THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

AN ASSESSMENT OF THE DIFFERENCES IN THE STATIC AND DYNAMIC PROPERTIES OF HELICAL COMPRESSION SPRINGS MANUFACTURED FROM TWO GRADES OF PHOSPHOR BRONZE WIRE

by

L.F. Reynolds, M.Sc.Tech., M.I.M.

Report No. 300

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SUMMARY AND CONCLUSIONS

The specification BS 2873: 1969 makes provision for two compositions of phosphor-bronze wire containing 5% tin (PB102) or 7% tin (PB103), both of which can be supplied in a variety of drawn conditions. However, there is only a 50 N/mm^2 difference in the specified tensile strengths of the two alloys in the equivalent hard drawn and extra hard conditions which would normally be used for the manufacture of springs. It was therefore thought desirable to assess the real difference in the static and dynamic properties of springs manufactured from the two alloys in the spring tempers available.

This work has shown that:-

1. There was no difference, at the 95% level of significance, between the fatigue properties of compression springs made from the two phosphor-bronze alloys in the hard drawn condition.

2. The fatigue properties of springs made from the extra hard drawn PB102 alloy were consistently slightly better than those made from the equivalent PB103 alloy. Although real in the statistical sense, however, the difference would probably not be considered significant in practice.

3. The stress relaxation properties of the PB102 alloy springs were consistently equal to or better than those made from the equivalent PB103 alloy. The difference was probably too small to be considered important in practice, however.

4. The present work has suggested therefore that little or no advantage is to be gained by using the PB103 alloy in place of the PB102 alloy, in either the hard drawn or the extra hard drawn conditions, for the manufacture of compression springs.

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1. INTRODUCTION

Wrought copper alloys offer a range of attributes which make them useful spring materials: they exhibit high electrical and thermal conductivities, are non-magnetic, show excellent corrosion resistance and possess good formability characteristics.

Of all the copper base alloys, the phosphor bronzes have been most commonly employed, being less expensive than copper-beryllium and more corrosion resistant than the spring brasses. Copper-beryllium is a precipitation hardening alloy, however, whilst both phosphor bronze and spring brass can only be strengthened by cold work.

A previous report(1) has dealt with the fatigue and relaxation properties of 5% Sn phosphor bronze springs manufactured from 1.2 mm diameter wire, in the Extra Hard Drawn (E.H.) condition, conforming to the PB102 specification of BS 2873: 1969.

This specification makes provision for two compositions of phosphor bronze wire, containing 5% Sn (PB102) or 7% Sn (PB103). Both these alloys can be supplied in a variety of forms, ranging from the Annealed state up to the Spring Hard (H) and Extra Spring Hard (EH) conditions.

There is, however, only 50 N/mm^2 difference in the specified tensile strengths of the two alloys in equivalent spring temper grades. Consequently, it was considered propitious to assess the real differences in the static and dynamic properties of springs manufactured from the two alloys in the two spring tempers available, i.e. to determine whether the more expensive

7% Sn alloy has any advantages over the cheaper 5% Sn alloy, for springs.

2. MATERIALS AND SPRING DESIGN

2.1 Composition

Phosphor bronze wires of diameter 1.2 mm, and manufactured to the PB102 (5% Sn) and PB103 (7% Sn) specifications of BS 2873: 1969, were obtained in both the Hard (H) and Extra Hard (EH) conditions. The chemical compositions, shown in Table I, conform to the appropriate designation within the above specification.

2.2 Spring Design and Manufacture

All springs were manufactured according to the designs given in Table II. The solid stress quoted was calculated from the standard relationship:-

$$\tau = \frac{G\delta K}{\pi C^2 n d} \qquad \text{..........} \; 1$$

where

τ = shear stress, N/mm^2
G = modulus of rigidity, N/mm^2
d = wire diameter, mm
n = number of active coils
C = spring index
K = Sopwith correction factor = $\frac{C+0.2}{C-1}$
δ = total deflection of spring to solid = $\left[L_o - (N-\frac{1}{2})d\right]$,
where
L_o = free length, mm, and N is the total number of coils

The springs were coiled on a Torrington 115A coiling machine, and were subsequently stress relieved at 200°C, for half an hour, this heat treatment being typical of that which is used in industry. After end grinding, the springs were prestressed to solid until no further decrease in length occurred.

3. EXPERIMENTAL PROCEDURE

3.1 Microscopic Examination

Microsections were taken from the four wire samples, in both the transverse and longitudinal directions. The polished sections were examined on the microscope both before and after etching in ferric chloride solution.

3.2 Mechanical Testing of Wire

3.2.1 Tensile tests

The tests were carried out on wire in both the 'as received' condition and after a low temperature heat treatment at 200°C, for half an hour. A vertical Amsler multi-range tensile testing machine was used for the tests, equipped with an automatic stress-strain recorder. The latter was used in conjunction with an extensometer having a 254 mm gauge length.

3.2.2 Torsion testing

Torsion tests were carried out both before and after low temperature heat treatment, using a vertical Amsler torsion testing machine. This had a maximum capacity of 5600 N.mm, and was used with a specimen gauge length of 100 times the wire diameter i.e. 120 mm.

The torsional stresses were calculated from the relationship

$$\tau = \frac{16T}{\pi d^3} \qquad \text{.......... } 2$$

where

τ = shear stress, N/mm^2
T = torque, N.mm
d = wire diameter, mm

The torsional strains were calculated from the expression

$$\phi = \frac{d\theta}{2L} \qquad \text{.......... } 3$$

where

ϕ = torsional strain, mm/mm

d = wire diameter, mm

θ = angular deflection, radians

L = gauge length, mm = 100d

3.3 Dynamic and Static Testing of Springs

3.3.1 Experimental design

Since the primary objective of the work was to detect differences between two alloys in equivalent temper grades, rather than to produce design data, it was considered appropriate to use a replicated paired sample technique, which tends to reduce the effects of systematic experimental variation upon the results. Where significant differences are small, such experimental scatter can seriously impair the sensitivity of the usual 't' test, which compares the estimated means and standard deviations of two "populations".

In the paired 't' technique, however, the tests on the samples to be compared (say groups A and B) are tested simultaneously. The tests are thus carried out on pairs of samples (A_1B_1; A_2B_2 etc) under conditions which are identical, within the limits of the experimental technique. The resulting data are transformed by taking the difference between the appropriate sample results, i.e. $A_1 - B_1$, etc. Hence this difference should remain relatively constant for any set of experimental conditions, if each pair of samples has been treated equally.

If we say (A - B) = x, then the differences should form a distribution with zero mean, on the assumption that no difference exists between the two sample "populations".

The value of 't' can be calculated from the simplified relationship

$$t = \frac{\bar{x}\sqrt{N_p}}{S_x} \qquad \ldots\ldots\ldots\ldots 4$$

where

$\bar{x}$ = mean of difference obtained from paired data

S_x = standard deviation of differences obtained from paired data

N_p = number of pairs considered, i.e. A_1B_1; A_2B_2 ------ A_NB_N

The difference between the two sets of data can then be assessed by testing the resulting value of 't' at the appropriate level of significance, for (N-1) degrees of freedom, via the Null Hypothesis that there is no significant difference between the two sets of data i.e. H_o; $\bar{x} = 0$. (Standard tables for the percentage points of the 't' distribution are available in the literature).

This statistical replication technique is well documentated in the literature, which should be consulted for further information(2,3).

3.3.2 Fatigue testing

A forced motion multiple station fatigue testing machine operating at 25 H_z was used for the tests.

A limited amount of initial work was carried out on a number of springs, selected at random, for each grade of wire used. From the results of this work, the form of the S/N curve was decided, and a series of suitable stress levels chosen for the statistical tests proper.

For each series of experiments on the springs manufactured from the two alloys in equivalent temper conditions, at least five pairs of samples were tested at each of the chosen stress levels the total number of samples being selected to give a minimum of 14 pairs of broken springs for the statistical analysis.

Tests were then conducted at equivalent initial and maximum stresses, as shown below in Table A.

TABLE A INITIAL AND MAXIMUM STRESSES (N/mm^2) EMPLOYED DURING FATIGUE TESTS ON PB102 AND PB103 SPRINGS

Temper condition	Initial Stress N/mm^2	Maximum Stress N/mm^2	Number of pairs tested, N
Hard	50	380	9
drawn	100	380	5;
Extra	100	380	5
hard	100	440	5
drawn	100	500	5

This paired replication experimental design is not generally suitable for the production of fatigue data with statistical levels of confidence. Such data has been produced where possible, however, by combining the appropriate data from the paired tests with the preliminary test data.

The springs were load tested to determine the deflection necessary for the minimum and maximum stresses required, the load having been calculated from the relationship:-

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \ldots\ldots\ldots\ldots 5$$

where

P = load, N
d = wire diameter, mm
τ = torsional stress, N/mm^2
D = mean coil diameter, mm
K = Sopwith correction factor = $\frac{c+0.2}{c-1}$

3.3.3 Time relaxation tests

Following previous work at the SRA(1) which suggested that the relaxation at 75°C of these materials was not confined to an initial 72 hour period, sequential time relaxation tests were carried out in the present work, at temperatures of 75°C and 125°C for times of up to 168 hours.

Tests on the springs manufactured from the hard drawn wires were carried out at an initial stress of 300 N/mm^2, whilst the springs manufactured from the extra hard drawn material were tested at initial stresses of 300 and 500 N/mm^2.

Springs were load tested individually on a Probat load tester with digital readout to determine the compressed length necessary to obtain the desired test stress, the required load being calculated using equation 5.

The ends of the springs were coated with graphite lubricant, and were then held at the required length using stainless steel nut and bolt assemblies, as described in earlier Association reports$^{(4,5)}$. After the required time under the test conditions, each spring was unbolted and load tested to its original compressed length. The percentage loss in load was taken as a measure of the relaxation which had occurred in the spring during the course of the test.

Triplicate tests were carried out on the springs for each combination of temperature and stress investigated.

No allowance was made for the reduction in applied stress due to the lower modulus of the material at elevated temperatures. If such an allowance is required, it can be shown that the stress at temperature T is given by the relationship

$$\tau_T = \tau_o \cdot \frac{G_T}{G_o} \qquad \text{..........} \; 6$$

where

τ_T = stress at temperature T°C
τ_o = stress at room temperature
G_T = modulus of rigidity at temperature T°C
G_o = modulus of rigidity at room temperature

3.3.4 Stress relaxation testing

Five stresses were chosen for this work, each series of tests being carried out at temperatures of 75, 100 and 125°C.

Stresses of 100, 200, 250, 300 amd 350 N/mm^2 were employed for the springs manufactured from the hard drawn wires, whilst the springs of the extra hard drawn material were tested at stresses of 100, 200, 300, 400 and 500 N/mm^2.

For each series of experiments on a particular temper grade for the two material compositions (PB102/PB103), triplicate tests were carried out at each stress level using a paired replication experimental design, thus permitting an assessment of the difference in relaxation behaviour by means of the paired 't' test technique previously described in Section 3.3.1.

The springs were load tested individually to determine the deflection necessary to give the desired test stress and, after coating the ends with graphite lubricant, were then bolted up to this length and tested at temperature for the required time, as described in Section 3.3.3.

A testing time at temperature of 168 hours was selected as being most suitable for the stress-relaxation tests, based on the results of the time-relaxation tests. After this time had elapsed, therefore, each spring was unbolted and was then load tested to its original compressed length, the percentage loss in load being taken as a measure of the relaxation.

