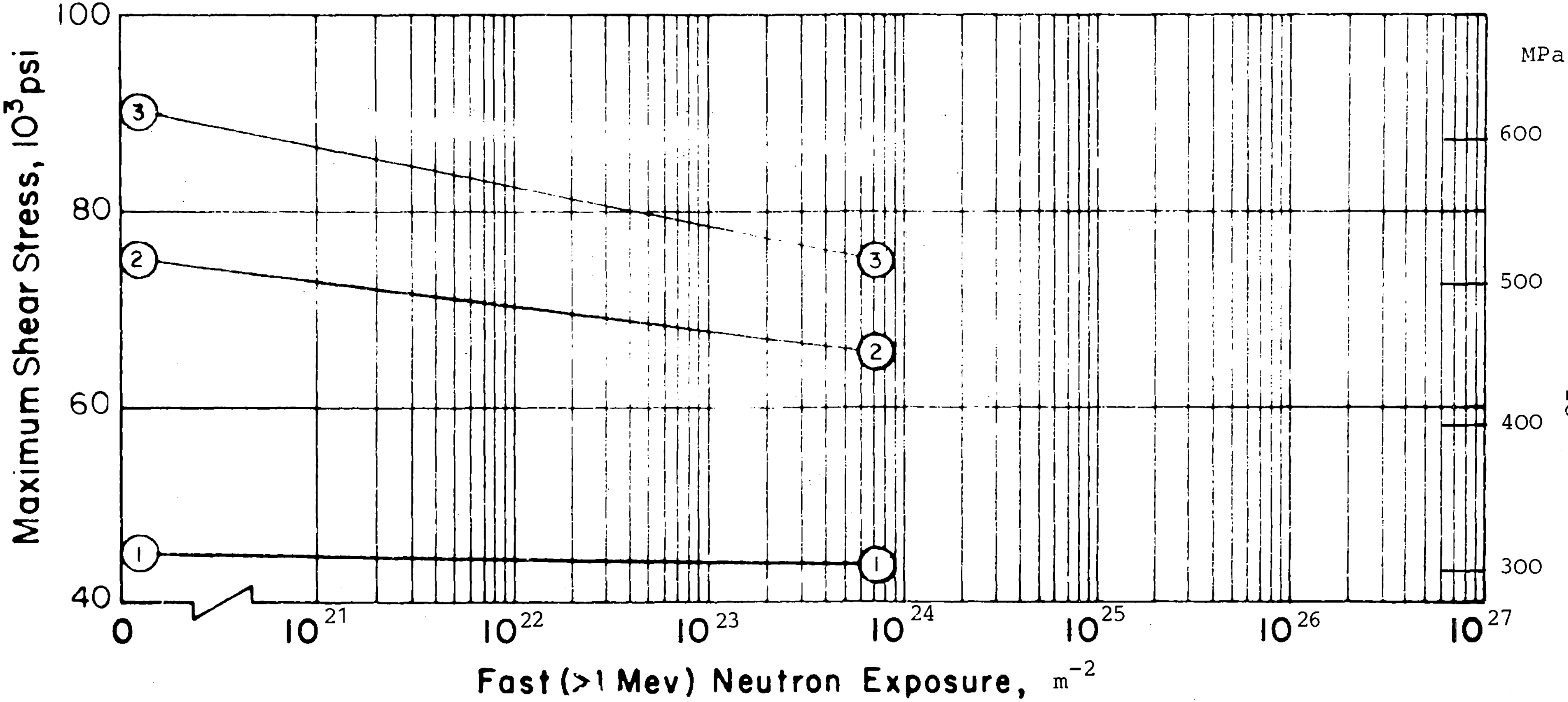

Fig. 7: Stress-relaxation of Stainless Steel 302. Data taken from Ref. (15).

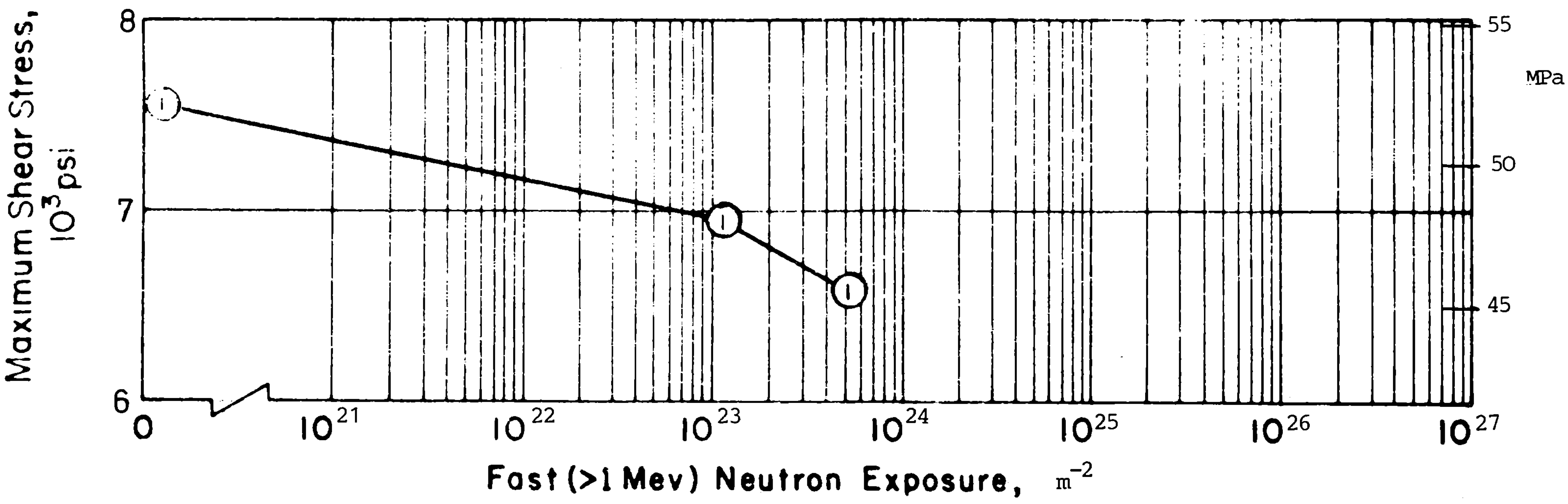

Fig. 8: Stress-relaxation of Stainless Steel 347. Data taken from Ref. (15).

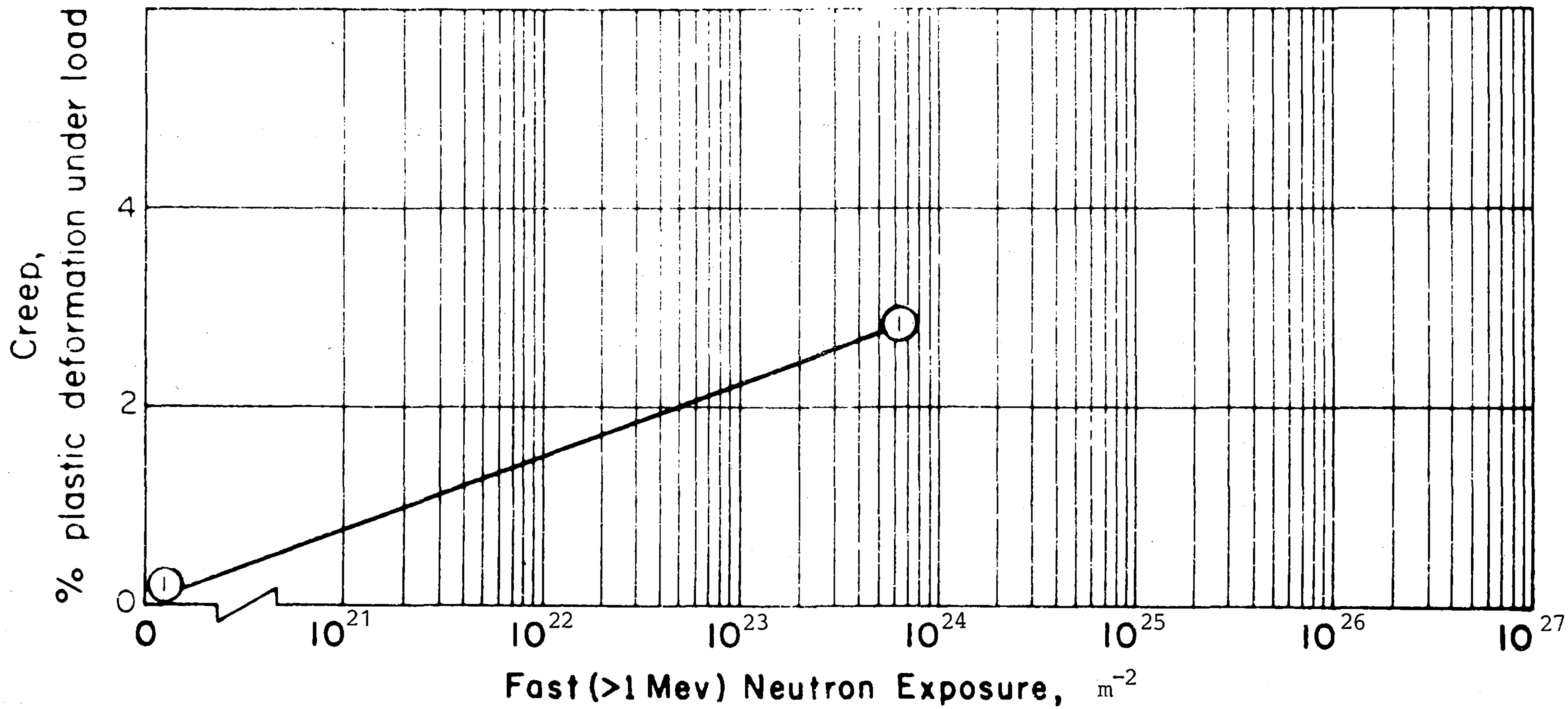

Fig. 9: Creep of Stainless Steel 302. Data taken from Ref. (15).

