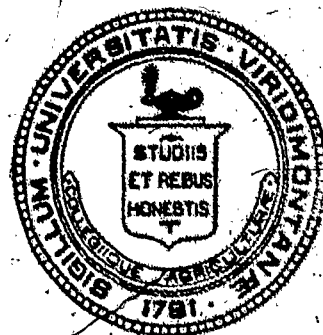


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On The Strength Degradation Of
Filament Wound Pressure Vessels
Subjected To A History Of Loading

Dr. John O. Outwater
Mr. Willard J. Seibert

April 22, 1963

Prepared at the request of
The Scientific Officer
U. S. Naval Research Laboratory
Washington 25, D. C.

Under
Contract Nonr - 3219(01)(x)

NRL Project 62 R05 19A
Technical Memo No. 196

The University of Vermont
Burlington, Vermont



FOREWORD

This research memorandum has been written under contract Nonr - 3219(01)(x). The memorandum was prepared by Dr. John O. Outwater, Principal Investigator under this contract, and Mr. Willard J. Seibert and summarizes the work to date on the theoretical aspects of the strength degradation of filament wound pressure vessels. It was carried out under the technical direction of the U. S. Naval Research Laboratory.

Mr. Joseph A. Kies of the U. S. Naval Research Laboratory and Messrs. Miner, Oldham, and Trono of the University of Vermont were of great help in the undertaking. The author also wishes to acknowledge the valued advice and encouragement of many others who helped in this project.

On The Strength Degradation of Filament Wound
Pressure Vessels Subjected To A History of Loading

by

J. O. Outwater*
W. J. Seibert**

ABSTRACT

If we assume that the rate of growth of a Griffith crack that controls the strength of a fiber is proportional to a power of the stress on that fiber we can predict that the ultimate strength of a filament wound pressure vessel decreases linearly with the time at a given load and also that the time to failure when the vessel is held at a given load will increase logarithmically. Both these observations are confirmed experimentally and form the basis for a simple method of predicting the life of a vessel at one load after it has been held for a given time at another.

INTRODUCTION

There have been many theories concerning the mechanics of failure of reinforced laminates and much experimental work has been done on their behavior. It is, however, not necessarily possible to correlate this directly or even indirectly with the failure of filament wound pressure vessels. The principal reason for this is the fact that most theories and experiments are done with parallel fiber bundles, where the loading is not directly in tension with the same tension on all the strands.

*Professor of Mechanical Engineering, The University of Vermont,
Burlington, Vermont

**Graduate Student, Department of Mechanical Engineering, The
University of Vermont, Burlington, Vermont

With a simple technique for winding and testing small pressure vessels we have an enormously powerful technique for evaluating and experimenting with glass filaments, without being plagued with the problem of anchoring the fibers evenly during test. Similarly, we avoid the tendency for NOL rings to break down in shear and hence confuse the actual mode of failure during a test that is apparently tensile.

Using these small vessels we are able to show how the filaments deteriorate under load and provide experimental backing for a simple hypothesis of filament breakdown based on the usual Griffith's theory of glass failure.

Armed with this hypothesis, confirmed by experimental work, we can use it to predict the strength of pressure vessels that have been subjected to a history of loading such as might be encountered in a proof test where the vessel is loaded to 80% of its burst strength for a minute and then unloaded and subsequently put into operation. Its burst strength is degraded by this treatment. This hypothesis shows to what extent. It is similarly possible to predict the strength of vessels that are operated at a given pressure after being proofed at another.

THEORETICAL EXPOSITION

Consider the walls of a pressure vessel to be made up of bundles of filaments having an initial crack depth c_0 . Let the depth of the crack be c after a time t when the strand is subjected to a stress s .

Assume the rate of growth of the depth of the crack to be proportional to s^n , then

$$dc/dt = k_1 s^n \quad \text{-----1}$$

where k_1 , k_2 , etc. are constants.