4. RESULTS

4.1 Analyses and Mechanical Tests

The analyses of the materials are shown in Table I, whilst the spring design data are given in Table II.

The results of the tensile tests on the original wire are shown in Table III and IV, whilst the torsional test results are presented in Tables V and VI.

4.2 Fatigue Test Results

The results of the paired fatigue tests on the springs manufactured from hard drawn PB102 and PB103 are shown in Table VII, whilst the equivalent results of the tests carried out on the springs made from the extra hard drawn materials are shown in Table VIII.

The limited amount of appropriate fatigue data have been plotted in Figs. 1-3, which present S/N curves for springs manufactured from PB103 (H), PB102 (EH) and PB103 (EH) respectively.

Although in the case of martensitic ferrous materials a straight line is generally used to represent the limited life data, it is well known that many non-ferrous materials do not show a fatigue limit, and that the fatigue data are better represented by a curve than by a straight line. This proved to be the case in the present instance, for all the alloys and conditions investigated. For all the data, therefore, reciprocal relationships were examined, and the relationships giving the best fit were selected to represent the data.

The relationships were then transformed back into the log-linear relationships shown in Figs. 1-3. In all cases, the correlation coefficients obtained were tested to determine whether they were significant at the minimum acceptable level of 95% confidence, and this was found to be the case.

It should be reiterated, however, that the experiments were not specifically designed to produce design data, but rather to efficiently detect differences in behaviour between the two alloys investigated in the appropriate temper conditions.

4.3 Relaxation Tests

4.3.1 Time relaxation results

The time relaxation data for the appropriate alloys and temper grades are shown in Tables IX and X.

The basic relaxation data were treated analytically to yield an expression of the form:-

$$\text{Rel} = a \ln t + b \qquad \text{..........}\ 7$$

where

Rel = % relaxation in 't' hours and 'a' and 'b' are constants for the particular experimental conditions employed.

Plots of (Rel) against (lnt) gave straight lines, all of which had correlation coefficients which were significant at the 99.8% level of confidence. The curves thus derived are shown plotted in Figs. 4-9, whilst the appropriate regression coefficients of the logarithmic relationships are shown in Table XI.

4.3.2 Stress relaxation results

The results of the paired stress relaxation tests, carried out on the appropriate temper grades of the two phosphor bronze alloys, are shown in Tables XII and XIII for the three temperatures investigated.

The stress relaxation at constant temperature was found to be adequately represented by an exponential relationship of the form

$$Rel = Ae^{\tau B} \qquad \text{..........} \; 8$$

where

Rel = % relaxation at 168 hours for a given temperature
τ = initial torsional stress, N/mm^2
and 'A' and 'B' are constants

The exponential relationships were transformed into the logarithmic form,

$$\ln(Rel) = \ln A + B\tau \qquad \text{..........} \; 9$$

Plots of ln(Rel) against τ gave straight lines, which could be treated by linear regression techniques to give the 50% mean relationships.

All the expressions thus derived to represent the stress relaxation data gave correlations which were significant at the 99.8% level.

The stress relaxation curves obtained from this analysis of the appropriate alloy springs are shown plotted in Figs. 10 and 11, whilst the analytical coefficients of the exponential relationship are given in Tables XIV and XV, together with the increment which must be added to or subtracted from the calculated relaxations to obtain the 95% confidence values.

5. DISCUSSION

5.1 Analysis and Static Mechanical Properties

British Standard BS 2873: 1969 specifies the appropriate grades of the phosphor bronze alloys PB102 and PB103 in terms of the chemical analysis and tensile strength only. The appropriate section of this specification is shown below in Table B.

TABLE B ANALYSIS AND TENSILE STRENGTH OF PHOSPHOR BRONZE WIRE TO BS 2873: 1969

Material	Chemical Composition Wt%				Wire Condition	Tensile Strength N/mm^2
	Sn	P	Pb	Cu		
PB102 1.2 mm diam.	4.5 6.0	0.02 0.40	0.02 max.	Rem.	H EH	700 - 850 850 min.
PB103 1.2 mm diam.	6.0 7.5	0.02 0.40	0.02 max.	Rem.	H EH	740 - 900 900 min.

Comparison of this data with that given in Tables I, II and III indicates that all the materials used conformed to the above specification, and that the conclusions reached from the work should therefore be valid with respect to the specification.

It is interesting to note, however, that whilst the tensile strengths conformed to the specification values given above, some differences in the elastic properties were in evidence.

Both the tensile elastic properties and the tensile strength of the hard drawn 7% Sn alloy tended to be generally rather higher than those of the hard drawn 5% Sn wire and, furthermore, these findings were supported by the relevant torsional properties.

In the extra hard drawn condition, however, both the tensile and the torsional elastic properties of the 7% alloy were lower than those of the 5% alloy. The former wires exhibited higher tensile strengths, however, suggesting that the 7% Sn alloy work hardened faster than the 5% Sn alloys, a finding which is not inconsistent with the known effects of tin on the work hardening characteristics of the bronze alloys. In general, however, the elastic properties of the extra hard drawn wires, determined during the present work, were at variance with published work, which suggests that the 7% Sn alloy possesses the better elastic properties.

This discrepancy was consistent throughout the work, but is not yet clearly understood. It should be emphasized, however, that all the wires conformed to BS 2873 with respect to the tensile strengths in every case.

5.2 Comparison of Fatigue Properties of PB102 and PB103

The results of the replicated fatigue tests were analysed statistically using the paired 't' test technique outlined in Section 3.3.1.

A summary of the information extracted from the paired data is given in Table XVI. In this table, 'x' refers to the difference between the log lives of the appropriate alloys tested at the same stress level.

i.e. x = log N (PB102) - Log N (PB103)

From these results, it is clear that, in terms of fatigue performance, there is no significant advantage to be gained by using the more expensive PB103 alloy in place of the cheaper PB102 material. Indeed it could be argued that, in the extra hard drawn condition, 5% Sn alloy has decided advantages over the 7% Sn alloy, if fatigue properties are the major criterion of performance. These results for the extra hard drawn alloys would appear to confirm published work, which indicates that the endurance limit, at 10^8 cycles in reversed bending, of the 7% Sn alloy is approximately ~~96%~~ of that shown by the equivalent 5% Sn alloy(6).

Consideration of the tensile and, in particular, the torsional elastic properties obtained after low temperature heat treatment of the appropriate wires at 200°C for half an hour, shown in Tables III - VI, cannot provide a complete explanation of these fatigue results, since the properties of the two alloys in the equivalent drawn conditions were consistently very similar, with only a slight tendency for the 5% Sn alloy to perform better in this respect.

This difference in properties generally lay within the range 20 - 90 N/mm^2, and was considered to be within the limits of experimental error for alloys which exhibit a relatively restricted range of elastic behaviour both in tension and in torsion.

On the basis of the work carried out in the present instance, therefore, there appears to be no advantage in using the PB102 7% Sn alloy in place of the cheaper PB102 5% Sn alloy, where fatigue behaviour is the major criterion of performance.

5.3 Time Relaxation Data

The time relaxation curves derived from the regression analysis are shown in Figs. 4 - 9.

Analysis of the regression data showed that, in every case, only 80% of the relaxation occurring in 168 hours had taken place in 72 hours. This confirms previous work at the SRAMA which suggested that the primary relaxation in these alloys was not confined to an initial 72 hour period(1).

All the subsequent stress-relaxation work was therefore carried out for a constant time of 168 hours.

5.4 Comparison of Stress Relaxation properties of PB102 and PB103 springs

The results of the paired 't' test statistical analyses are shown in Table XVII.

From this table, it is apparent that in every case but one the stress relaxation properties of the PB102 (5% Sn) alloy springs tended to be either equal to or superior to those for the PB103 (7% Sn) springs.

These conclusions, based on the statistical analysis of the paired 't' test, are supported by the appropriate stress relaxation curves, which show that there was generally very little difference in the stress relaxation behaviour of the two alloys in both drawn conditions. The curves do indicate the tendency for the 5% Sn alloy springs to possess the better stress relaxation properties, however, particularly at combinations of lower stresses and temperatures. As in the case of the fatigue properties (Sect. 5.2) this slight difference may be partially attributable to the rather higher torsional elastic properties of the PB102 alloy wires.

In general, it would seem that 5% Sn alloy springs possess relaxation properties which are at least equal to those of the 7% Sn alloy under all conditions other than those obtained with the extra hard drawn wire at high stresses and temperatures. Since the maximum recommended working temperature for phosphor bronze alloys is 110°C when operating at stress levels of 300 - 400 N/mm^2 (1), the slightly higher relaxation of the 5% Sn extra hard drawn alloy springs at 125°C might be interpreted as being of no practical significance in the present instance.

Based on the results of the present work, therefore there would appear to be no practical advantage in using the 7% Sn alloy in place of the cheaper 5% Sn alloy, where stress relaxation properties are the major criterion of performance.

5.5 Apparent Activation Energy for Stress Relaxation

During the course of the work, it became apparent that the relaxation at constant initial stress varied exponentially with the reciprocal of the absolute temperature.

i.e.

$$\mathrm{Rel} = De^{\frac{-F}{T}} \qquad \text{..........10}$$

where

Rel = % relaxation in 168 hours

T = relaxation temperature, $^{\circ}$K (absolute)

D and F = constants, for any given level of initial stress

This can therefore be expressed in the form of a linear relationship:

$$\ln(\mathrm{Rel}) = \ln D - F\left(\frac{1}{T}\right) \qquad \text{..........11}$$

- F is the slope of the straight line obtained by plotting (Rel) against $(\frac{1}{T})$

and

lnD = constant of proportionality

Regression analyses carried out on the appropriate data gave correlations which were significant at the 99% level of the 't' distribution in every case.

The apparent thermal activation energy for the physical processes leading to a reduction in the strain energy of the stressed material (i.e. relaxation) can be calculated from the slope of the regression curve, since

$$-F = \frac{Q}{R} \qquad \text{..........12}$$

where

Q = apparent activation energy, in units of Joules/mol or eV, depending on the units of R

and

R = gas constant = 8.36 Joules/mol /$^{\circ}$K
= 8.68×10^{-5} eV. /$^{\circ}$K

Hence, from 9 and 11, we can say

$$\text{Rel\% / 168 hours} = De^{Q/RT} \qquad \text{..........13}$$

This rate expression is of the form previously found in work carried out on the stress relaxation of Titanium 318 alloy at the SRAMA(7), and is very similar to the expressions relating creep rate, $d\varepsilon/dt$, to temperature in both metals and thermoplastics(8,9).

Values of the activation energy for the two alloys are shown in Table XVIII, and are shown plotted against initial stress in Fig. 12.

It is clear that the apparent thermal activation energy decreases as both the initial stress and the internal stress (i.e. temper grade) increase.

Similar behaviour was observed in previous work on the Titanium 318 alloy, the report of which suggests a tentative explanation of the phenomenon. A fuller explanation of stress relaxation behaviour has also been recently published by SRAMA(10).

The activation energies generally lay within the range 0.43 - 0.93 eV, the actual value depending upon the alloy and the applied initial stress. These values are considerably higher than those obtained for the Titanium alloy, the magnitude of Q in the latter case lying within the range 0.1 - 0.5 eV.