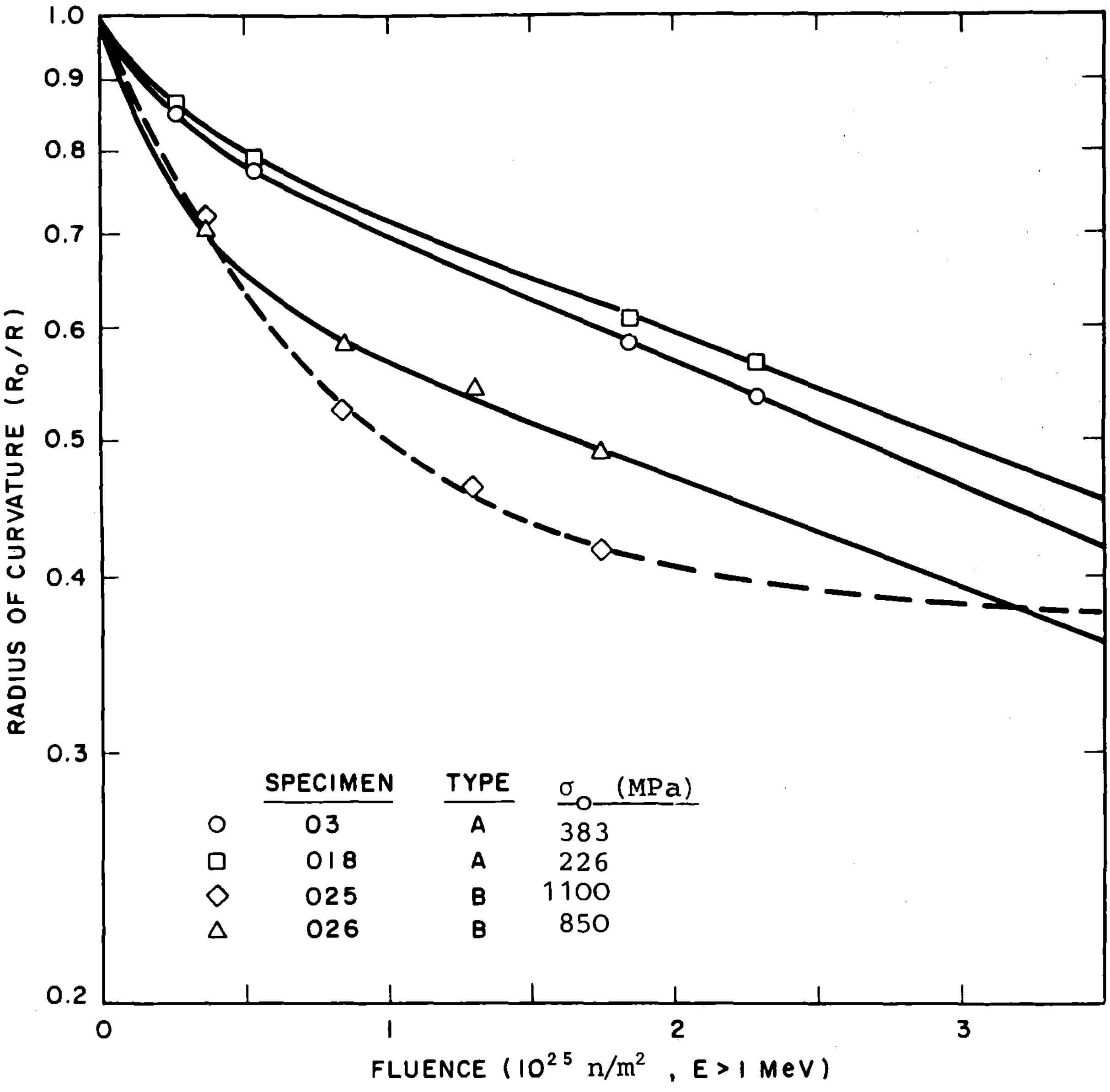

Fig. 10: In-pile stress-relaxation of Almar-362 at a nominal temperature of 333 K. Data taken from Ref. (16).

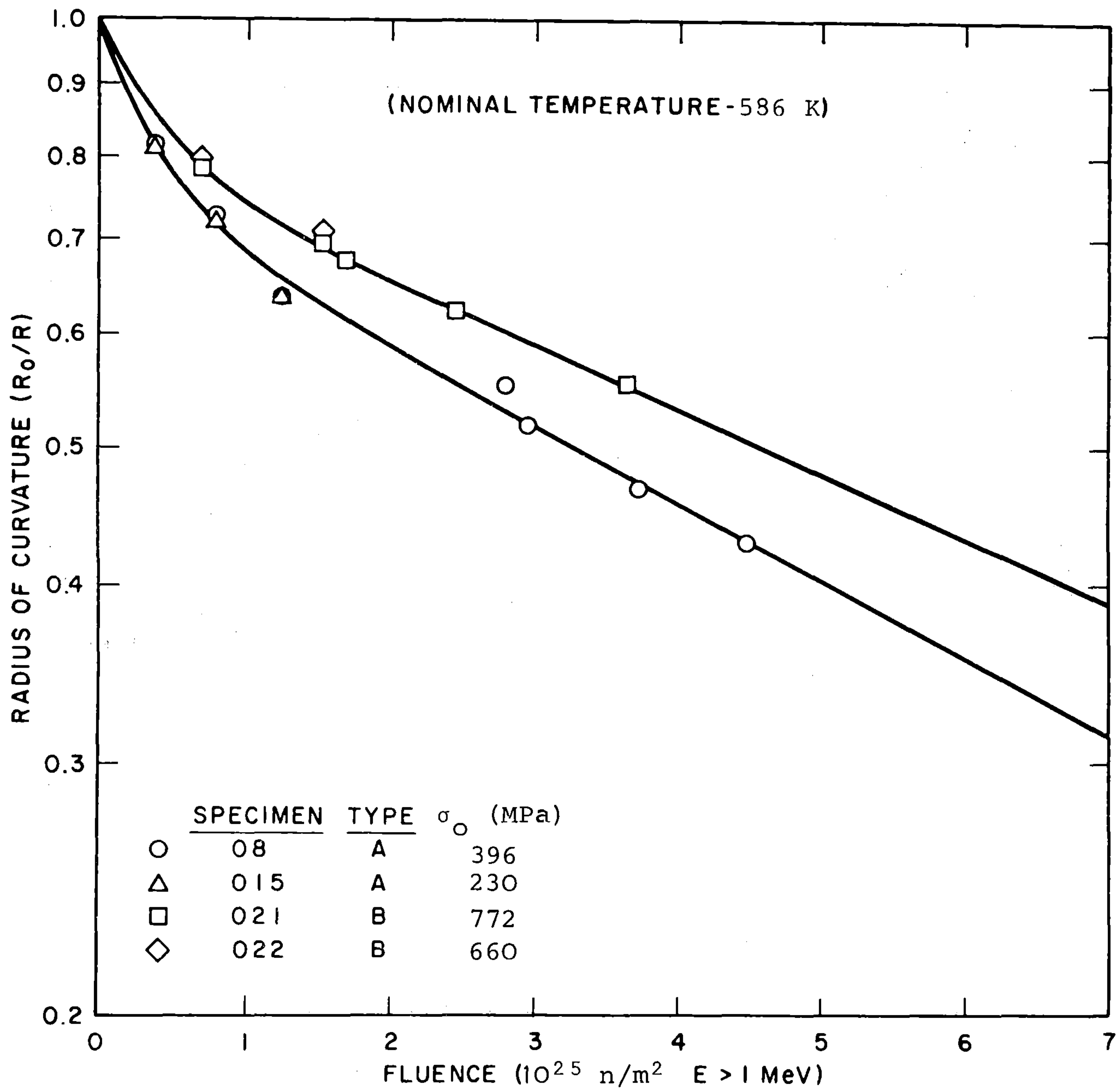

Fig. 11: High temperature in -pile relaxation of Almar-362. Data taken from Ref. (16).

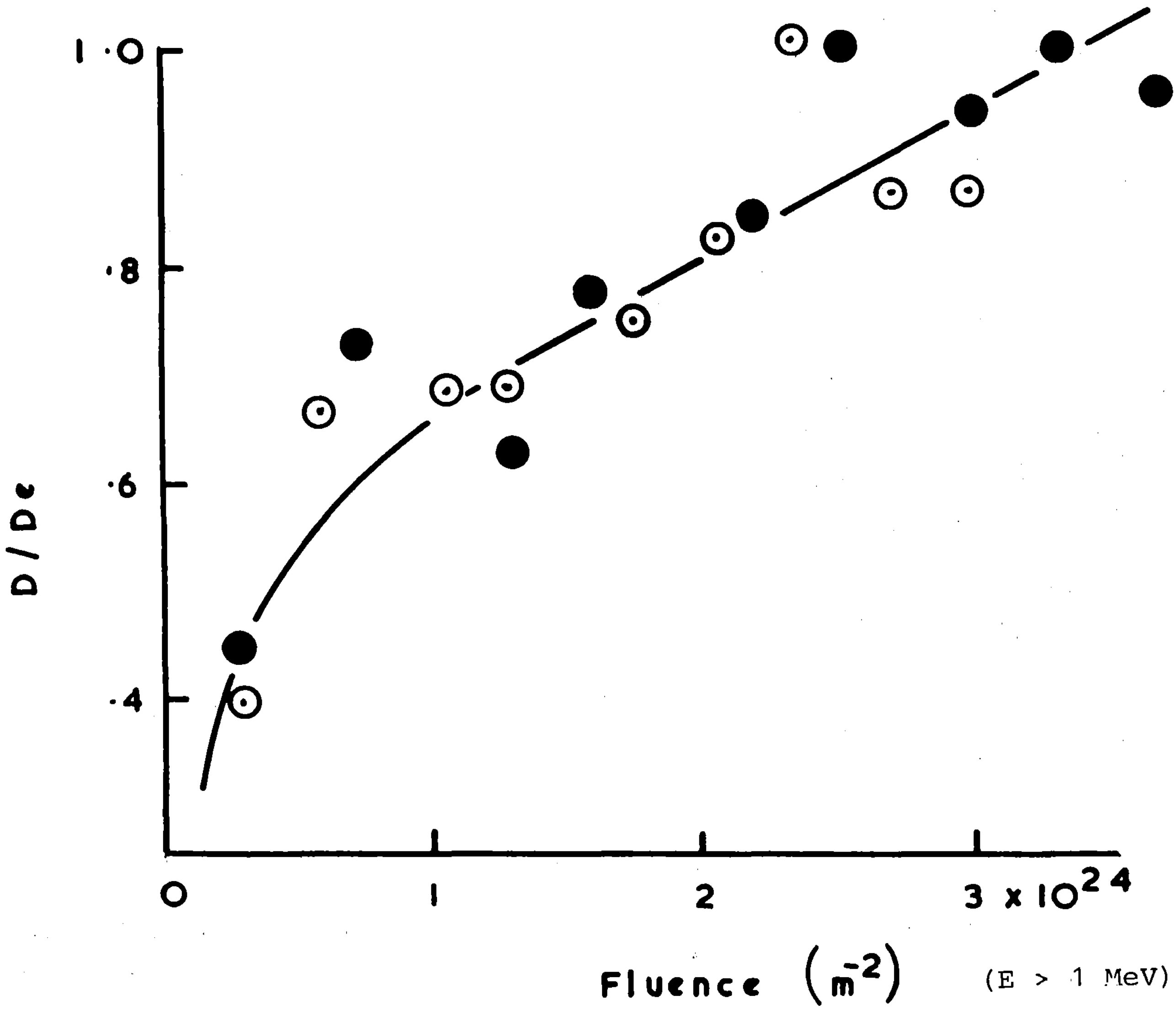

Fig. 12: Creep of cold-worked FV 548 springs; ⊙ 43.3 MPa, ○ 26.6 MPa.
Data taken from Ref. (18).