Solving this equation we get

$$c = k_1 s^n t + c_0 \quad \text{-----2}$$

where c_0 is initial crack depth.

Then, by the Griffith theory, the filament will fail when it is kept under a constant stress s when

$$s^2 = \frac{k_2}{k_1 s^n t + c_0} \quad \text{-----3}$$

Now as the initial strength of the glass is much higher than the load at which it ultimately breaks, we may, at the first approximation, consider c_0 small compared with $k_1 s^n t$ and then the failure load will be given by

$$k_1 s^{n+2} t = k_2 \quad \text{-----4}$$

or

$$(n+2) \log s + \log t = k_3 \quad \text{-----5}$$

If we do not make the assumption that c_0 is small compared to $k_1 s^n t$ then we will get a $\log (1-s^2)$ term in equation 5. This is ignored as the plot of the load at which a vessel is held against the time required for the vessel to fail at that load is shown in fig. 1. This pleasantly shows a configuration similar to that predicted by equation 5 and the straight line hypothesis is experimentally demonstrated.

The next problem is to determine what the strength of a vessel might be after it has been subjected to a load for a period of time less than that required to burst it. This is an equivalent of showing its deterioration under load, and is accomplished by rapidly raising the load to burst after vessels have been held at a load for varying times.

If we hold a vessel at a load s_1 for a time t , then, from equation 2, its depth of crack will be $c_0 + k_1 s_1^n t$ or its breakage load will be given by

$$s_b^2 = \left(\frac{k_2}{k_1 s_1^n t + c_0} \right) \quad \text{-----6}$$

or

$$s_b = \frac{k_2^{\frac{1}{2}}}{c_0^{\frac{1}{2}}} \left(\frac{k_1}{c_0} s_1^n t + 1 \right)^{-\frac{1}{2}} \quad \text{-----7}$$

In this case c_0 is not necessarily small compared to the crack depth as the vessel may not have seriously deteriorated so

$$s_b = \frac{k_2^{\frac{1}{2}}}{c_0^{\frac{1}{2}}} \left\{ 1 - \frac{1}{2} \cdot \frac{k_1}{c_0} \cdot s_1^n t \right\} \quad \text{-----8}$$

$$= S_0 - \frac{S_0}{2} \cdot \frac{k_1}{c_0} s_1^n t \quad \text{-----9}$$

if S_0 is the initial strength of the glass.

It should be noted here that the relationship between s_b and t is linear.

This relationship determined experimentally is shown in fig. 2. The slope of the curves in fig. 2 are given by proportional to s_1^n . n is given by the slope of the curves in fig. 1 and it can also be obtained for X-994 glass from the values of degradation obtainable from fig. 2.

EXPERIMENTAL RESULTS

To test the above hypothesis a series of vessels were wound from X-994 glass roving and also from E-glass using the VERMONT BALL WINDING SYSTEM*. The vessel configuration is described earlier**. It is essentially an onion shaped filament wound vessel using planar windings and an isotensoid geometry. It is necessary to use this shape rather than NOL rings as it is only by using such a specimen that we can confidently approach the conditions that actually occur in wound vessels, with their unique problems of interlaminar shear, balanced construction and end anchoring.

These vessels are then loaded under internal hydrostatic pressure and the time that elapses before the vessel bursts is plotted against the glass stress that the vessel is subjected to as in fig. 1. The roving in each case is 12 end with an O-C HTS finish. The resin is 100 parts Epon 826, 90 parts Nadic Methyl anhydride and one part DMBA. Cure conditions are 24 hours at 250°F in all cases.