This discrepancy might reasonably be expected, since the face centred cubic solid solution bronzes would tend to possess lower stacking fault energies than the duplex close packed hexagonal/body centred cubic titanium alloy.

Such a difference in the stacking fault energy can be observed qualitively, of course, in the sense that the recrystallized structures of cold worked and annealed solid solution copper alloys often show extensive evidence of annealing twins (i.e. stacking faults), whereas these features of the microstructures are only rarely found in the higher stacking fault energy titanium alloys, when the latter are examined in the equivalent recrystallised condition.

6. CONCLUSIONS

1. The tensile strengths of the PB103 alloy were consistently higher than those for the PB102 alloy, the difference in strength being small and lying within the range 50 - 90 N/mm^2 for wires in the equivalent drawn condition.

2. Both the tensile and torsional elastic properties of the two alloys in equivalent temper grades were very similar, although there was a slight tendency for the lower tin alloy to possess the better elastic properties.

3. There was no difference, at the 95% level of significance, between the fatigue properties of springs made from the two phosphor bronze alloys in the hard drawn condition.

4. The fatigue properties of springs made from the extra hard drawn PB102 alloy were consistently slightly better than those made drom the equivalent PB103 alloy. This disparity would probably not be considered important in practice, however, even though the difference was significant in statistical terms at the 99.8% level of the 't' distribution.

5. The time relaxation work confirmed that the primary relaxation was not confined to an initial period of 72 hours. The relaxation in each case showed a logarithmic relationship with time.

6. The stress relaxation properties of the PB102 alloy springs were consistently equal to or better than those made from the equivalent PB103 alloy. The difference was probably too small to be considered important in practice, however. In each case, the relaxation in 168 hours at constant temperature varied exponentially with the applied initial stress.

7. The present work suggests that little or no advantage is to be gained by using the PB103 alloy in place of the cheaper PB102 alloy, in either the hard drawn or the extra hard drawn condition, for the manufacture of compression springs.

8. It has been demonstrated that the relaxation at constant stress varied exponentially with the reciprocal of the absolute temperature.

   Activation energies for relaxation have been calculated, and it has been demonstrated that the values for the PB103 (7% Sn) alloys are consistently lower than those for the equivalent PB102 (5% Sn) alloys. This suggests that the relaxation resistance of the PB103 springs may be inherently lower than that for springs manufactured from the PB102 material.

7. RECOMMENDATIONS

1. The slight difference observed between the elastic properties of the two alloys in equivalent temper grades requires further investigation.

2. The reasons for the rather lower fatigue and relaxation performance of the PB103 (7% Sn) alloy are not completely clear and require further work.

3. Since the 5% Sn alloy (PB102) has been shown to be in no way inferior to the 7% Sn alloy (PB103) with respect to both the fatigue and the relaxation properties, it may be considered desirable to investigate the relevant properties of the appropriate phosphor bronze alloys containing less than 5% Sn.

   Such alloys should be cheaper than the PB102 material, but based on the results of the present comparison they may offer static and dynamic properties which are comparable to those of the 5% Sn alloy.

8. REFERENCES

1. Heyes P.F. "The fatigue and relaxation properties of helical compression springs manufactured from phosphor-bronze wire". SRA Report No. 243, March, 1975.

2. Erricker B.C. "Advanced general statistics". Hodder and Stoughton, 1976.

3. Little R.E. "Manual on statistical planning and analysis". A.S.T.M. Technical Publication 588, 1975.

4. Graves G.B. "The stress-temperature relaxation properties of springs made from oil tempered and patented hard drawn wires". C.S.F.R.O. Report No. 115, May, 1960.

5. Graves G.B. "The stress-temperature relaxation and creep properties of some spring materials". SRAMA Report No. 143, April, 1963.

6. Whittaker J.J. "Copper base alloys for springs". Spring Journal, 1969, (95), June, p. 33.

7. Reynolds L.F. "The fatigue and relaxation of high strength titanium 318 alloy springs". SRAMA Report No. 288, Feb., 1978.

8. McLean D and Hale K.F. "The stress sensitivity of creep". Iron and Steel Institute Special Report No. 70. "Structural processes in creep". p. 19 (paper) and p. 90 (discussion).

9. Ellis B. "The structure and properties of thermoplastics". Metallurgist and Material Technologist, 1976, (3), March, p. 150.

10. Gray P. "On the mechanism responsible for the changes in the elastic and relaxation properties with stress, strain and temperature in spring materials". SRAMA Report No. 284, Oct., 1977.

9. ACKNOWLEDGEMENTS

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TABLE I CHEMICAL ANALYSES OF PB102 AND PB103 ALLOY WIRES

Sample Specification	Wire Condition	Analysis	Chemical Composition%			
			Cu	Sn	P	Pb
PB102 (5% Sn)		Nominal	Rem.	4.5-6.0	0.02-0.40	<0.02
	H	Actual	94.0	5.05	0.31	<0.01
	EH		94.2	4.9	0.325	<0.01
PB103 (7% Sn)		Nominal	Rem.	6.0-7.5	0.02-0.40	<0.02
	H	Actual	92.0	7.1	0.407	<0.01
	EH		91.3	7.4	0.396	<0.01

TABLE II SPRING DESIGNS

Design Parameters	Wire Condition and Type			
	H		EH	
	PB102	PB103	PB102	PB103
Wire diameter, mm	1.2	1.2	1.2	1.2
Mean coil diameter, mm	9.75	9.75	9.75	9.75
Total coils	9	9	9	9
Active coils	7	7	7	7
Free length, mm, after end grinding and prestressing	27	31	31	36
Solid stress, N/mm^2	480	480	580	580

TABLE III TENSILE PROPERTIES OF PB102 WIRE

Wire Treatment		Rm	L of P	R_p 0.05	R_p 0.1	R_p 0.2
Temper	Condition*	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
H	As drawn (1)	800	470	610	670	690
	L.T.H.T. 200°C/½h (2)	770	470	580	650	690
EH	As drawn (1)	860	530	720	780	840
	L.T.H.T. 200°C/½h (3)	830	500	700	760	800

TABLE IV TENSILE PROPERTIES OF PB103 WIRE

Wire Treatment		Rm	L of P	R_p 0.05	R_p 0.1	R_p 0.2
Temper	Condition*	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
H	As drawn (2)	900	450	680	780	850
	L.T.H.T 200°C/½h (3)	860	420	670	750	810
EH	As drawn (3)	910	430	660	760	850
	L.T.H.T. 200°C/½h (3)	880	410	650	750	820

* Figures in parentheses refer to number of samples tested.

TABLE V TORSIONAL PROPERTIES OF PB102 WIRE

Wire Treatment		L of P	0.1% P.S.	0.2% P.S.	G
Temper	Condition*	N/mm^2	N/mm^2	N/mm^2	N/mm^2
H	As drawn (3)	270	460	510	3.99x10^4
	L.T.H.T. 200°C/½h (3)	360	510	560	4.13x10^4
EH	As drawn (3)	370	550	610	4.43x10^4
	L.T.H.T. 200°C/½h (3)	310	510	570	4.67x10^4

TABLE VI TORSIONAL PROPERTIES OF PB103 WIRE

Wire Treatment		L of P	0.1% P.S.	0.2% P.S.	G
Temper	Condition*	N/mm^2	N/mm^2	N/mm^2	N/mm^2
H	As drawn (2)	220	460	540	4.33x10^4
	L.T.H.T. 200°C/½h (3)	260	480	540	4.31x10^4
EH	As drawn (2)	260	480	540	4.17x10^4
	L.T.H.T. 200°C/½hr (2)	230	500	560	4.09x10^4

* Figures in parentheses refer to number of samples tested.

TABLE VII RESULTS OF PAIRED FATIGUE TESTS ON SPRINGS MANUFACTURED FROM HARD DRAWN PB102 AND PB103 WIRES

Initial Stress N/mm^2	Maximum Stress N/mm^2	Cycles to Failure N x 10^6	
		PB102 (5% Sn)	PB103 (7% Sn)
100	380	8.46	1.584
"	"	20.43	5.76
"	"	3.555	1.8
"	"	1.44	2.61
"	"	4.68	15.228
"	"	5.022	1.926
"	"	2.295	2.106
50	380	0.684	0.927
"	"	0.675	0.675
"	"	0.441	0.585
"	"	0.936	0.792
"	"	0.405	1.854
"	"	1.188	0.801
"	"	0.891	1.125
Total pairs, N_p		14	

TABLE VIII RESULTS OF PAIRED FATIGUE TESTS ON SPRINGS MANUFACTURED FROM EXTRA HARD DRAWN PB102 AND PB 103 WIRES

Initial Stress N/mm^2	Maximum Stress N/mm^2	Cycles to Failure N x 10^6	
		PB102 (5% Sn)	PB103 (7% Sn)
100	380	6.66	1.899
"	"	9.72	1.89
"	"	7.56	2.853
"	"	11.7	1.611
"	"	3.96	1.404
100	440	2.304	0.873
"	"	1.773	0.432
"	"	0.639	0.621
"	"	1.278	0.396
"	"	0.765	0.405
100	500	0.477	0.468
"	"	0.342	0.234
"	"	0.405	0.234
"	"	0.513	0.342
"	"	0.495	0.351
Total pairs, N_p		15	

TABLE IX RESULTS OF SEQUENTIAL TIME RELAXATION TESTS AT 75°C FOR SPRINGS MANUFACTURED FROM PB102 AND PB103 WIRE

Relaxation time, hours	PB102 Condition and Stress, N/mm^2			PB103 Condition and Stress, N/mm^2		
	Hard Drawn	Extra Hard Drawn		Hard Drawn	Extra Hard Drawn	
	300	300	500	300	300	500
8	0.4	0.7	4.5	0.8	0.7	1.6
"	0.2	0.6	3.5	0.2	0.6	1.9
"	0.7	0.6	2.5	0.7	0.7	1.3
16	0.2	1.2	5.1	2.2	0.8	1.9
"	0.4	0.8	4.1	0.3	0.8	1.9
"	1.1	0.8	3.2	0.7	0.7	1.9
24	1.1	1.6	5.4	3.4	0.7	2.5
"	0.0	1.2	5.7	0.7	1.7	2.2
"	0.4	1.1	4.1	1.0	0.7	2.2
48	0.9	2.5	6.4	3.0	1.8	2.5
"	1.0	1.6	6.4	1.2	1.6	2.9
"	1.5	1.5	4.5	1.6	1.9	2.5
72	1.0	2.5	6.4	3.6	1.9	3.2
"	0.9	1.4	5.7	1.3	2.4	2.9
"	0.7	1.4	5.1	2.0	1.5	3.5
100	1.6	2.7	7.0	3.7	2.5	3.8
"	1.2	2.4	7.0	2.1	2.3	3.5
"	2.1	2.1	5.7	2.7	2.1	4.1
168	2.4	2.8	7.6	4.0	2.2	4.1
"	1.7	2.5	7.6	2.2	2.5	4.4
"	2.4	2.4	6.0	2.7	2.6	3.8