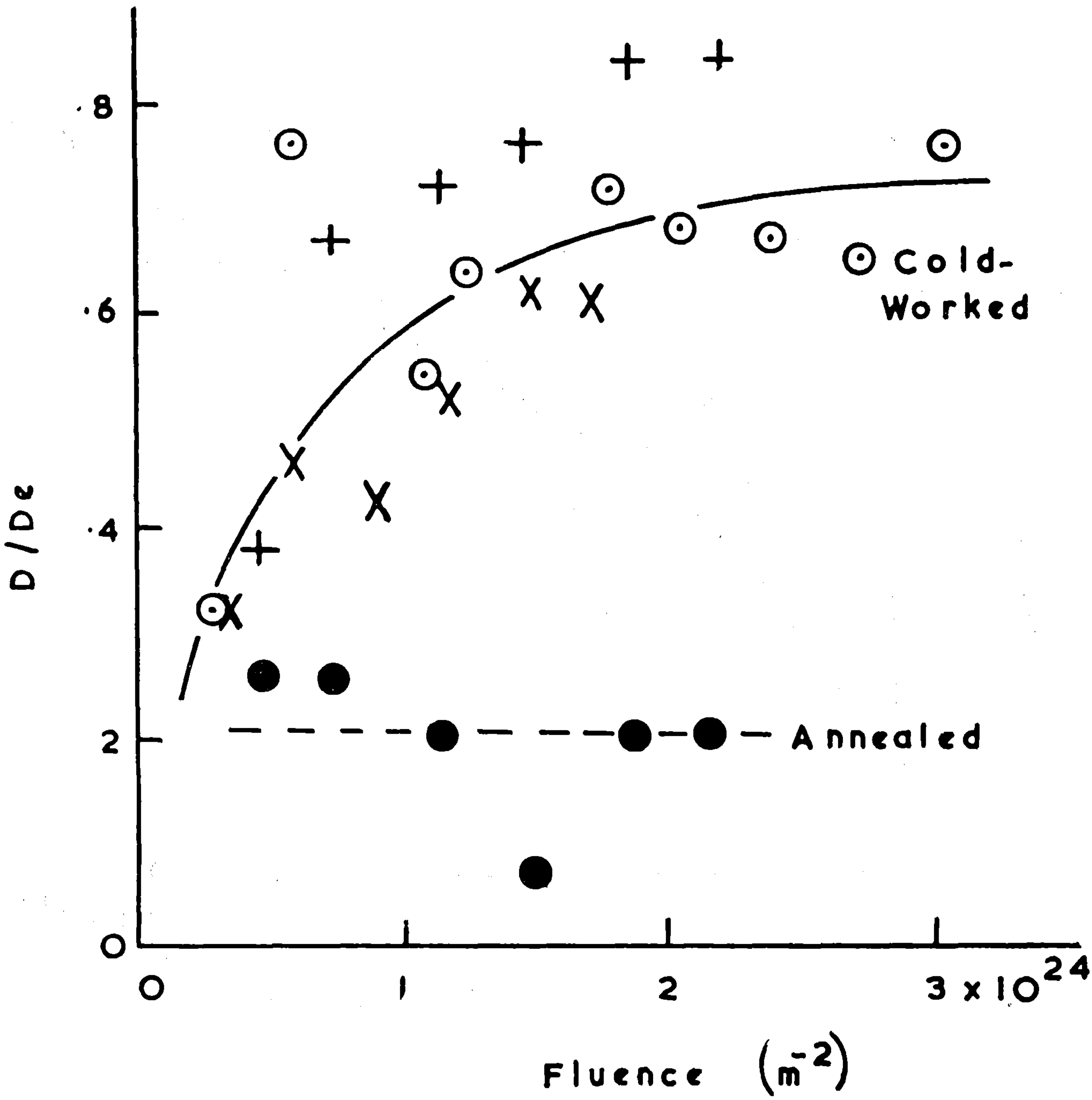

Fig. 13: Creep of 316 springs; ⊙ 41.8 MPa and, from first experiment, o 39.5 MPa, + 38.2 MPa, x 62.5 MPa. Data taken from Ref. (18).

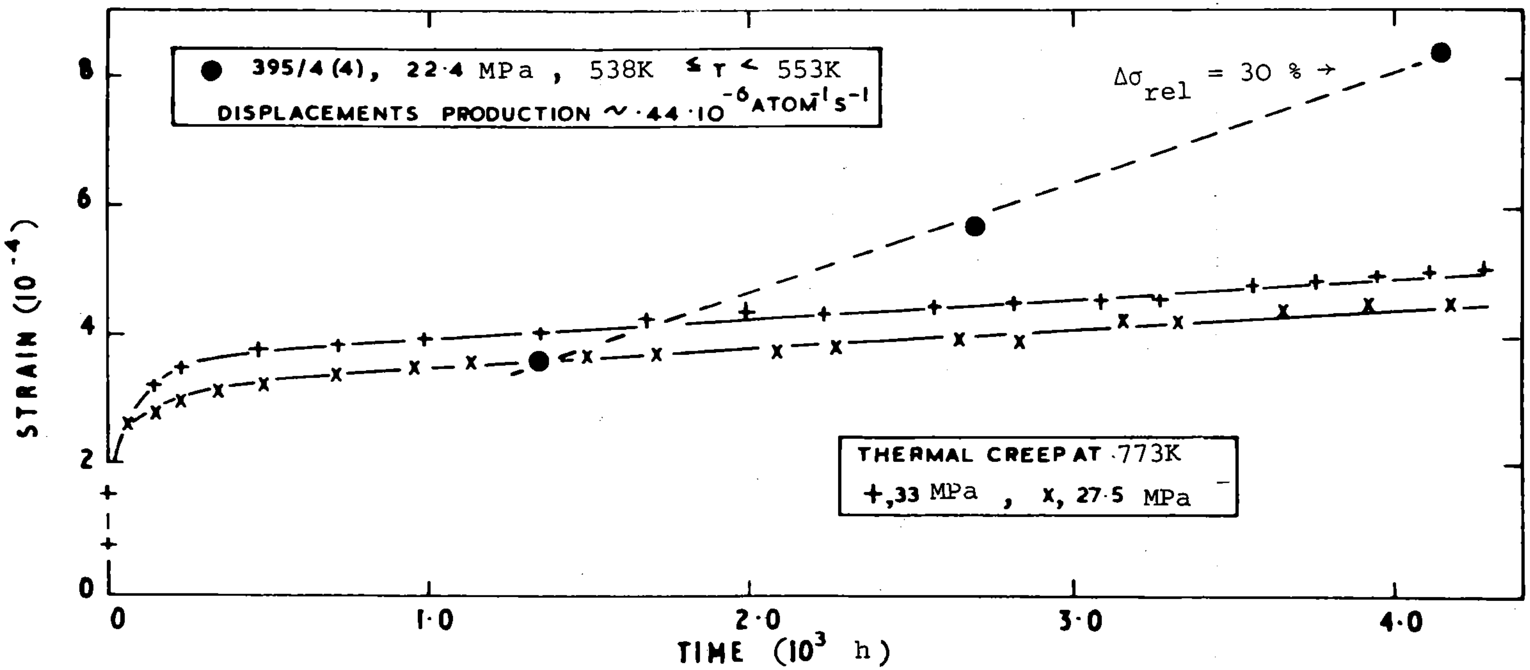

Fig. 14: Comparison of irradiation creep at 538K-553K and thermal creep at 773K of cold-worked M316 (Batch 2) springs. Data taken from Ref. (17).

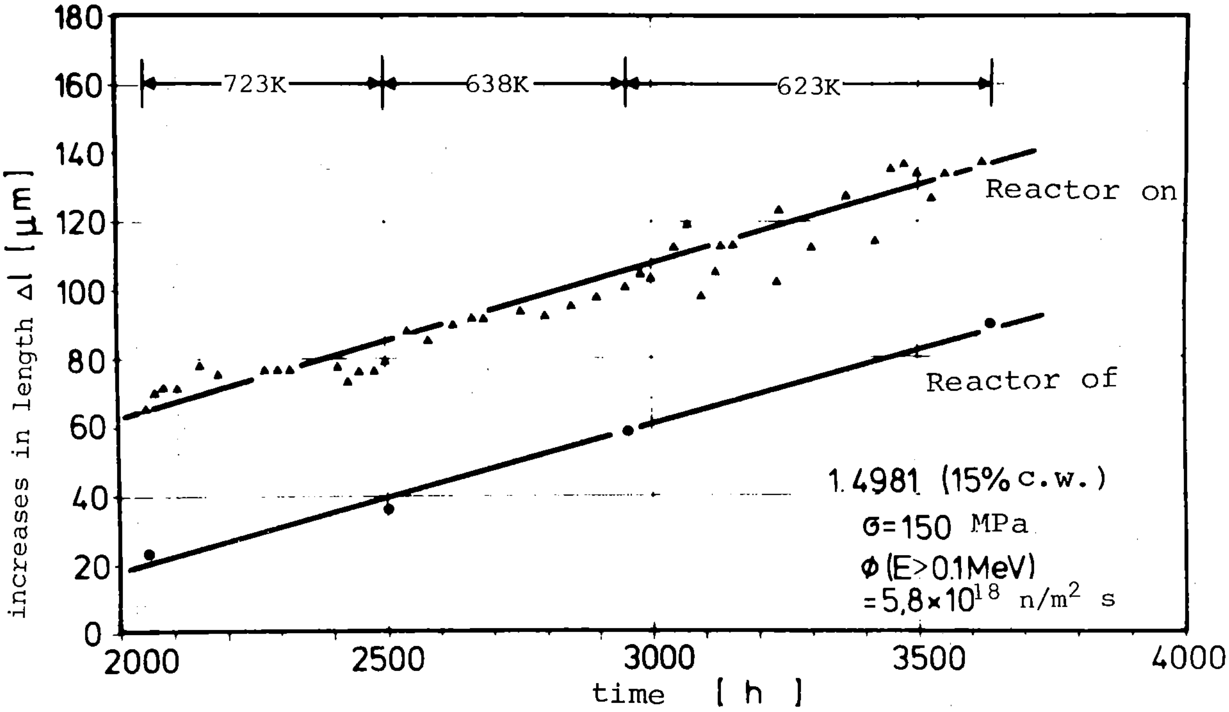

Fig. 15: In-pile creep of Stainless Steel 1.4981. Data taken from Ref. (19).

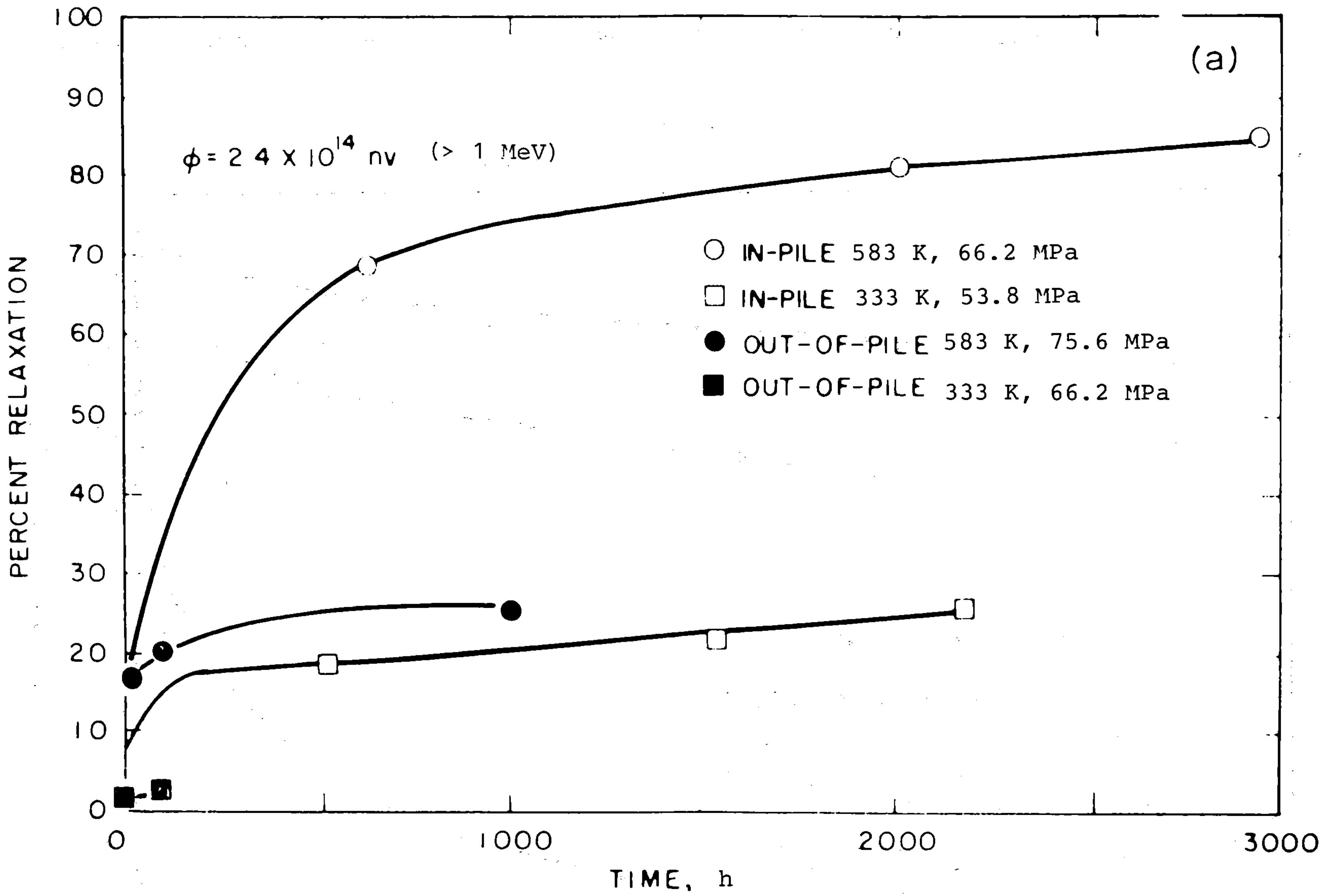

Fig. 16a: Relaxation of alpha-annealed Zircaloy-4. Data taken from Ref. [20].