TABLE X RESULTS OF SEQUENTIAL TIME RELAXATION TESTS AT 125°C FOR SPRINGS MANUFACTURED FROM PB102 AND PB103 WIRE

Relaxation time, hours	PB102 Condition and Stress, N/mm^2			PB103 Condition and Stress, N/mm^2		
	Hard Drawn	Extra Hard Drawn		Hard Drawn	Extra Hard Drawn	
	300	300	500	300	300	500
8	6.8	7.5	14.6	6.9	7.9	11.1
"	6.9	7.1	13.4	7.3	8.4	12.7
"	6.0	7.1	12.4	6.8	7.9	12.1
16	9.8	10.8	18.5	11.3	10.5	14.6
"	9.6	10.3	17.2	11.9	11.1	15.9
"	9.0	10.1	16.9	9.6	10.0	15.5
24	11.8	13.0	21.0	12.7	12.7	17.1
"	11.5	12.9	20.1	13.3	13.2	18.1
"	10.5	12.9	19.4	12.0	12.1	18.1
48	15.8	17.8	26.4	16.3	16.7	21.9
"	15.3	17.3	25.2	16.7	16.6	22.5
"	14.7	17.7	24.8	15.8	16.1	22.5
72	17.9	20.4	29.3	18.4	19.4	24.8
"	17.8	19.8	28.3	19.0	19.1	25.7
"	17.0	20.0	28.0	18.0	18.2	25.7
100	20.2	23.1	32.5	20.7	21.7	27.3
"	20.6	22.4	31.2	21.1	21.1	27.9
"	19.5	22.7	30.9	20.3	20.5	27.6
168	23.3	27.1	36.3	24.4	24.7	31.4
"	23.2	26.6	35.3	24.5	24.3	31.4
"	22.7	26.5	35.0	24.0	24.2	31.7

TABLE XI REGRESSION COEFFICIENTS OF LOGARITHMIC RELATIONSHIPS FOR SEQUENTIAL TIME RELAXATION TESTS

Test Temp °C	Test Stress N/mm^2	Regression Coefficient for Alloy and Condition in Relationship Rel = alnt + b							
		PB102				PB103			
		H		EH		H		EH	
		a	b	a	b	a	b	a	b
75	300	0.5536	-1.0003	0.6531	-0.7652	0.8078	-1.0707	0.6594	-0.8761
	500	-	-	0.8957	2.1874	-	-	0.8669	-0.4128
125	300	5.5023	-5.6203	6.4531	-7.0766	5.5419	-4.7446	5.4540	-4.1534
	500	-	-	7.3460	-2.5726	-	-	6.5082	-2.3812

TABLE XII RESULTS OF PAIRED STRESS RELAXATION TESTS AT 75°C, 100°C and 125°C, MANUFACTURED FROM HARD DRAWN PB102 AND PB103 WIRES

Initial Stress N/mm^2	Relaxation % for alloy type and temperature °C					
	75°C		100°C		125°C	
	PB102	PB103	PB102	PB103	PB102	PB103
100	0.16	1.43	2.86	3.65	12.54	12.54
"	-0.79	1.11	2.69	4.13	10.16	13.65
"	0.32	0.95	2.54	3.97	11.11	13.02
200	0.71	1.44	4.05	4.56	14.29	14.56
"	2.22	1.12	2.38	4.48	12.38	14.64
"	0.16	1.04	3.49	4.40	13.57	15.28
250	1.02	1.46	3.69	4.84	15.73	17.01
"	1.02	1.59	3.38	4.39	16.18	17.07
"	1.91	1.78	4.01	4.33	15.79	16.94
300	0.85	2.02	5.03	4.73	17.99	17.87
"	2.12	1.65	4.87	4.73	16.72	18.14
"	2.28	1.97	4.81	5.05	17.46	18.14
350	2.27	2.28	5.45	5.48	18.64	20.55
"	1.36	1.83	5.45	6.39	19.09	19.18
"	3.18	-	5.00	5.94	-	19.63
Total pairs N_p	14		15		14	

TABLE XIII RESULTS OF PAIRED STRESS RELAXATION TESTS AT 75°C, 100°C and 125°C ON SPRINGS MANUFACTURED FROM EXTRA HARD DRAWN PB102 AND PB103 WIRES

Initial Stress N/mm^2	Relaxation % for alloy type and temperature °C					
	75°C		100°C		125°C	
	PB102	PB103	PB102	PB103	PB102	PB103
100	0.32	1.75	4.29	5.56	16.03	16.03
"	0.63	1.27	3.17	4.29	15.71	18.41
"	0.48	0.95	3.33	5.08	15.40	15.40
200	0.56	2.06	4.44	5.48	18.89	17.86
"	1.43	1.98	3.89	5.16	17.78	17.46
"	1.43	1.83	4.52	5.95	17.78	17.86
300	1.33	2.33	5.11	5.50	21.38	19.52
"	1.22	2.33	4.31	5.66	21.33	19.47
"	0.90	1.48	5.21	5.40	20.74	19.84
400	1.59	2.78	5.98	6.75	25.10	22.98
"	1.99	2.78	7.17	6.35	24.30	21.55
"	4.38	2.38	5.98	6.35	24.70	21.59
500	6.37	2.86	9.55	8.25	29.62	25.71
"	3.82	6.67	10.83	7.62	29.94	25.08
"	4.78	3.81	10.51	8.89	30.25	26.35
Total pairs N_p	15		15		15	

TABLE XIV ANALYTICAL CONSTANTS FOR EXPONENTIAL STRESS RELAXATION OF PB102 SPRINGS

Material Condition	Test Temperature ^{o}C	Coefficients for $Rel = Ae^{B\tau}$		Increment for 95% confidence $= \pm 1.96xS_R{}^*$
		A	$Bx10^{-3}$	
Hard	75	0.105	9.042	1.4
Drawn	100	1.927	2.870	0.8
	125	8.858	2.262	1.5
Extra	75	0.273	5.559	1.6
Hard	100	2.566	2.515	1.7
Drawn	125	13.232	1.598	1.0

$^*S_R$ = Standard deviation of the Residuals derived from the difference between the experimental stress-relaxation data and the values obtained from the analytical expression.

TABLE XV ANALYTICAL CONSTANTS FOR EXPONENTIAL STRESS RELAXATION OF PB103 SPRINGS

Material Condition	Test Temperature ^{o}C	Coefficients for $Rel = Ae^{B\tau}$		Increment for 95% confidence $= \pm 1.96xS_R{}^*$
		A	$Bx10^{-3}$	
Hard	75	0.828	2.555	0.4
Drawn	100	3.295	1.47	0.7
	125	10.906	1.693	0.9
Extra	75	1.005	2.66	1.7
Hard	100	4.241	1.18	1.1
Drawn	125	14.447	1.097	1.7

$^*S_R$ = Standard deviation of the Residuals derived from the difference between the experimental stress-relaxation data and the values obtained from the analytical expression.

TABLE XVI ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED FATIGUE TESTS CARRIED OUT ON PB102/PB103 SPRINGS

Wire Condition	Total pairs, N_p	Mean Value $\bar{x}$ *	Std. Dev. S_x *	t Value	Comments
Hard drawn	14	0.0345	0.3843	0.34	Difference not significant at 95% level
Extra Hard Drawn	15	0.3706	0.2524	5.69	PB102 springs significantly better than PB103 springs at 99.8% level

* $\bar{x}$ = Log N (PB102) - Log N (PB103)

= The mean of the differences in log fatigue life obtained from the paired data

* S_x = Standard deviation of the differences obtained from the paired log life data

TABLE XVII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED STRESS RELAXATION TESTS CARRIED OUT ON PB102/PB103 SPRINGS

Wire Condition	Test Temp ^{o}C	Total pairs, N_p	Mean Value $\bar{x}^*$	Std. Dev. S_x^*	t Value	Comments
Hard Drawn	75	13	-0.32	0.69	1.61	Difference not significant at 95% level
	100	15	-0.76	0.65	4.53	Difference significant at 99.8% level
	125	14	-1.21	1.01	4.48	Difference significant at 99.8% level
Extra Hard Drawn	75	15	-0.40	1.53	1.01	Difference not significant at 95% level
	100	15	-0.27	1.40	0.75	Difference not significant at 95% level
	125	15	1.59	1.97	3.13	Difference significant at 99% level

* $\bar{x}$ = Relaxation % (PB102) - Relaxation % (PB103)

= The mean.of the differences in relaxation obtained from the paired tests

* S_x = Standard deviation of the differences obtained from the paired relaxation data.

TABLE XVIII APPARENT ACTIVATION ENERGIES FOR STRESS RELAXATION OF PB102 AND PB103 PHOSPHOR BRONZE ALLOYS

Alloy Designation	Wire Condition	Apparent activation energy (ev) for initial stress of (N/mm^2)						
		100	200	250	300	350	400	500
PB102 (5% Sn)	Hard Drawn	-0.93	-0.73	-0.61	-0.57	-0.55	-	-
	Extra Hard Drawn	-0.85	0.69	-	-0.70	-	-0.56	-0.43
PB103 (7% Sn)	Hard Drawn	-0.58	-0.61	-0.57	-0.54	-0.55	-	-
	Extra Hard Drawn	-0.62	-0.53	-	-0.55	-	-0.51	-0.43

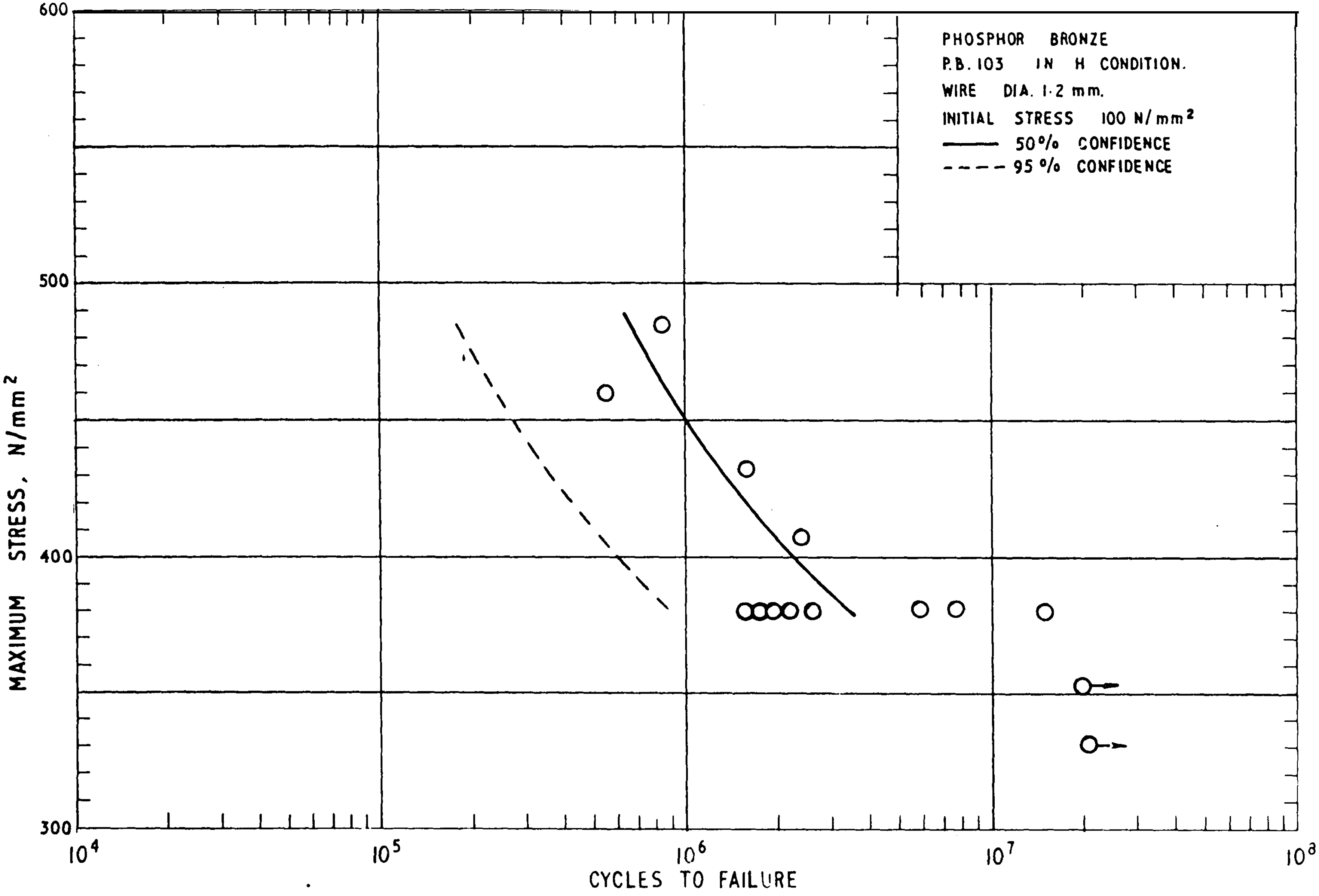

FIG. I TORSIONAL FATIGUE CURVE FOR PHOSPHOR-BRONZE SPRINGS MANUFACTURED FROM PB 103 HARD DRAWN WIRE. INITIAL STRESS 100 N/mm²