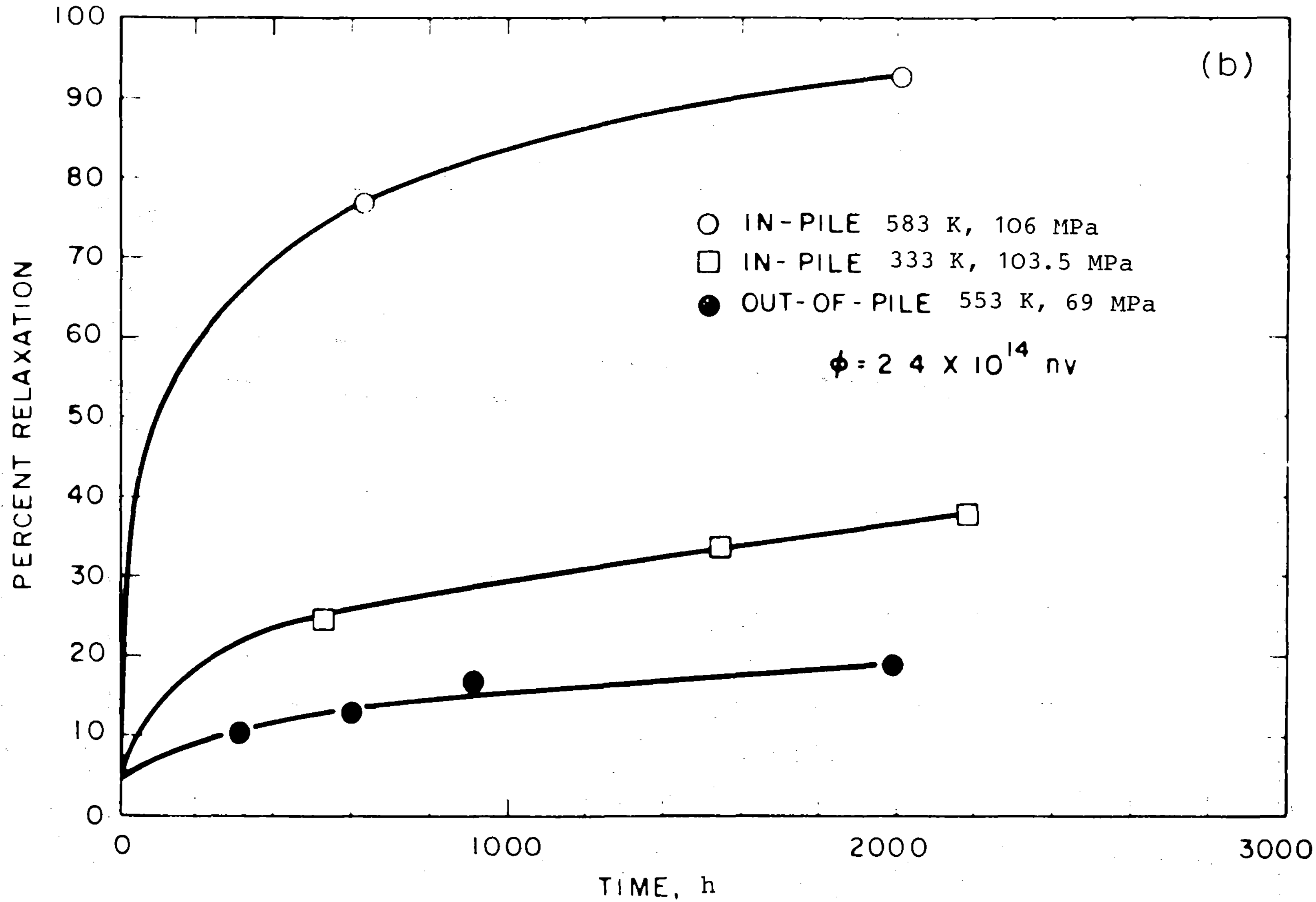

Fig. 16b: Relaxation of beta-quenched Zircaloy-4. Data taken from Ref. [20].

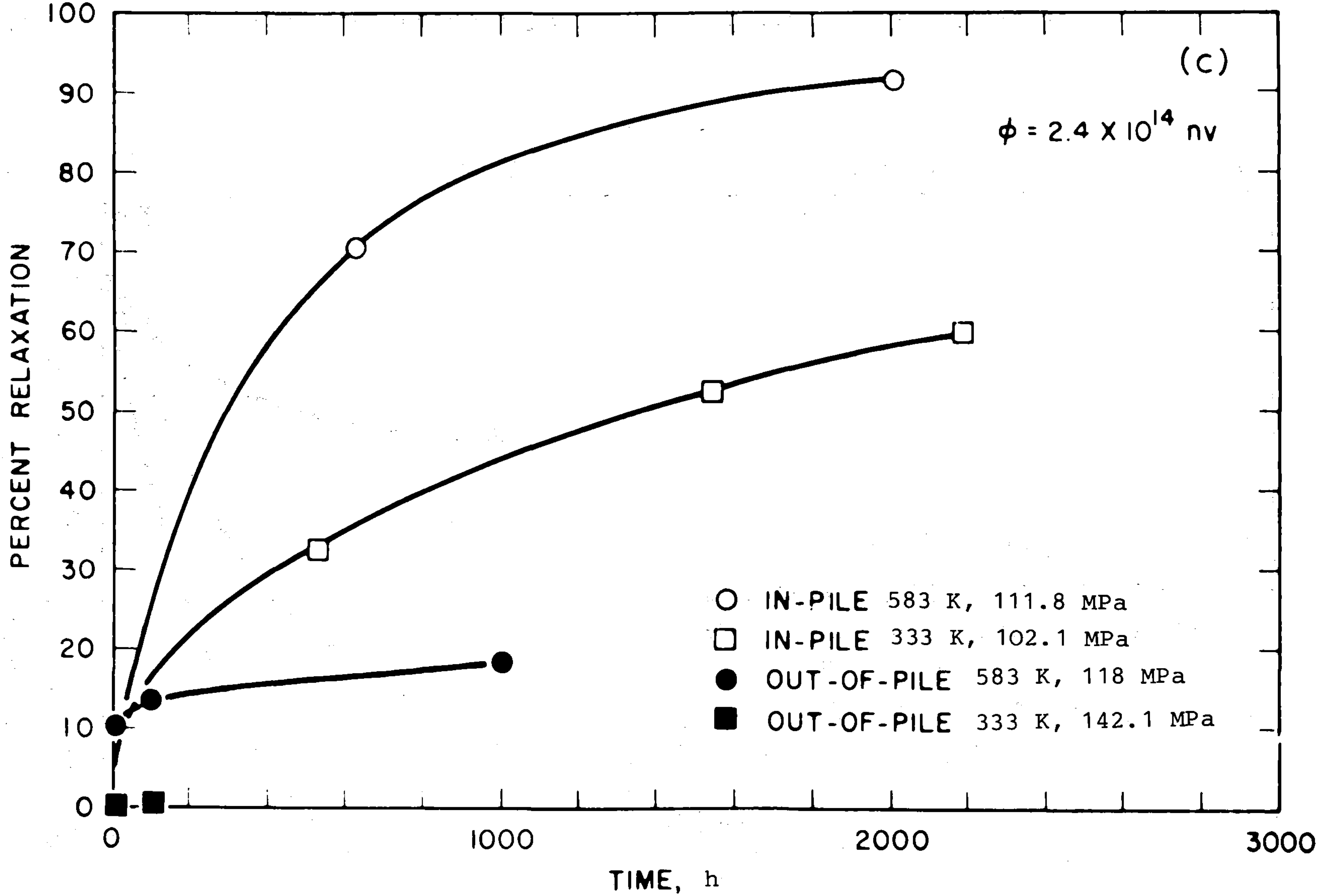

Fig. 16c: Relaxation of 15% cold-worked Zircaloy-4. Data taken from Ref. [20].

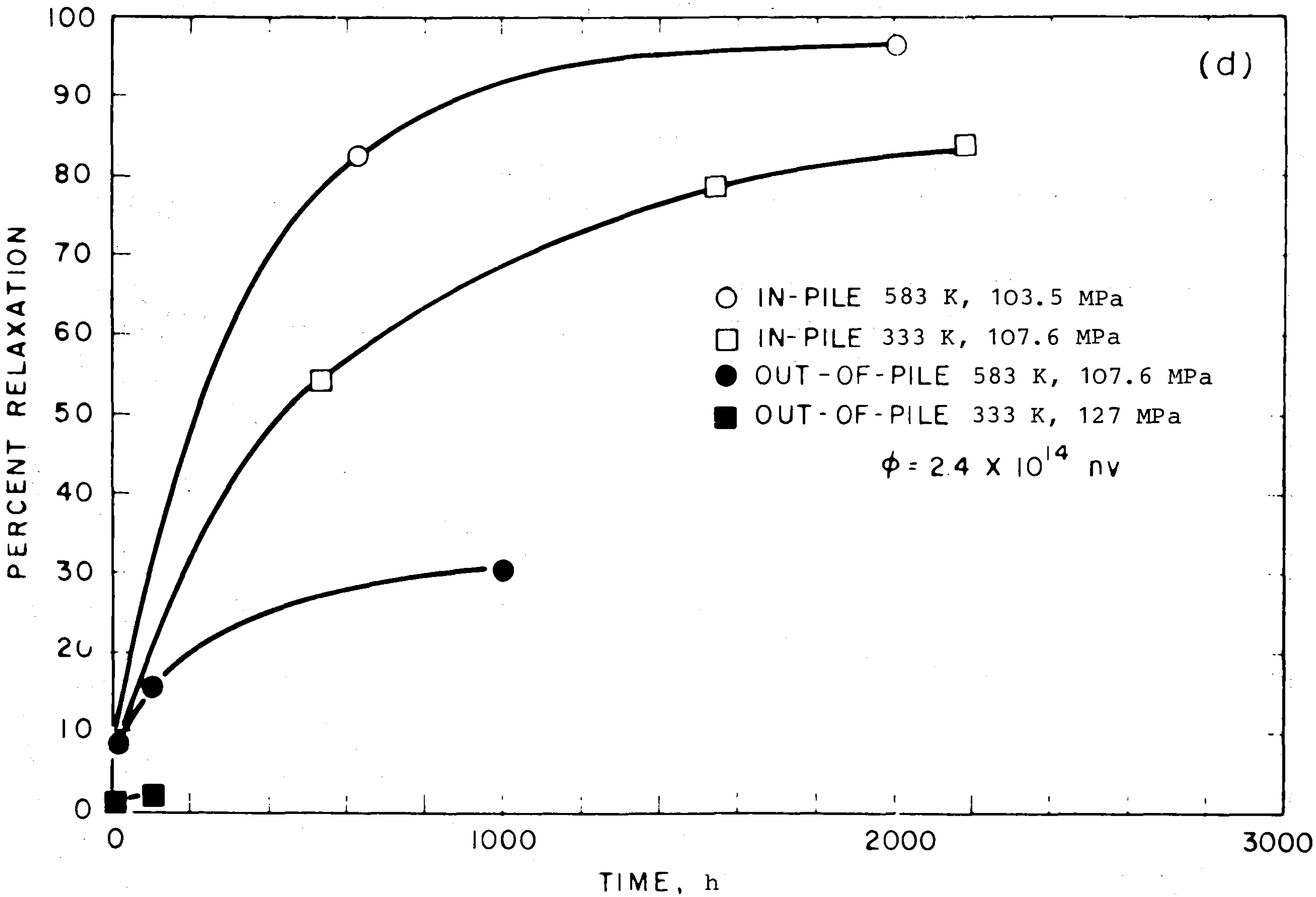

Fig. 16d: Relaxation of 79% cold-worked Zircaloy-4. Data taken from Ref. [20].

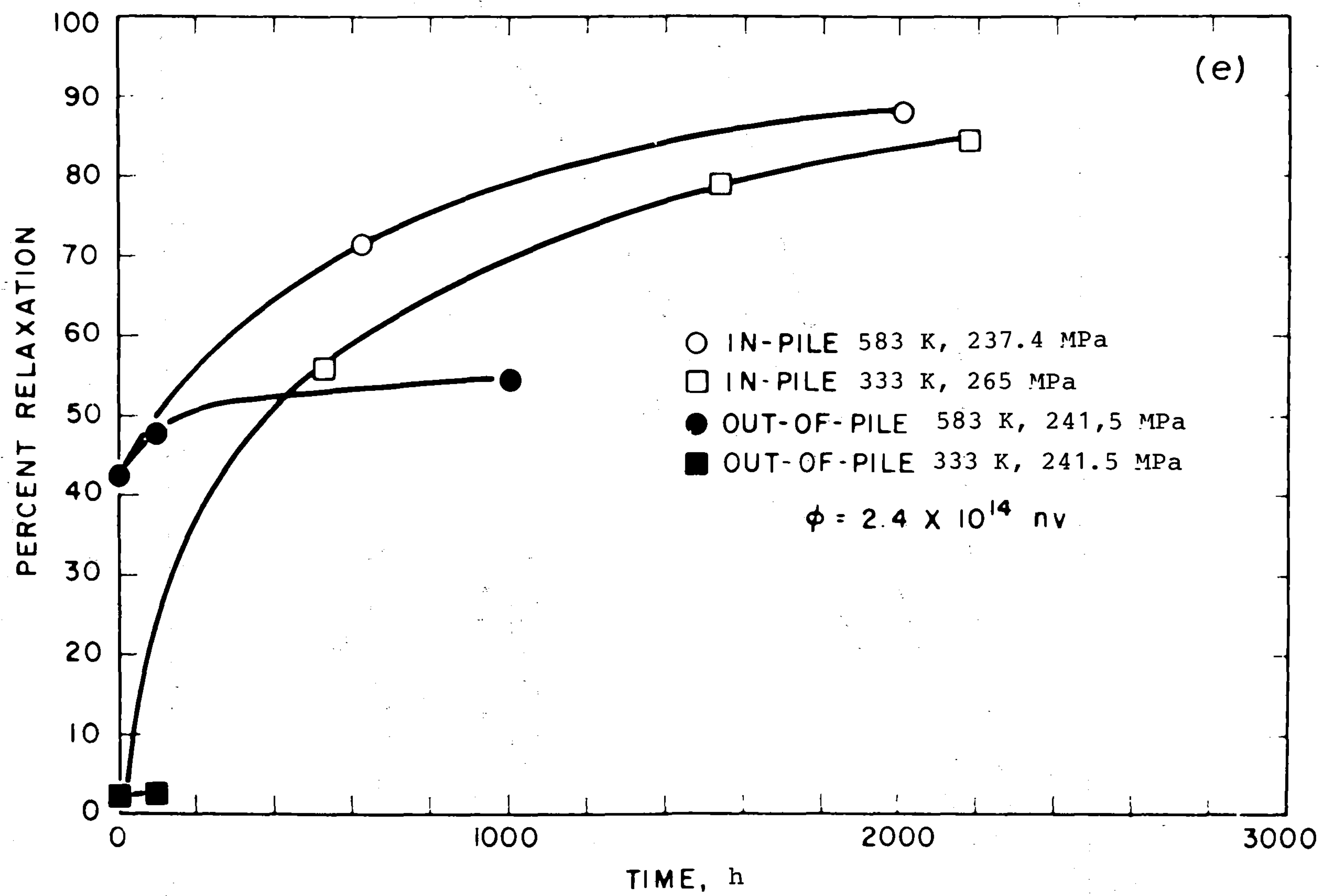

Fig. 16e: Relaxation of Zr+2.5 wt% Nb + 0.5 wt% Cu. Data taken from Ref. (20).

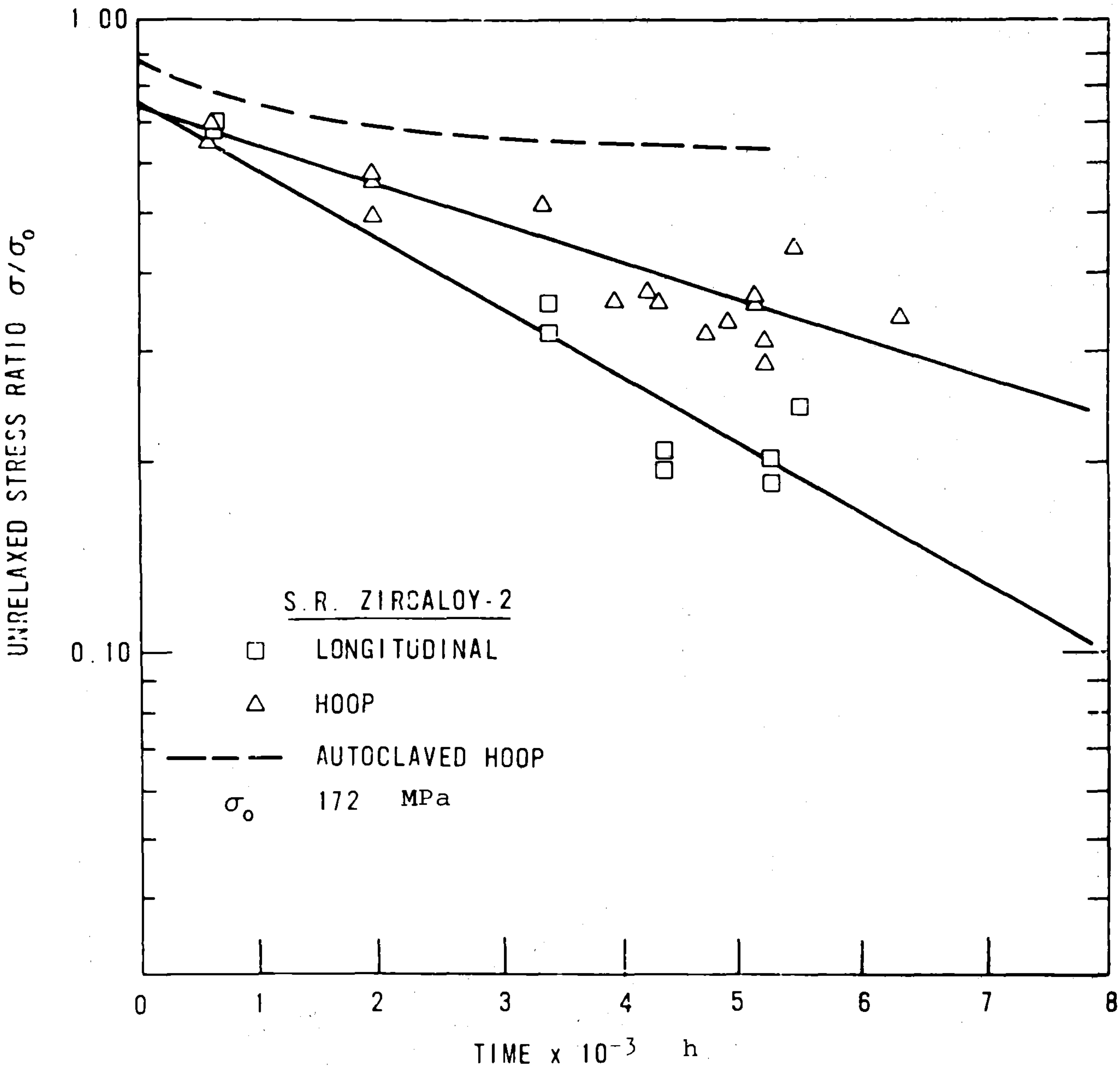

Fig. 17a: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566K, stress-relieved. The autoclace tests were performed at 573 K. Data taken from Ref.(23).

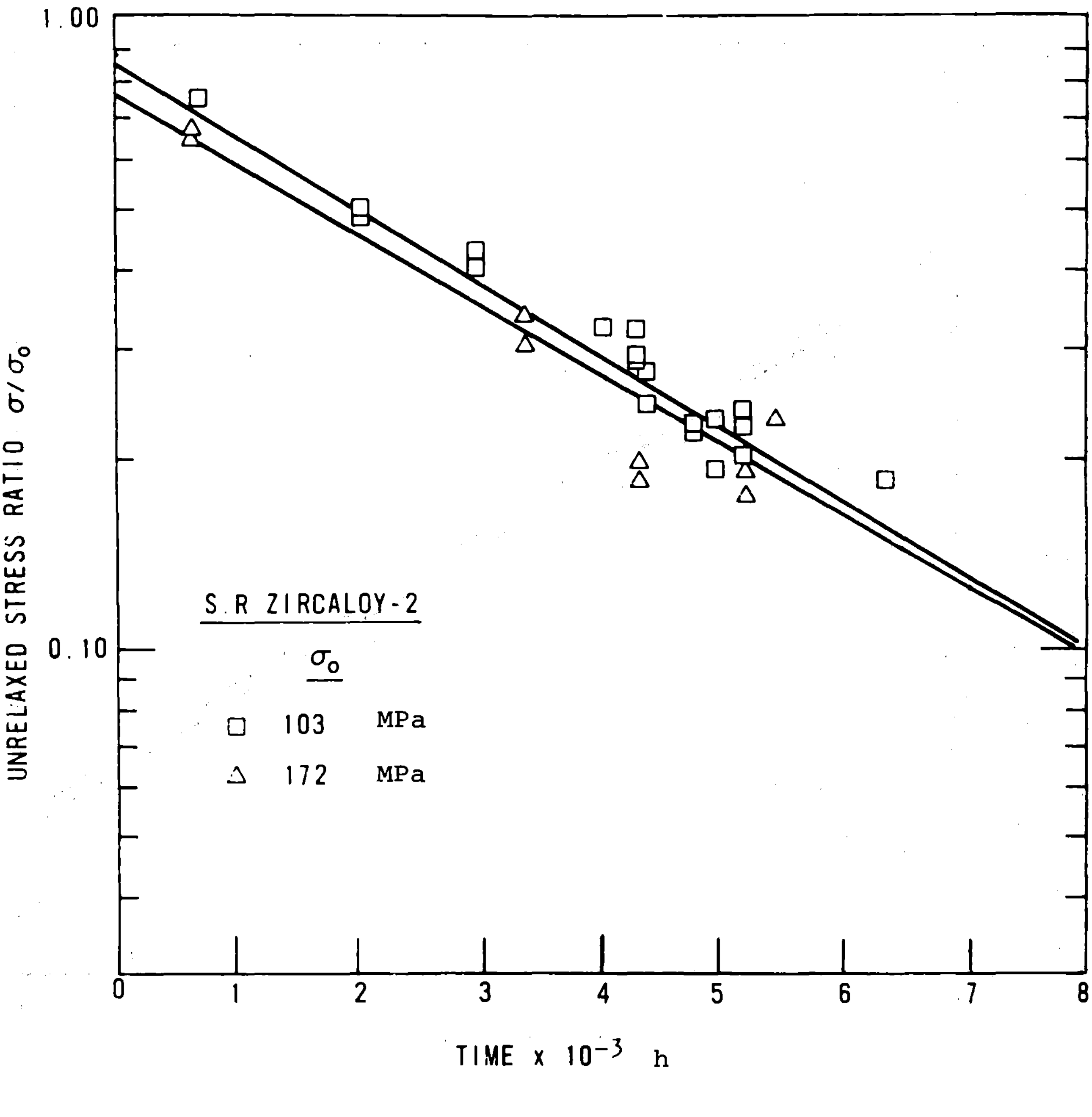

Fig. 17b: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566 K, stress-relieved. The autoclave tests were performed at 573 K. Data taken from Ref.(23).