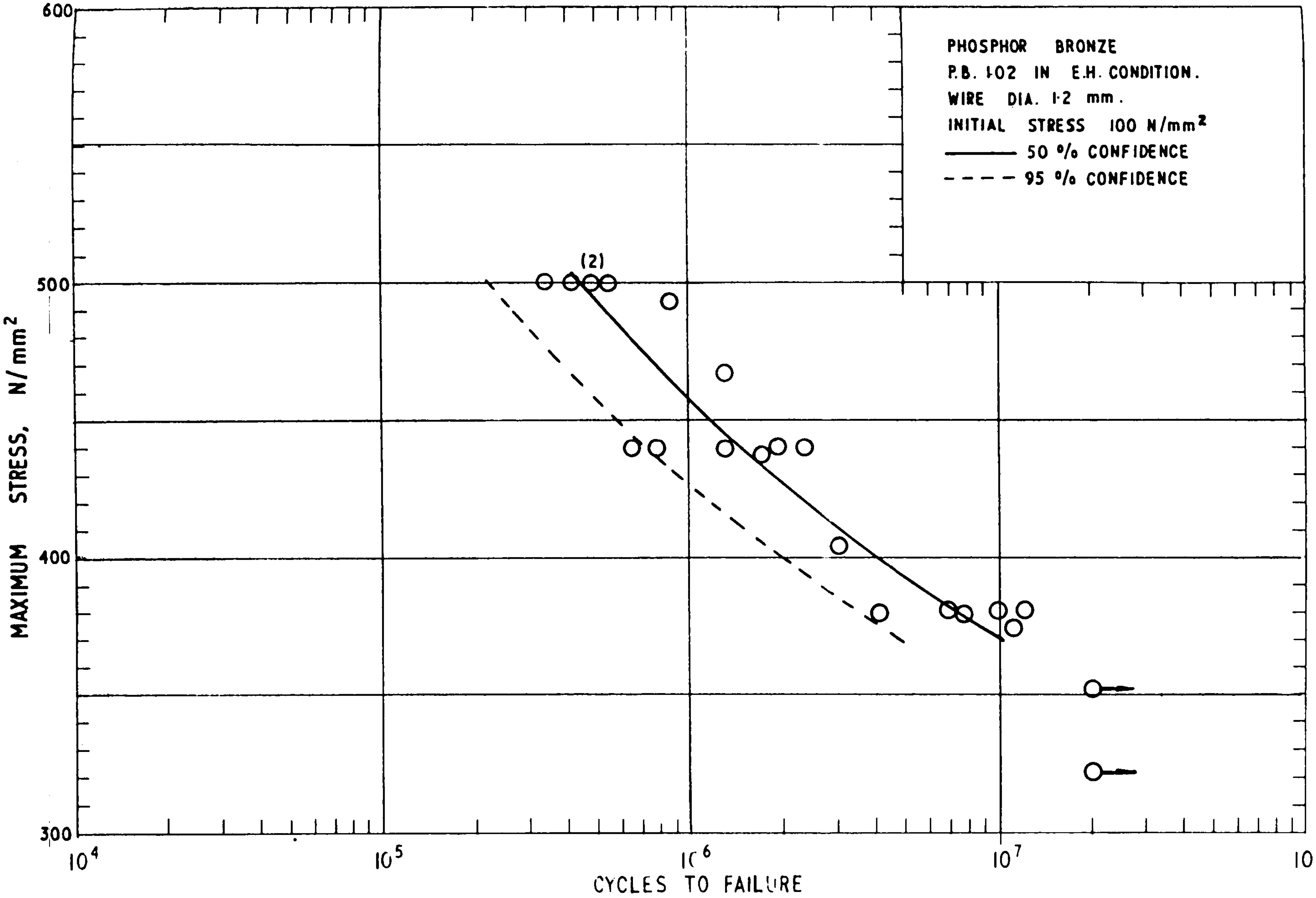

FIG. 2. TORSIONAL FATIGUE CURVE FOR PHOSPHOR – BRONZE SPRINGS MANUFACTURED FROM P.B. 102 EXTRA HARD DRAWN WIRE. INITIAL STRESS 100 N/mm²

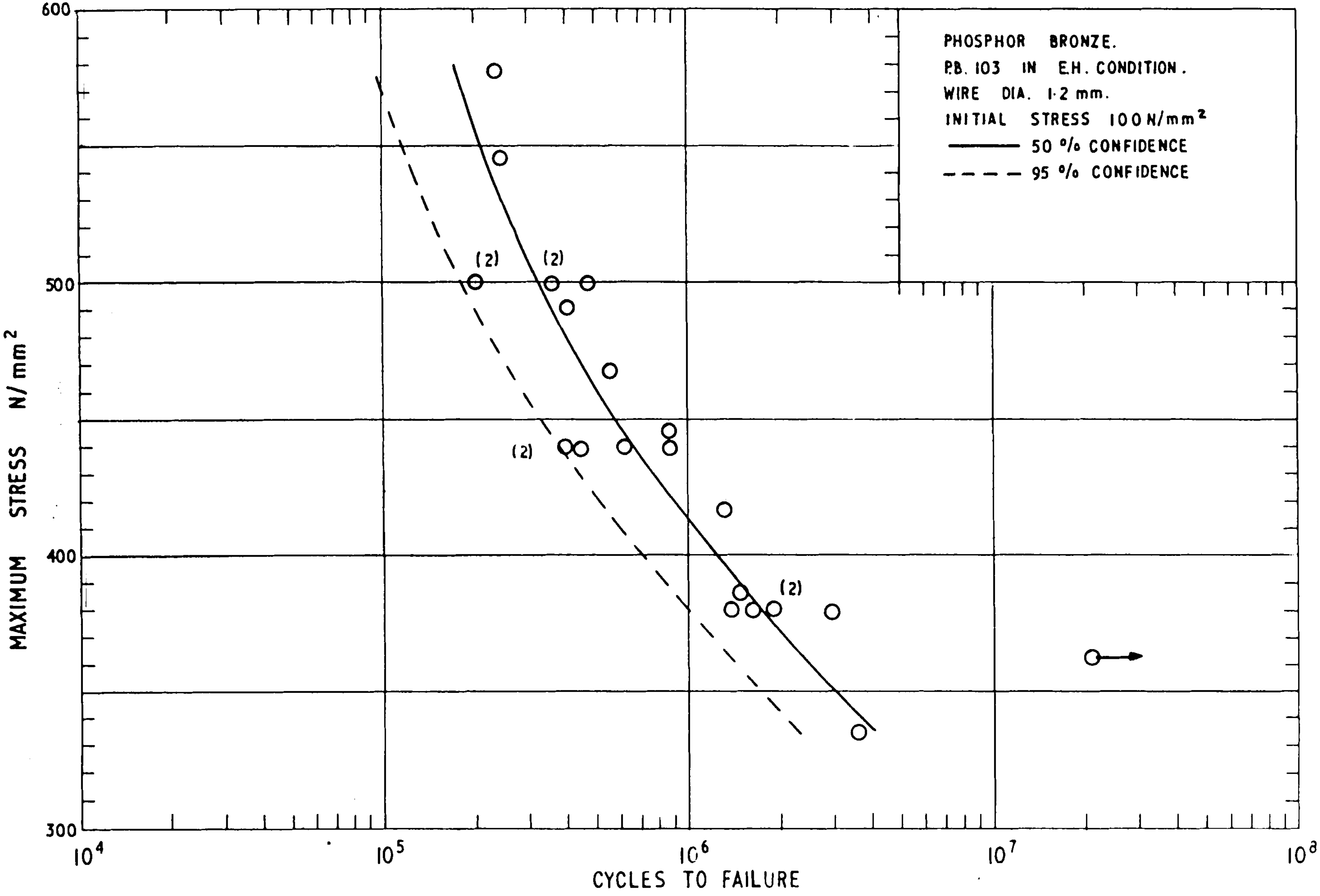

FIG. 3 TORSIONAL FATIGUE CURVE FOR PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM PB 103 EXTRA HARD DRAWN WIRE. INITIAL STRESS 100 N/mm²