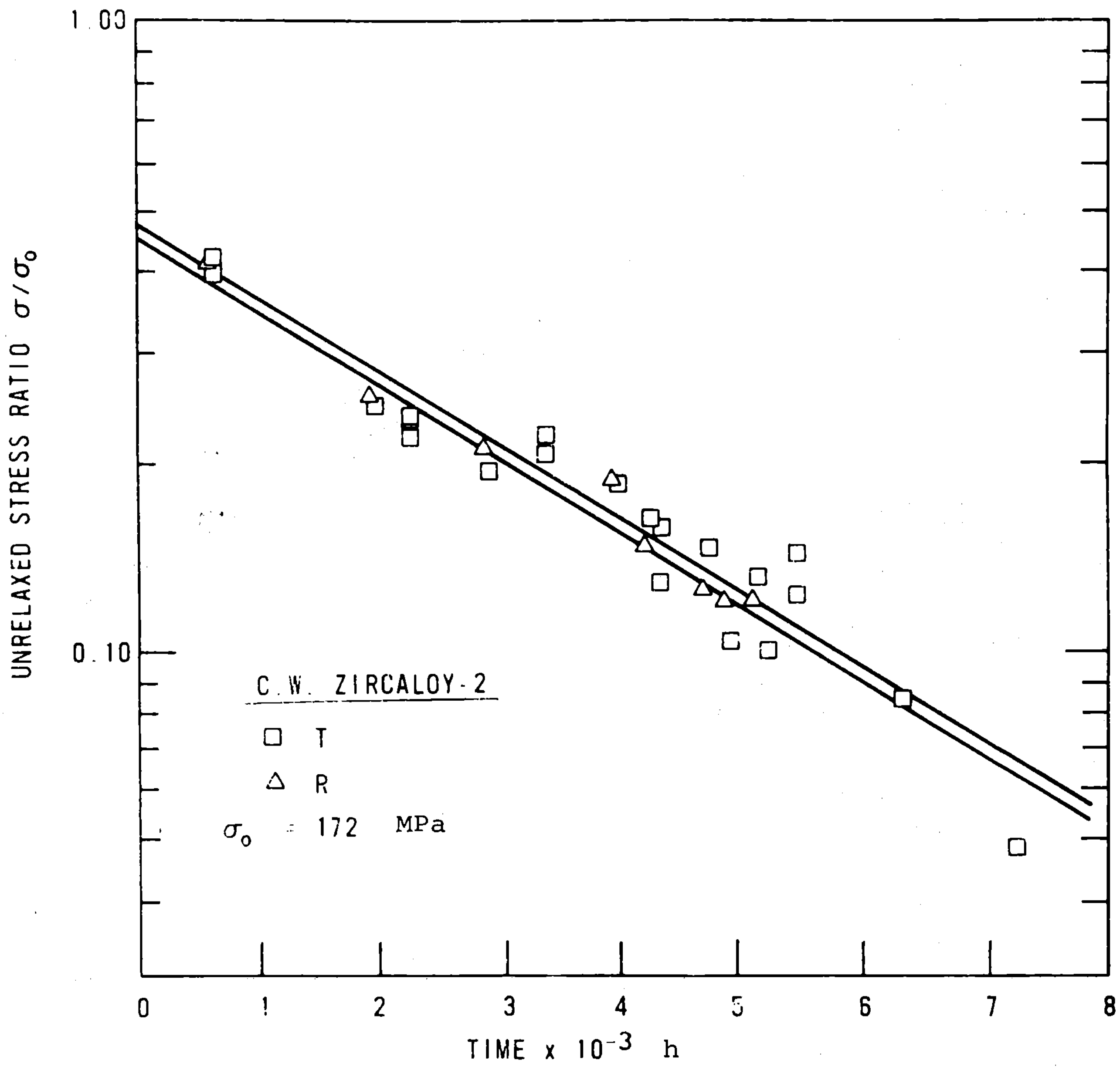

Fig. 17c: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566 K, cold-worked. The autoclave tests were performed at 573 K. Data taken from Ref. (23).

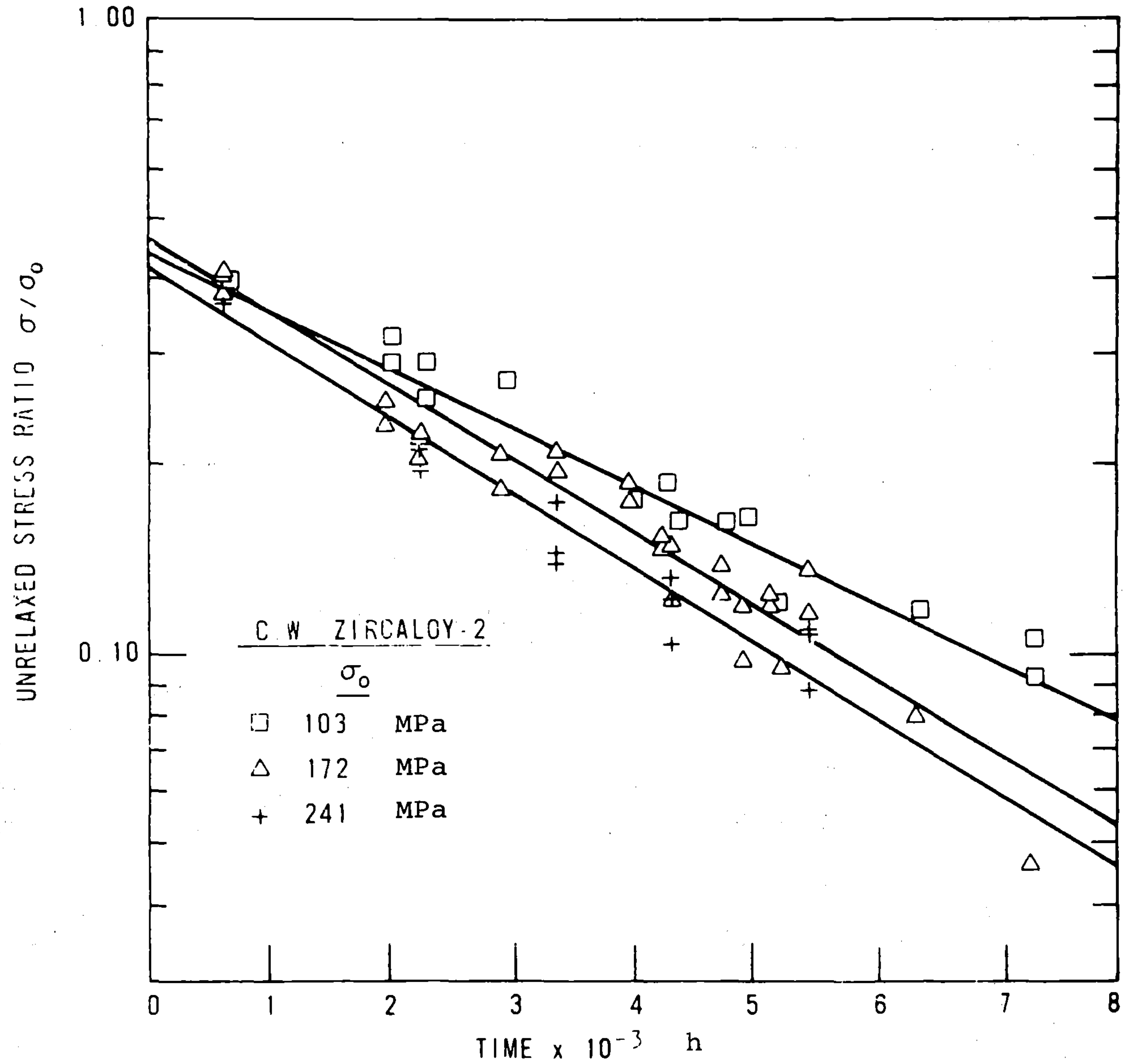

Fig. 17d: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566 K, cold-worked. The autoclave tests were performed at 573 K. Data taken frome Ref. (23).

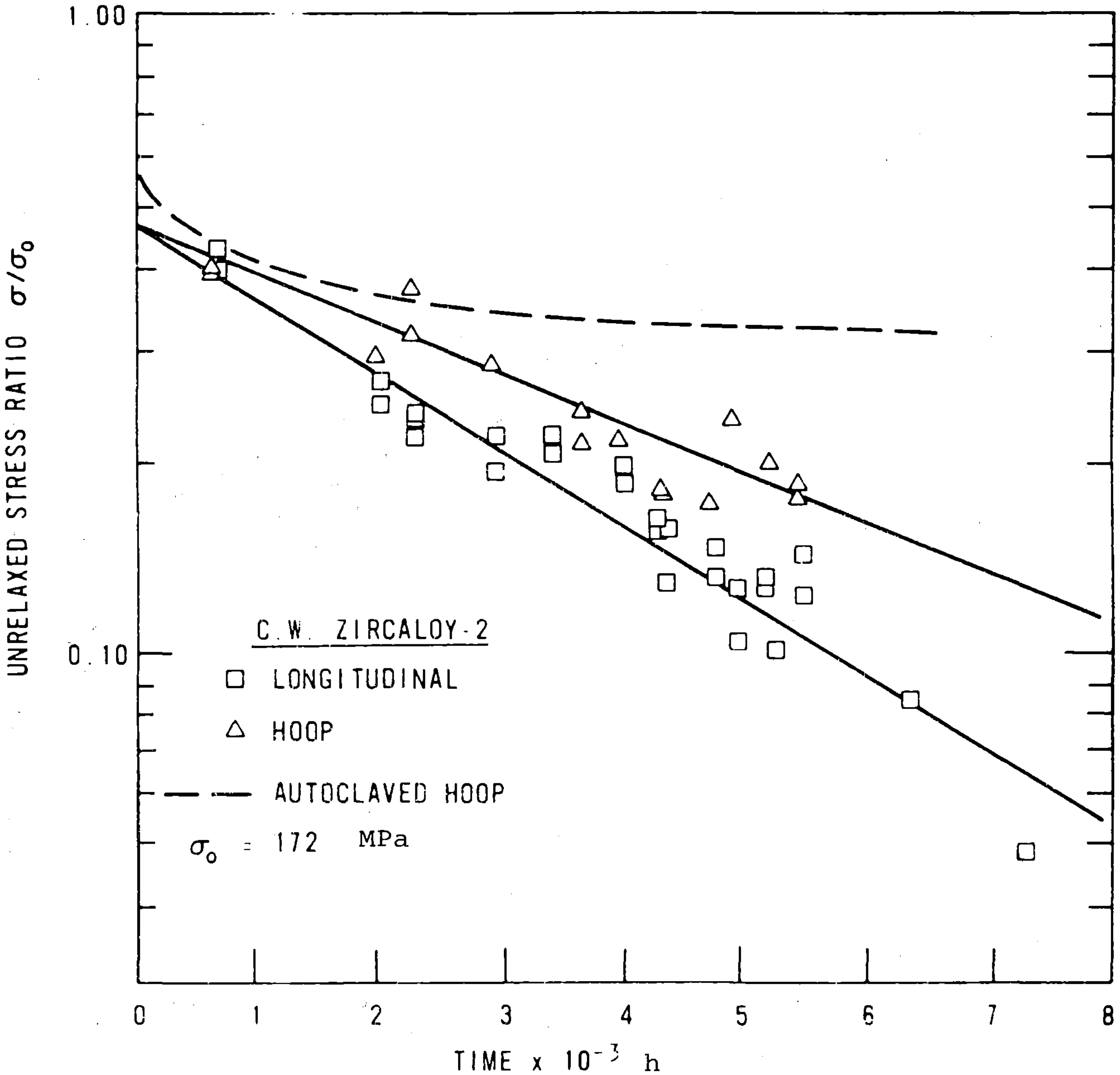

Fig. 17e: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566 K, cold-worked. The autoclave tests were performed at 573 K. Data taken from Ref. (23).

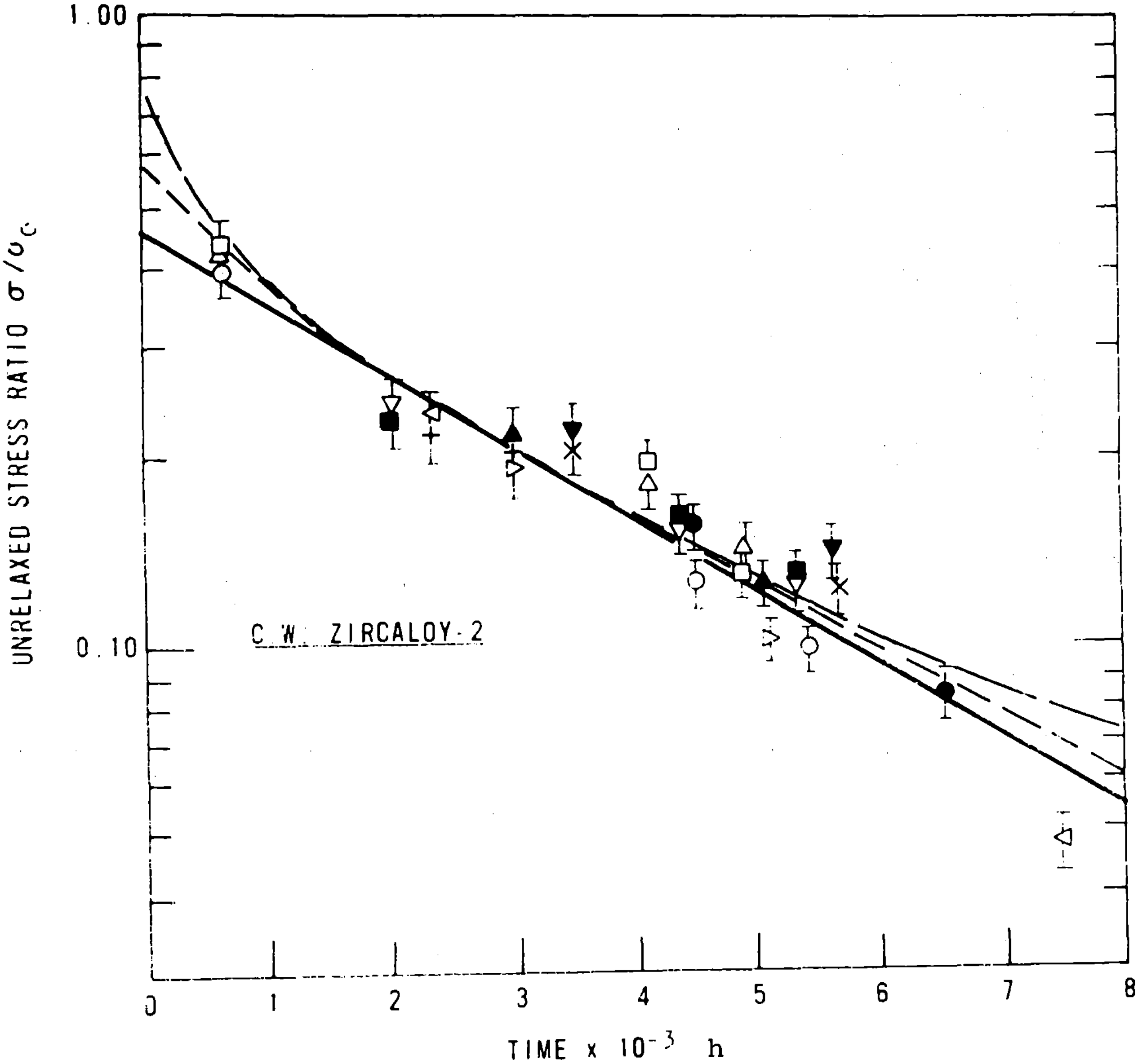

Fig. 17f: Unrelaxed stress ratio as a function of time for Zircaloy-2 at 566 K, cold-worked. The autoclave tests were performed at 573 K. Data taken from Ref. (23).

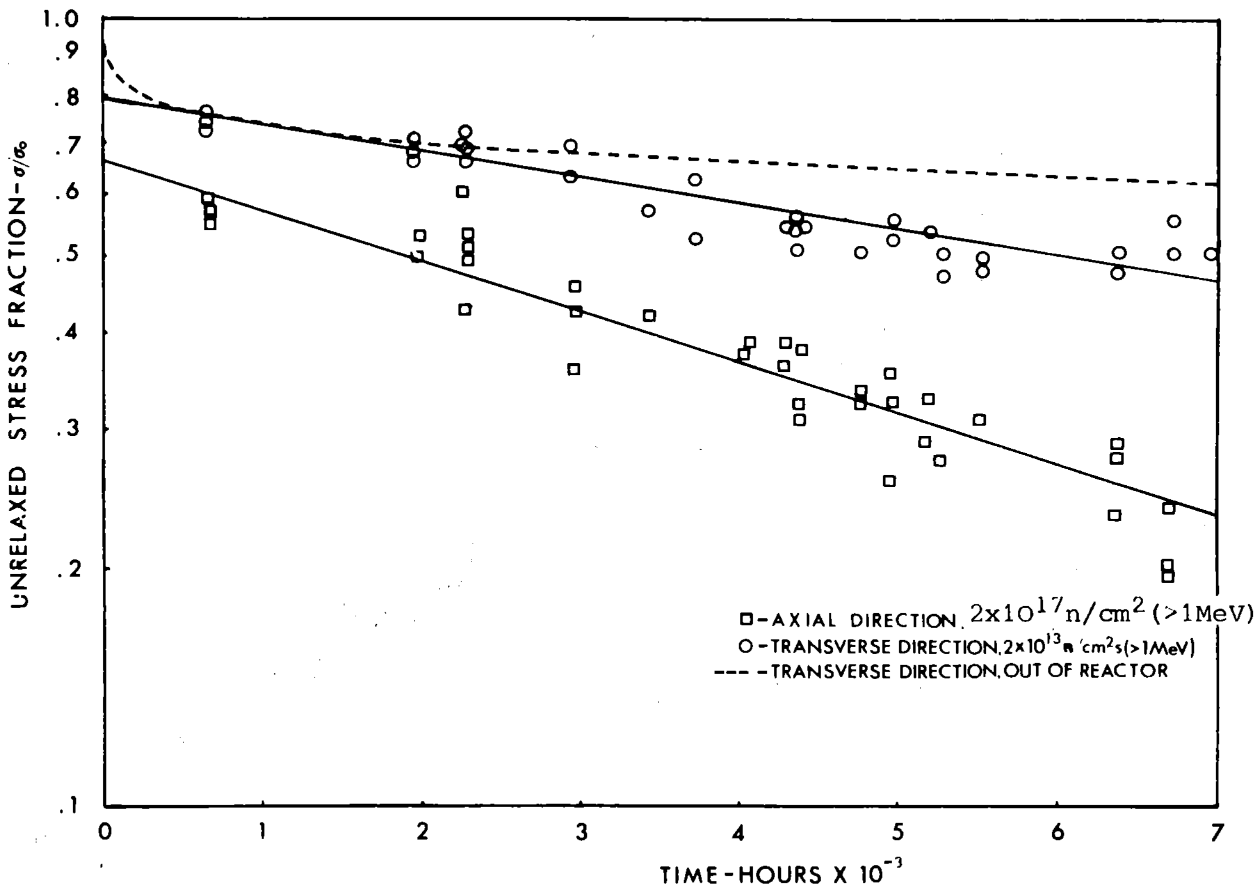

Fig. 18: Results from stress-relaxation tests with specimens from heat-treated Zr-2.5 wt% Nb tubes. Tests performed at 558 K and at a nominal initial stress of the order of 150 MPa. Data taken from Ref. (22).

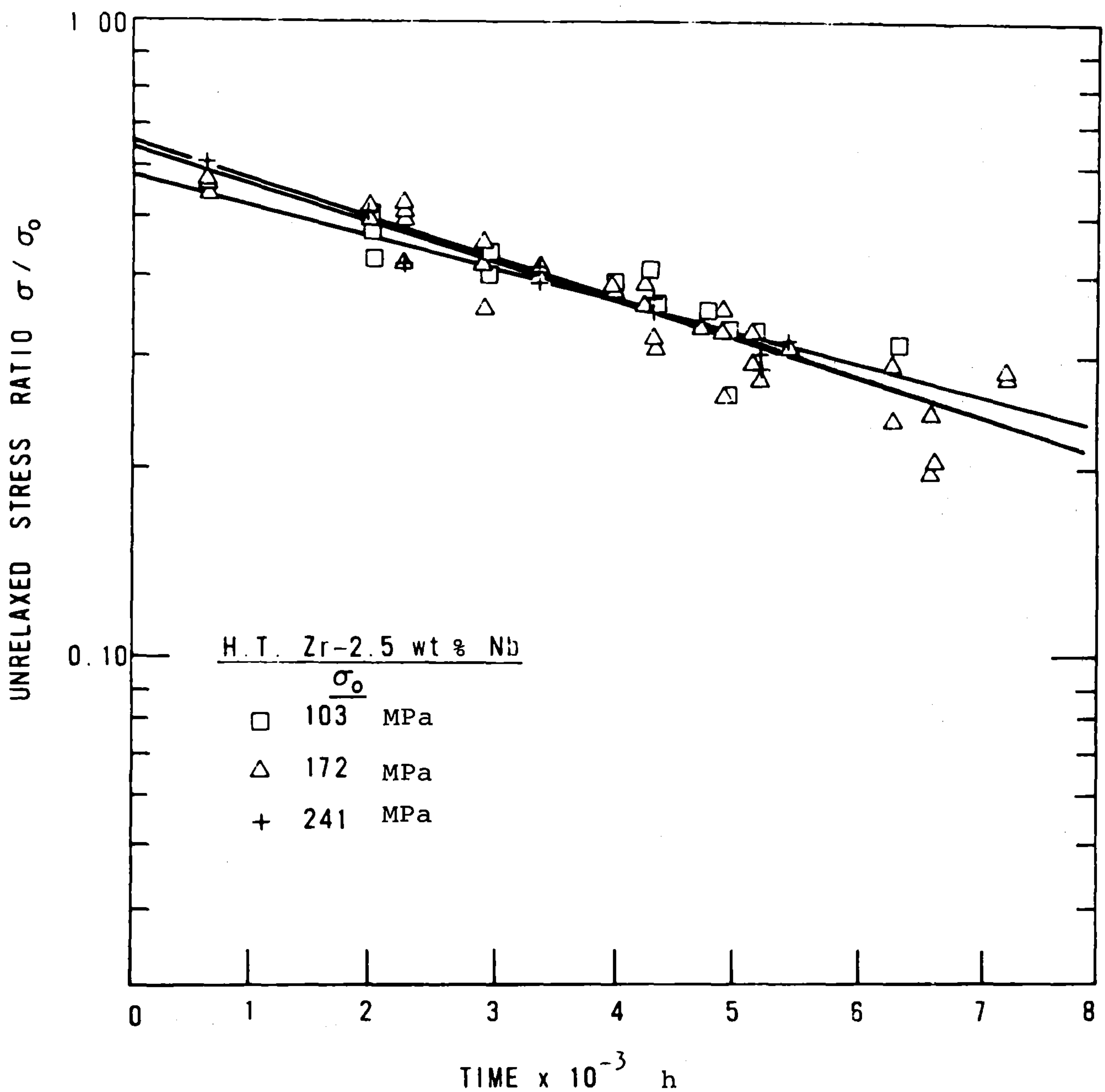

Fig. 19a: Unrelaxed stress ratio as a function of time for Zr-2.5 wt% Nb. Inreactor tests at 566 K and autoclave tests at 573 K, heat-treated. Data taken from Ref. (23).