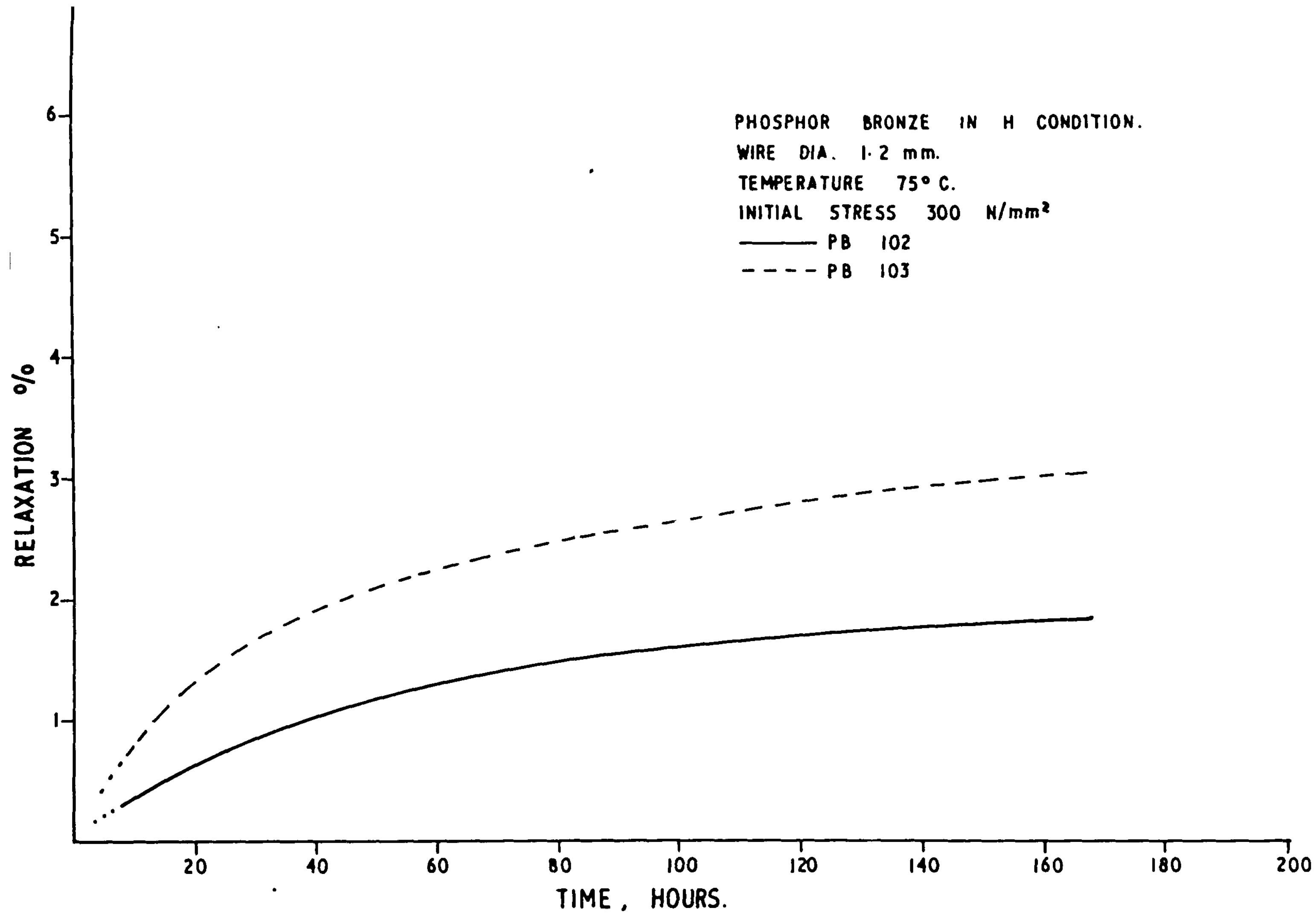

FIG. 4. TIME-RELAXATION CURVES FOR PHOSPHOR-BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 HARD DRAWN WIRE.

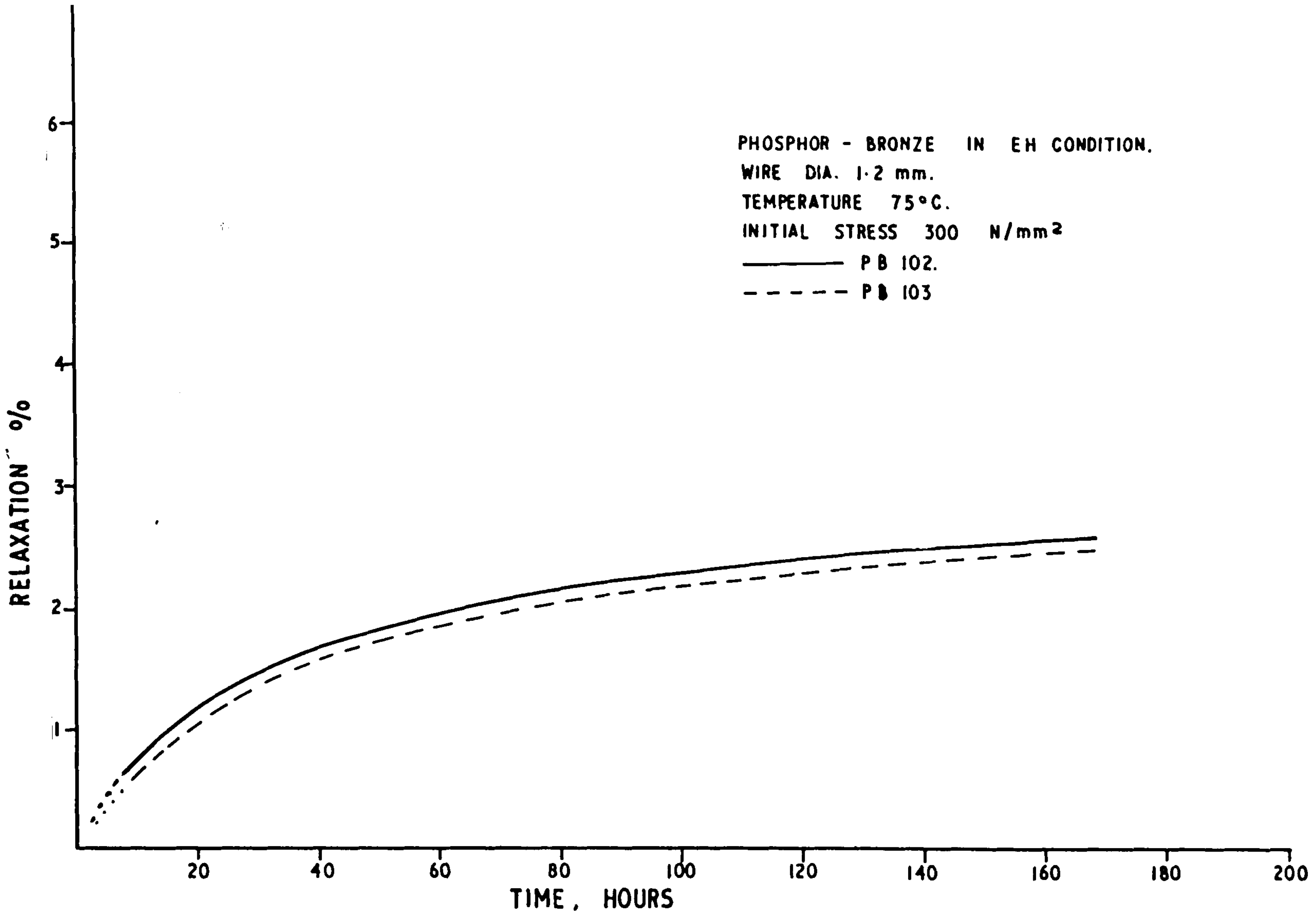

FIG. 5. TIME - RELAXATION CURVES FOR PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM P.B 102 AND P.B 103 EXTRA HARD DRAWN WIRE.

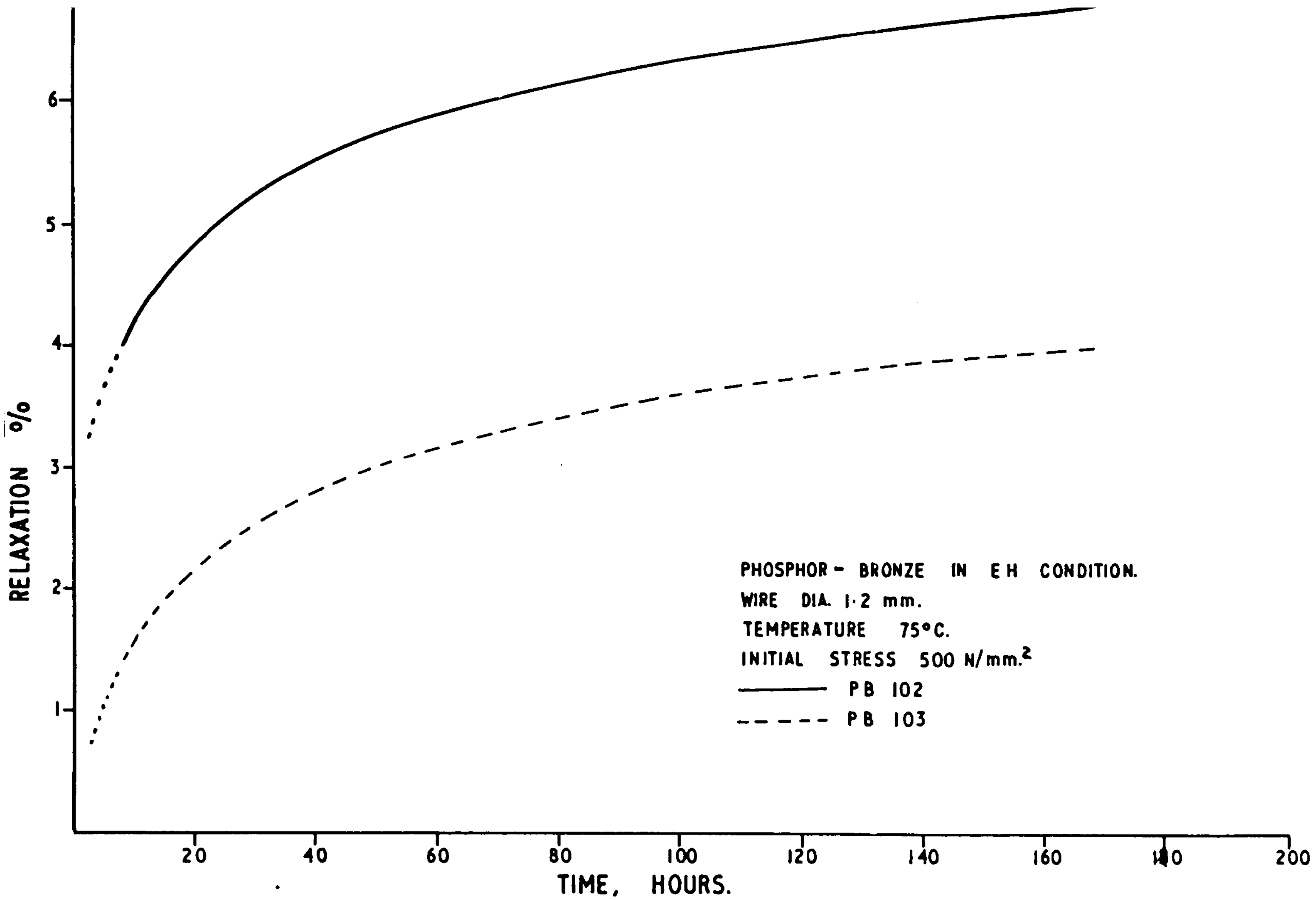

FIG. 6. TIME-RELAXATION CURVES FOR PHOSPHOR-BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 EXTRA HARD DRAWN WIRE.