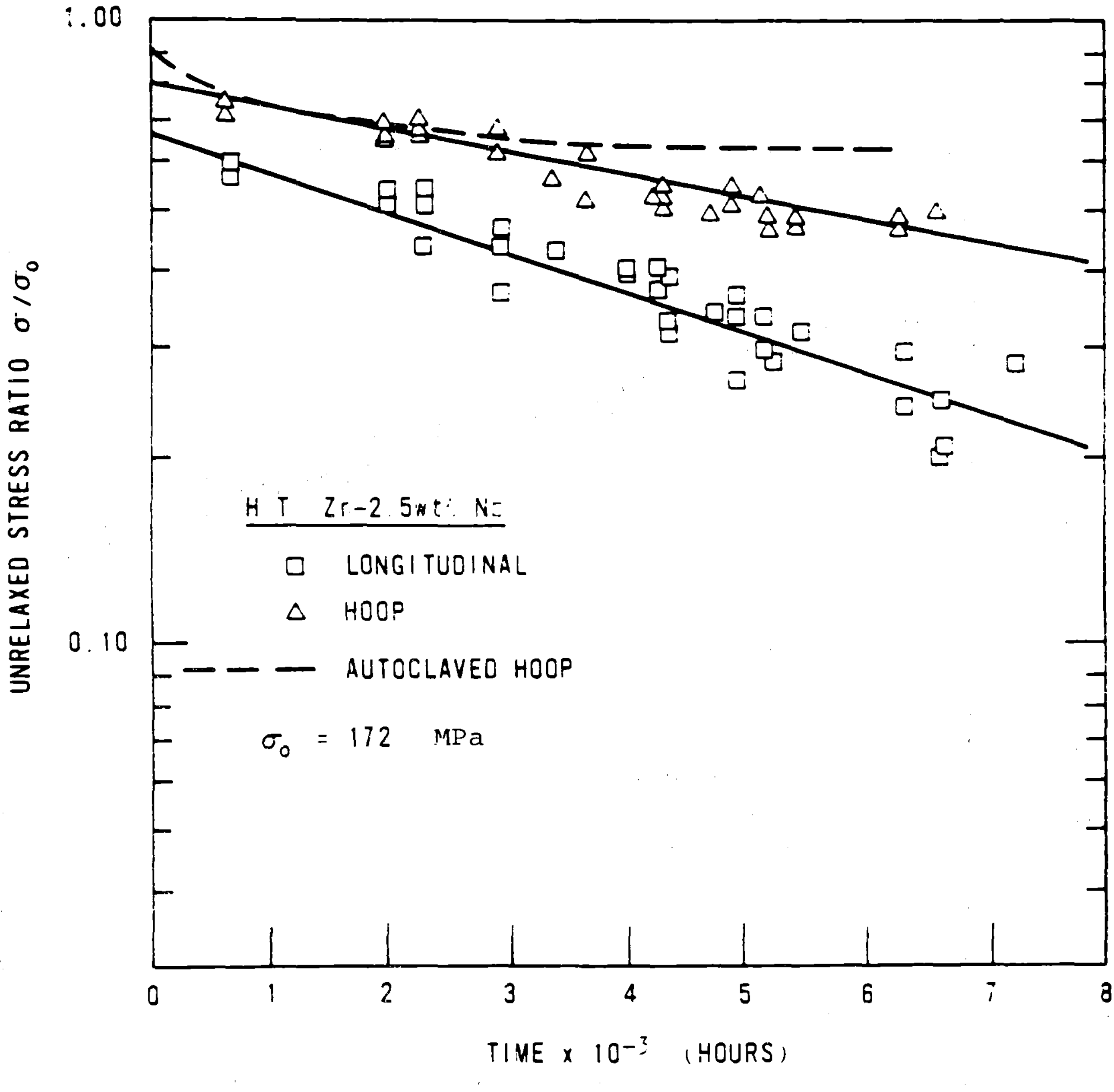

Fig. 19b: Unrelaxed stress ratio as a function of time for Zr-2.5 wt% Nb. Inreactor tests at 566 K and autoclave tests at 573 K, heat-treated. Data taken from Ref. (23).

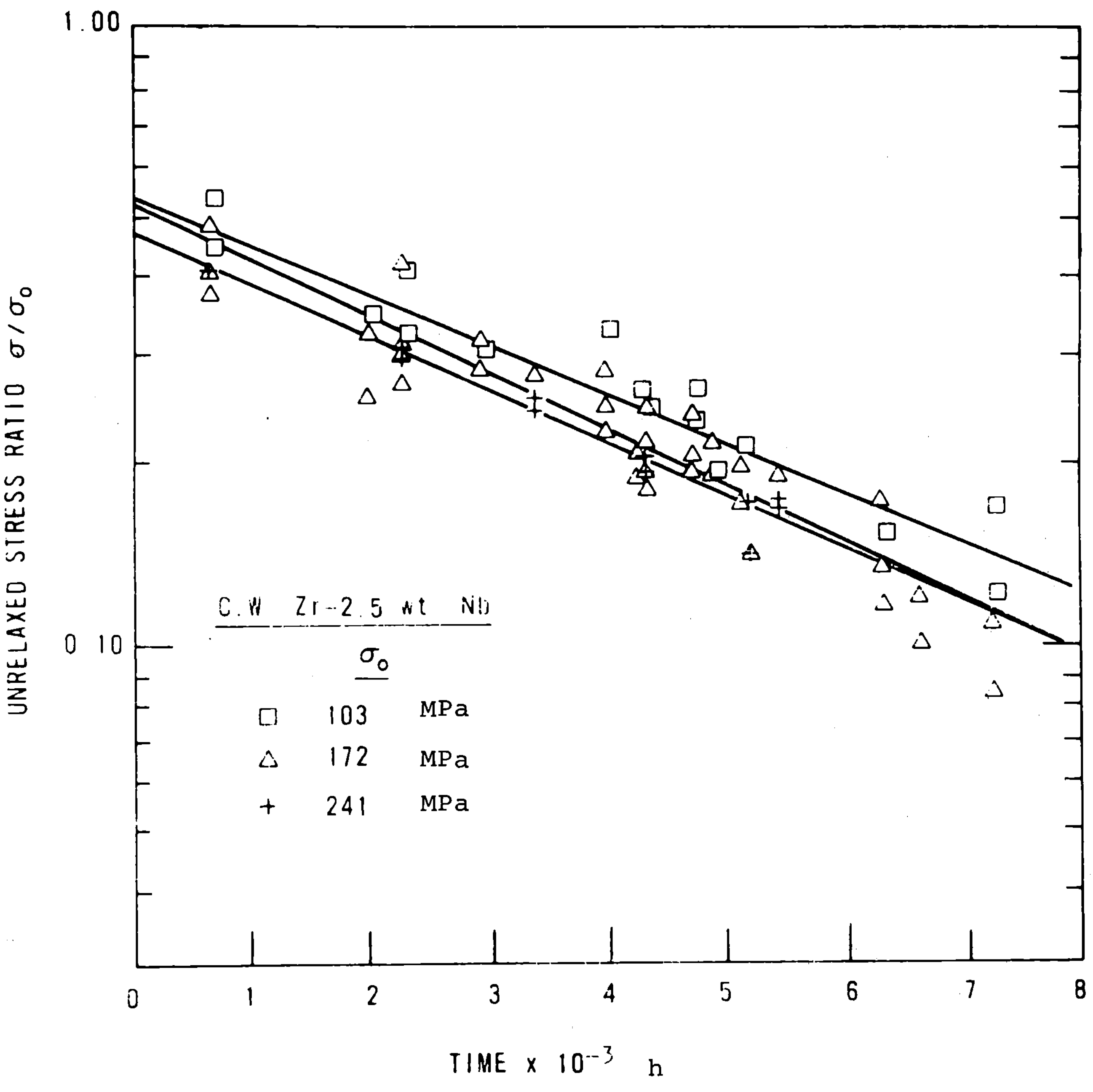

Fig. 19c: Unrelaxed stress ratio as a function of time for Zr-2.5 wt% Nb. Inreactor tests at 566 K and autoclave tests at 573 K, cold-worked. Data taken from Ref. (23).

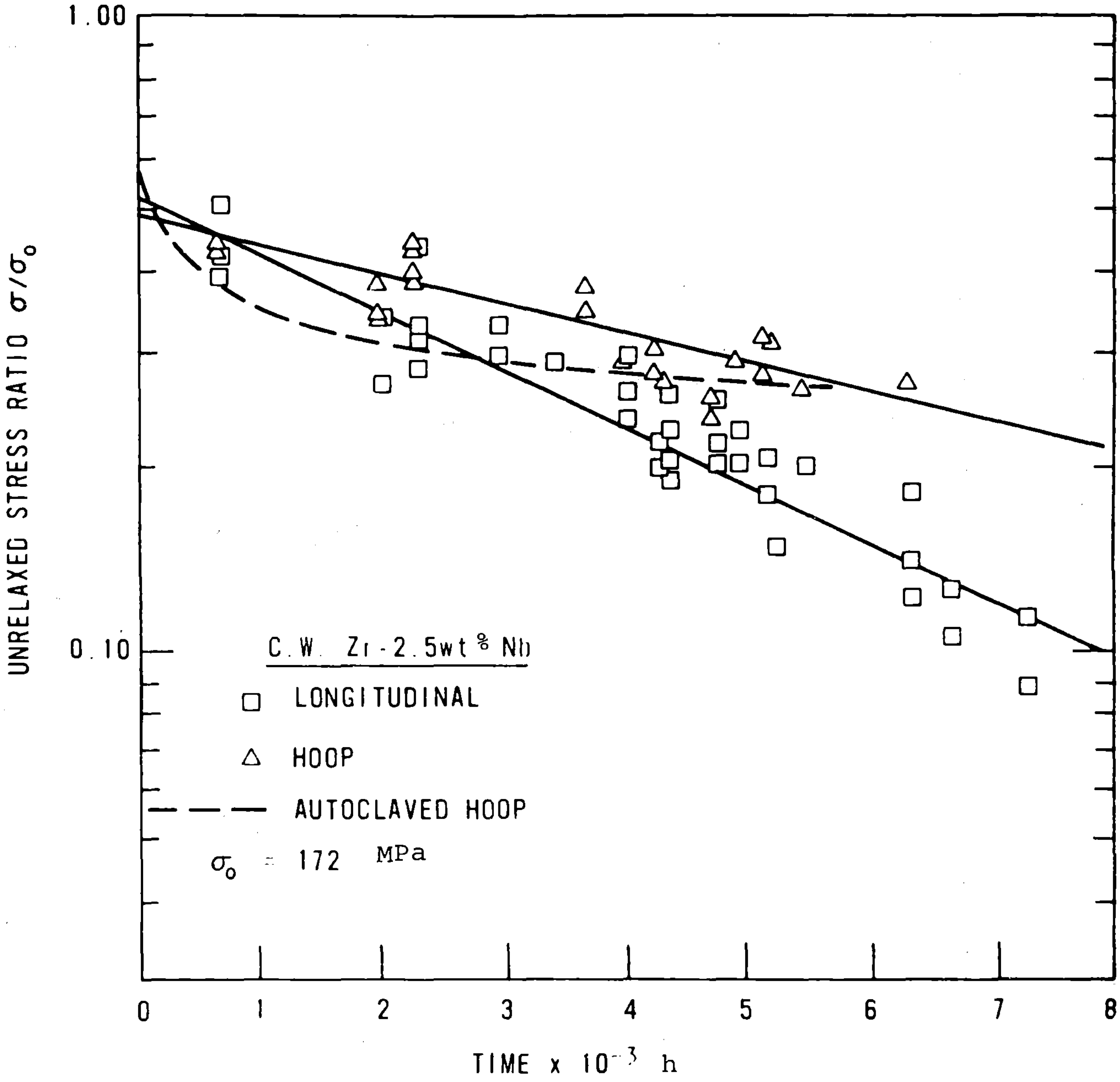

Fig. 19d: Unrelaxed stress ratio as a function of time for Zr-2.5 wt% Nb. Inreactor tests at 566 K and autoclave tests at 573 K, cold-worked. Data taken from Ref. (23).