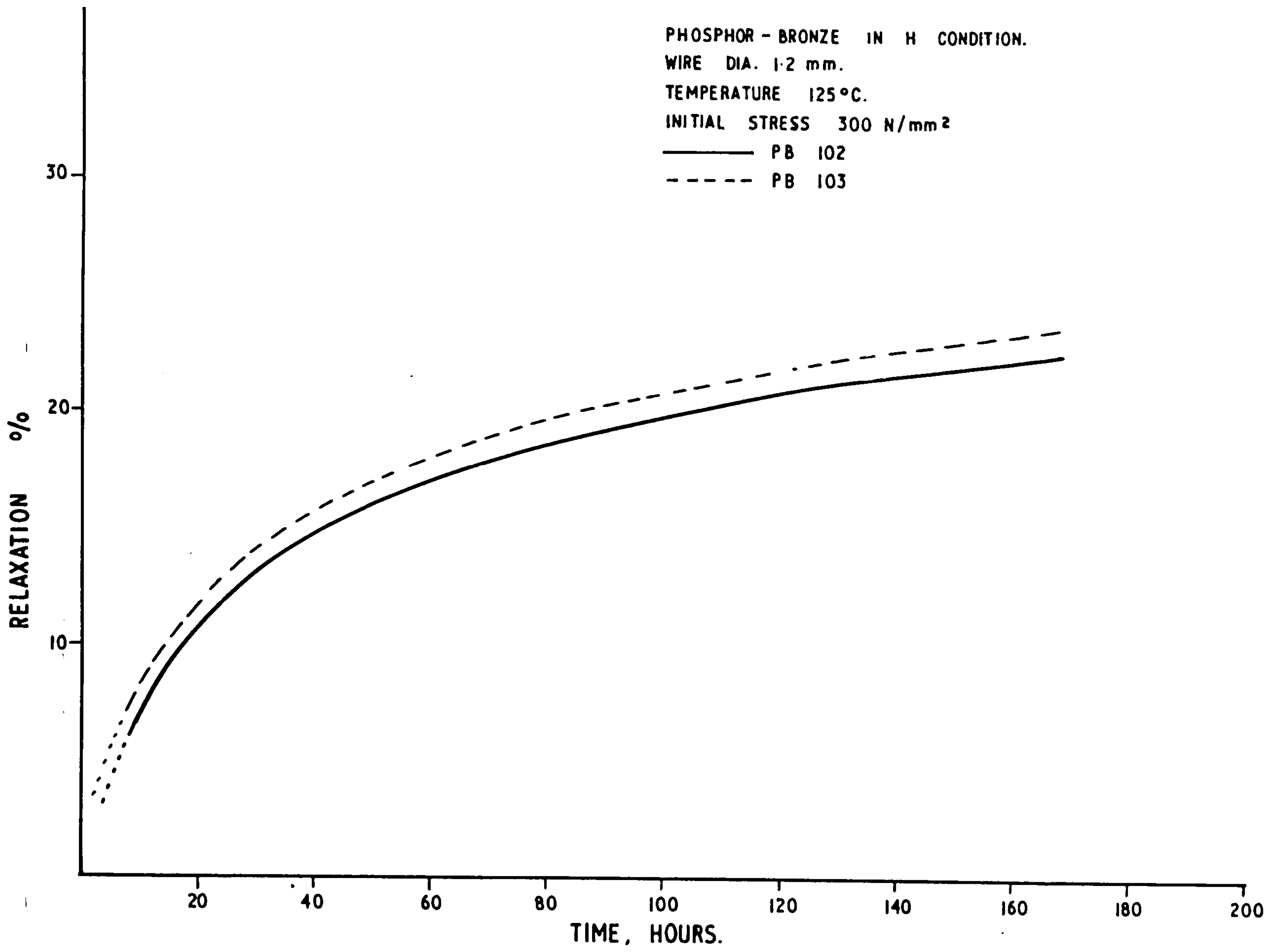

FIG. 7 TIME - RELAXATION CURVES FOR PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM P.B. 102 AND P.B. 103 HARD DRAWN WIRE.

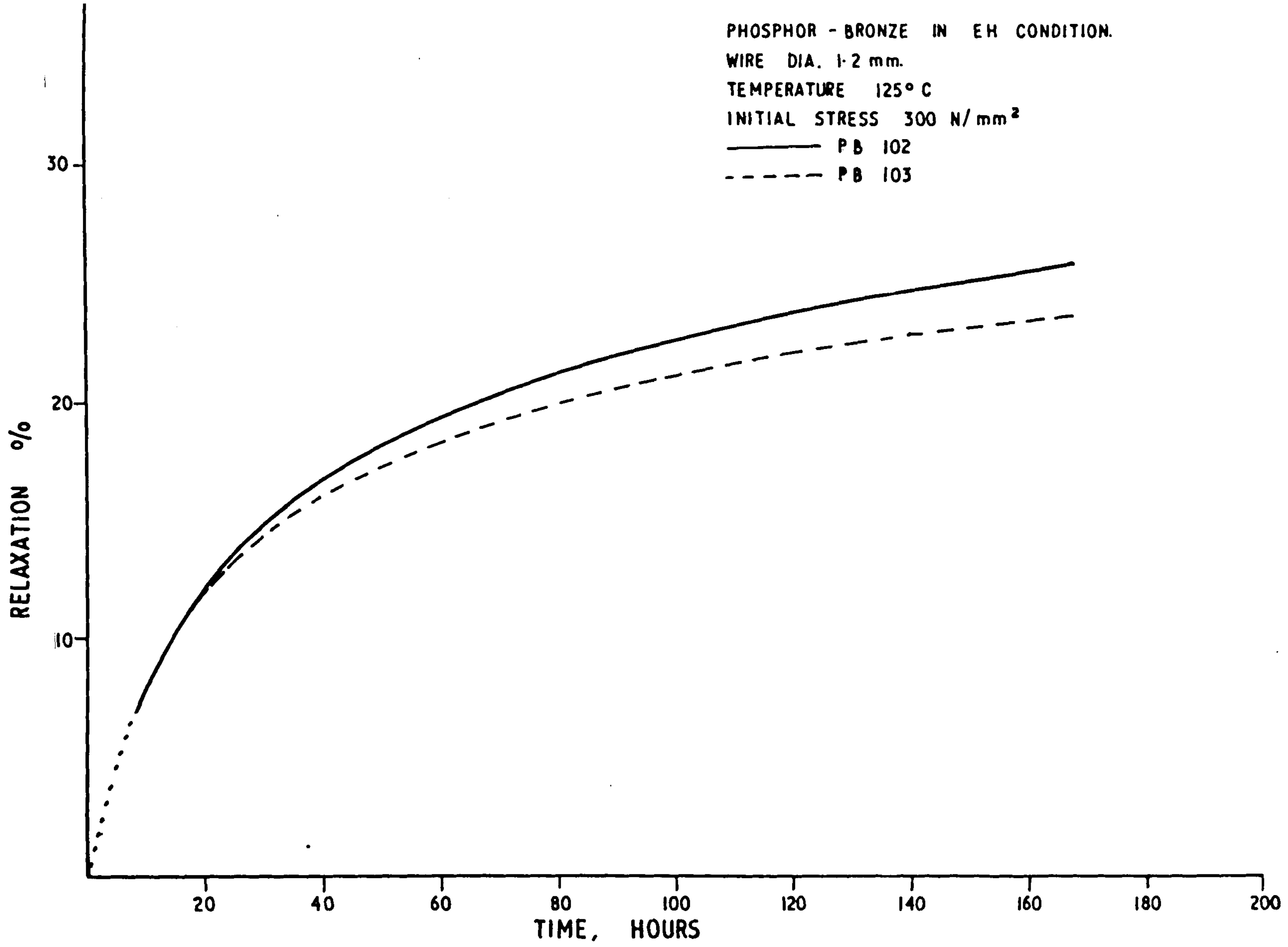

FIG. 8 TIME RELAXATION CURVES FOR PHOSPHOR– BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 EXTRA HARD DRAWN WIRE.

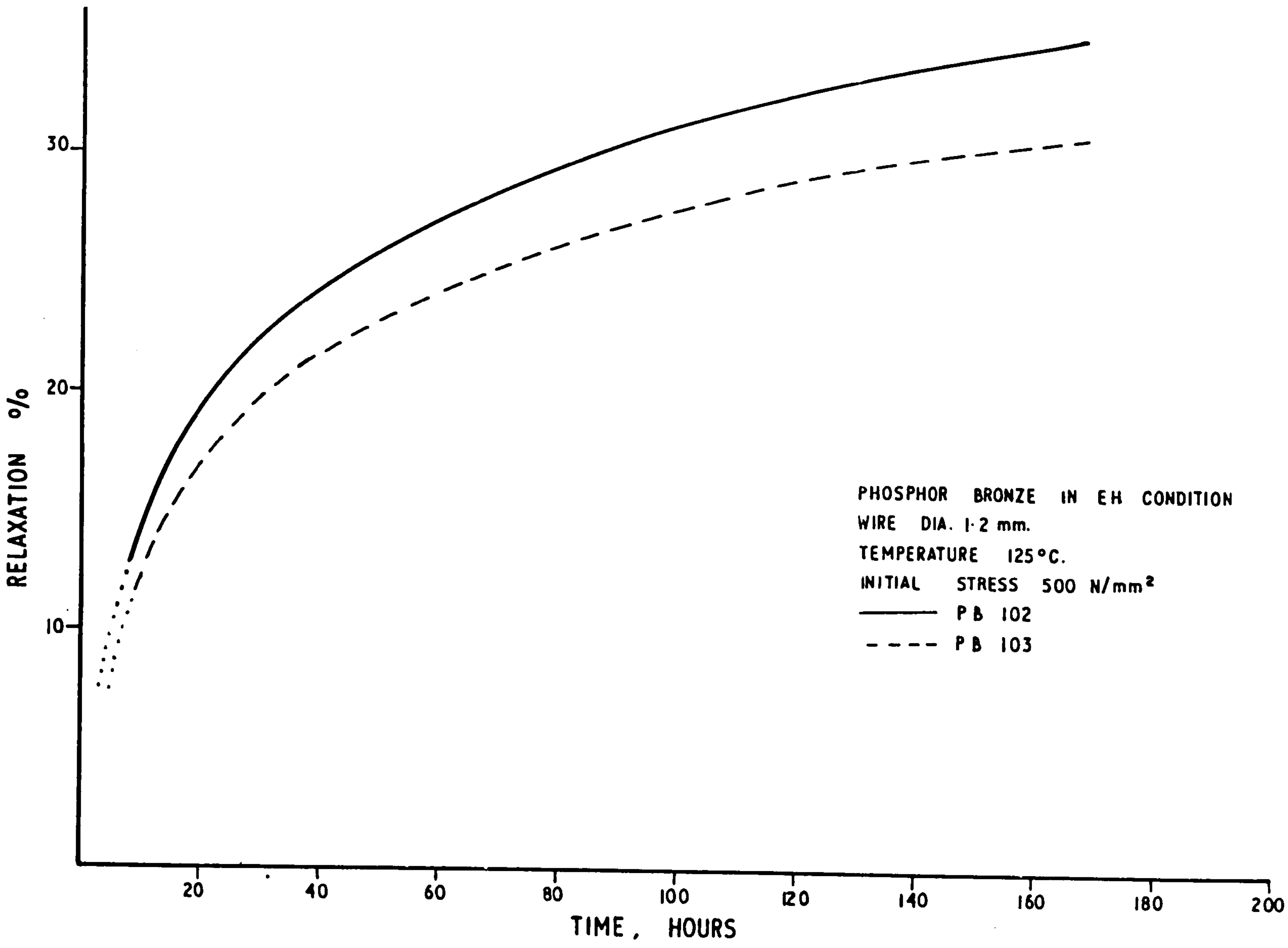

FIG. 9 TIME - RELAXATION CURVES FOR PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 EXTRA HARD DRAWN WIRE.

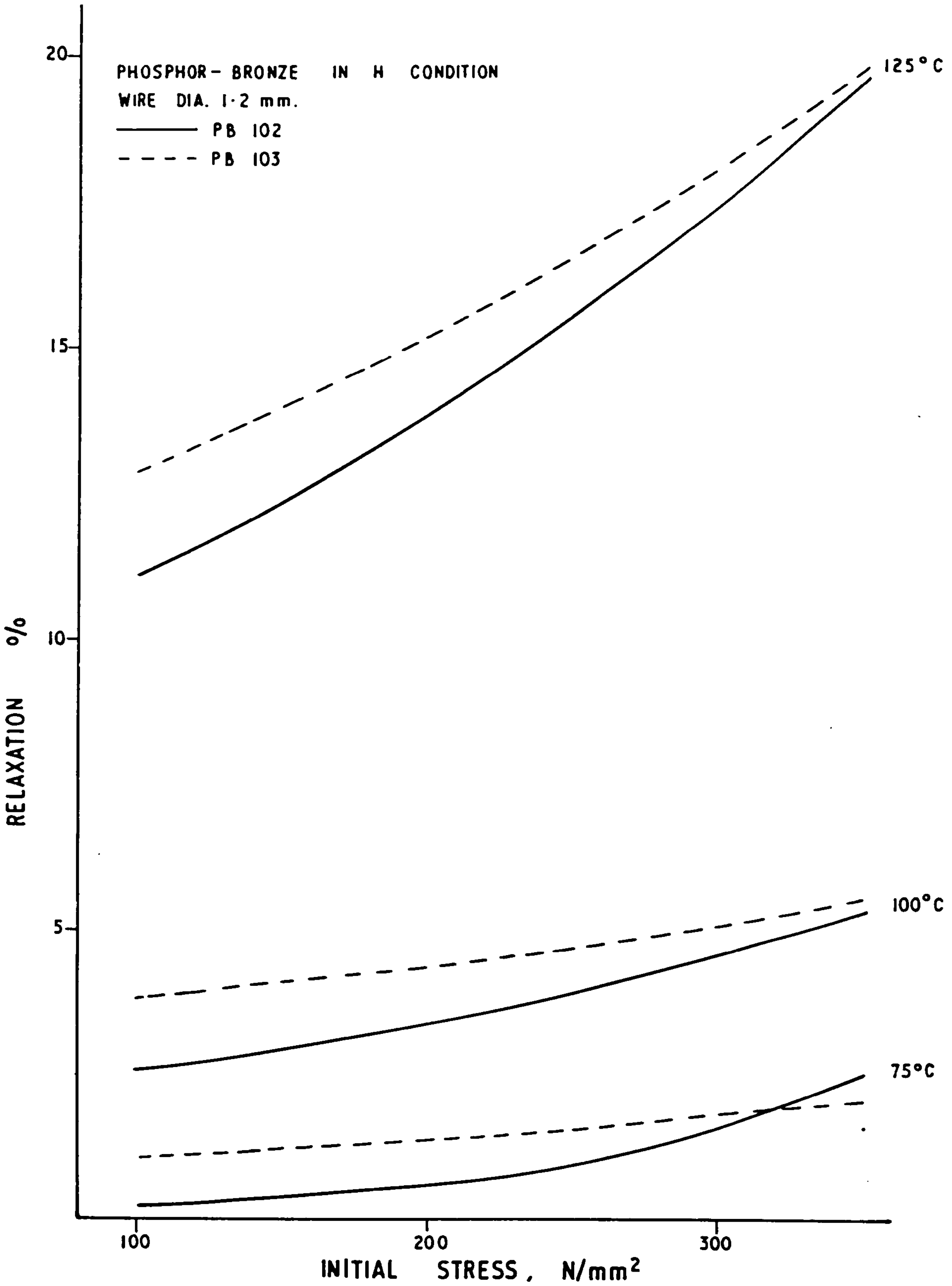

FIG. 10 STRESS - RELAXATION CURVES FOR PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 HARD DRAWN WIRE.

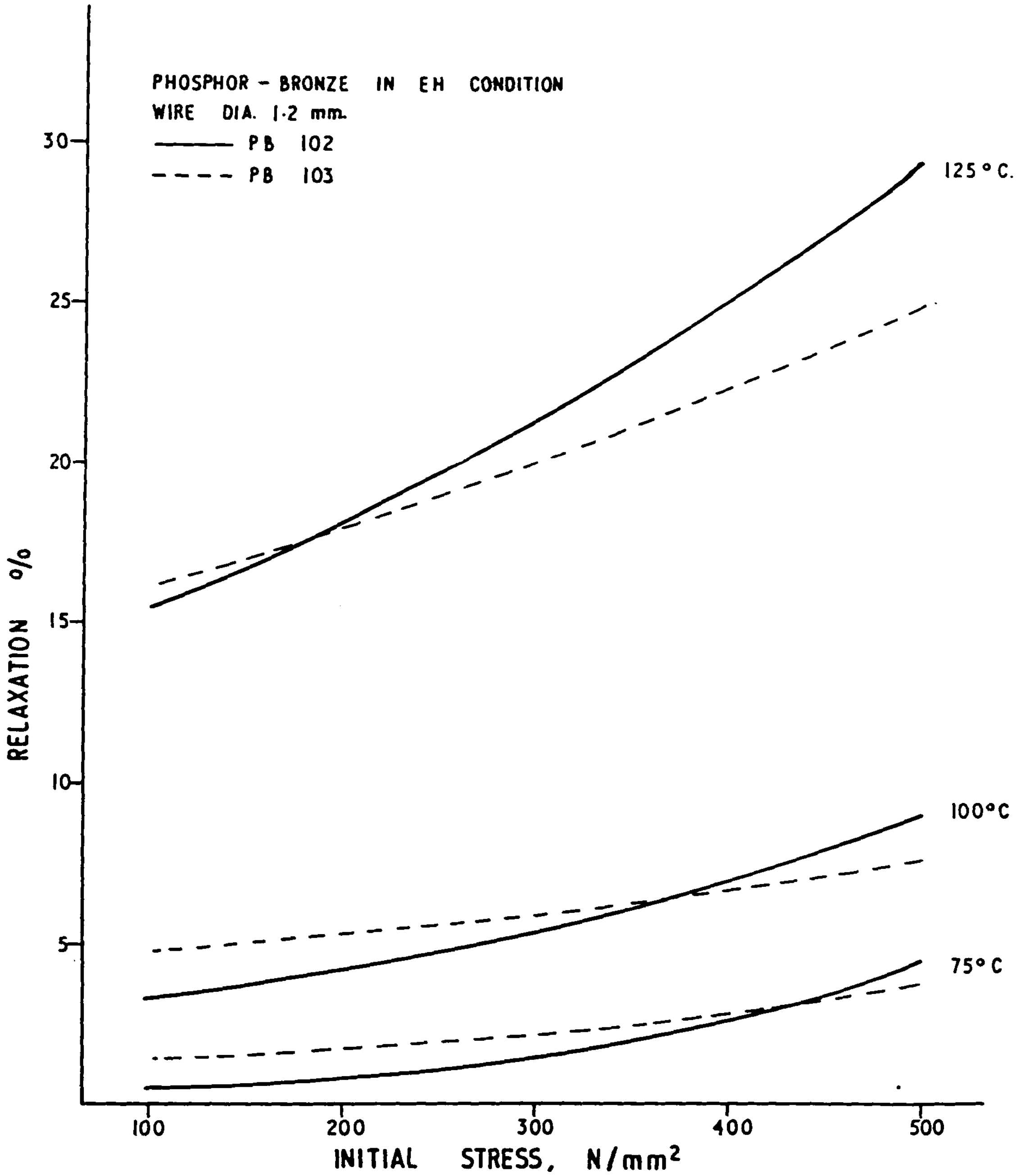

FIG. 11. STRESS - RELAXATION OF PHOSPHOR - BRONZE SPRINGS MANUFACTURED FROM PB 102 AND PB 103 EXTRA HARD DRAWN WIRE.

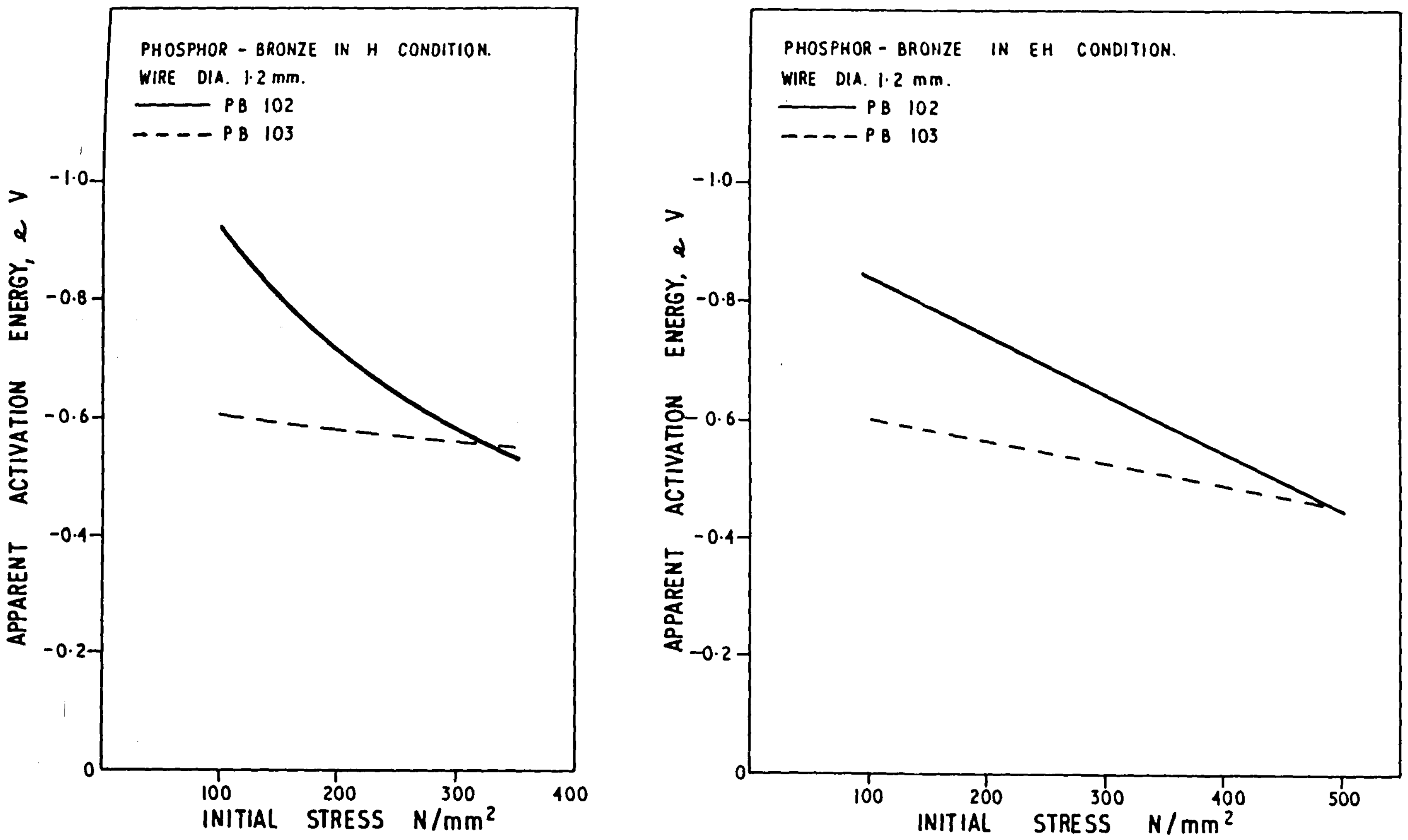

FIG. 12 VARIATION OF APPARENT THERMAL ACTIVATION ENERGY FOR RELAXATION WITH INITIAL STRESS FOR PHOSPHOR - BRONZE COMPRESSION SPRINGS.