From these curves we can see that there is a distinct difference between X-994, and E-glass as far as their bursting strengths are concerned. There also appears to be a logarithmic decrement with time in their bursting strengths, giving a straight line curve for each material. The slopes of the

*VERMONT INSTRUMENT CO., INC.
62 Overlake Park, Burlington, Vermont

**The Development of a Laboratory Scale Filament Winding System to Produce Pressure Vessels, Rapidly and Simply. July 26, 1962. NRL Project 62 R05 19A, Tech. Memo No. 192

lines appear to be the same. Using the curves in fig. 1 we can evaluate the constant n in equation 1 by correlating the data by a computer to give:

<u>Material:</u>	<u>n</u>
X-994	25
E glass	25

It will be noticed that the curves do not extend for a time period greater than about three hours. This results from the nature of the loading device which uses an Instron testing machine to maintain the load. The most rapid and indicative portions of the loading curve are during this region. We may perhaps be able to extrapolate our findings to the longer life cycles expected of much equipment.

The next step was to determine the strength degradation of a vessel as it is exposed to a load less than its burst strength for a varying period of time. The vessel was held at a load for different times and then rapidly brought up to its bursting pressure. The variations in the bursting strength that result from this preloading are shown in fig. 2. When we use fig. 2 to give us a value of n through equation 9, we obtain a value of $n = 25$ for X-994 glass.

DISCUSSION

The use of the simple hypothesis that the strength of the filaments depends on the critical microcrack on their surface and that this microcrack grows at a rate proportional to s^n leads to a logarithmic relationship of time and burst strength.

It also leads to a linear relationship between time at a lesser load and the burst strength after a rapid increase in load after it has been held at this load. Both these predictions are born out experimentally.

It will be noted that the values of n derived from the slope of the time-burst curve is identical to that derived from the degradation under constant load curves. It will also be noted that the slopes of the curves for X-994 and for E-glass are also identical. These data suggest strongly that there is a universal n for glasses and indicate strongly that the simple hypothesis suggested in equation 1 does indeed indicate the controlling factor in the strength of vessels of glass fibers.

THE PREDICTION OF THE BURST STRENGTH OF VESSELS AFTER A HISTORY OF LOADING

From the results of experiments shown in figs. 1 and 2 and by using the hypothesis of equation 1 we can set up a simple method of predicting the strengths of pressure vessels that have been loaded at one pressure for a period of time and then tested to burst at a rapid load or held at another pressure until they burst.

The slope of the burst curves for X-994 and E-glass are the same, so, as in fig. 3, we can plot a universal degradation curve at a slope given by $-1/n+2$ where $n = 25$ or the slope being -0.037 . This line should be drawn through the rapid load bursting value of stress obtained experimentally.

The effects of static fatigue can now be predicted from this curve by obtaining the time to burst under a given load from the intercept of the load with this inclined line.

If now we wish to show the degradation under a partial load, then we should replot the equivalent of straight lines shown in fig. 2 on the double logarithm curve of fig. 3. The end point of each degradation curve will be obtained by the time to burst under the same continued load. The initial point of the curve will be the rapid load breaking point and all points in between will be obtainable by replotting from the straight line curve of fig. 2.

The degradation under a partial load will be obtainable by following the partial load curve of the appropriate load for the time prescribed by actual loading. The burst pressure after that partial load will be obtainable from the ordinate of fig. 3. If now we subject the material to another pressure, then the ordinate is transferred to another load degradation curve, and that curve is followed for the prescribed time-- or followed to burst as in the example shown in fig. 3. The predicted burst time of a vessel via this method was 750 seconds. The actual burst time was 709 seconds. The data on degradation shown in figs. 1 and 2 also follow this prediction system based on the hypothesis in equation 1 as illustrated in figs. 1, 2, and 3.

CONCLUSIONS

The following conclusions may be drawn from the above experimental work:

1. The rate of propagation of a microcrack in a glass fiber varies with s^n , where s is the glass stress.
2. The value of n for X-994 and E-glass is about 25.
3. This crack propagation hypothesis indicates a double logarithmic burst stress curve plotting burst tensile stress against time to burst at that pressure.
4. This hypothesis also indicates a linear relationship between the rapid load burst strength after it has been held at a lower pressure for a length of time.
5. This hypothesis can also be used to predict the burst pressure of a vessel after a history of loading.

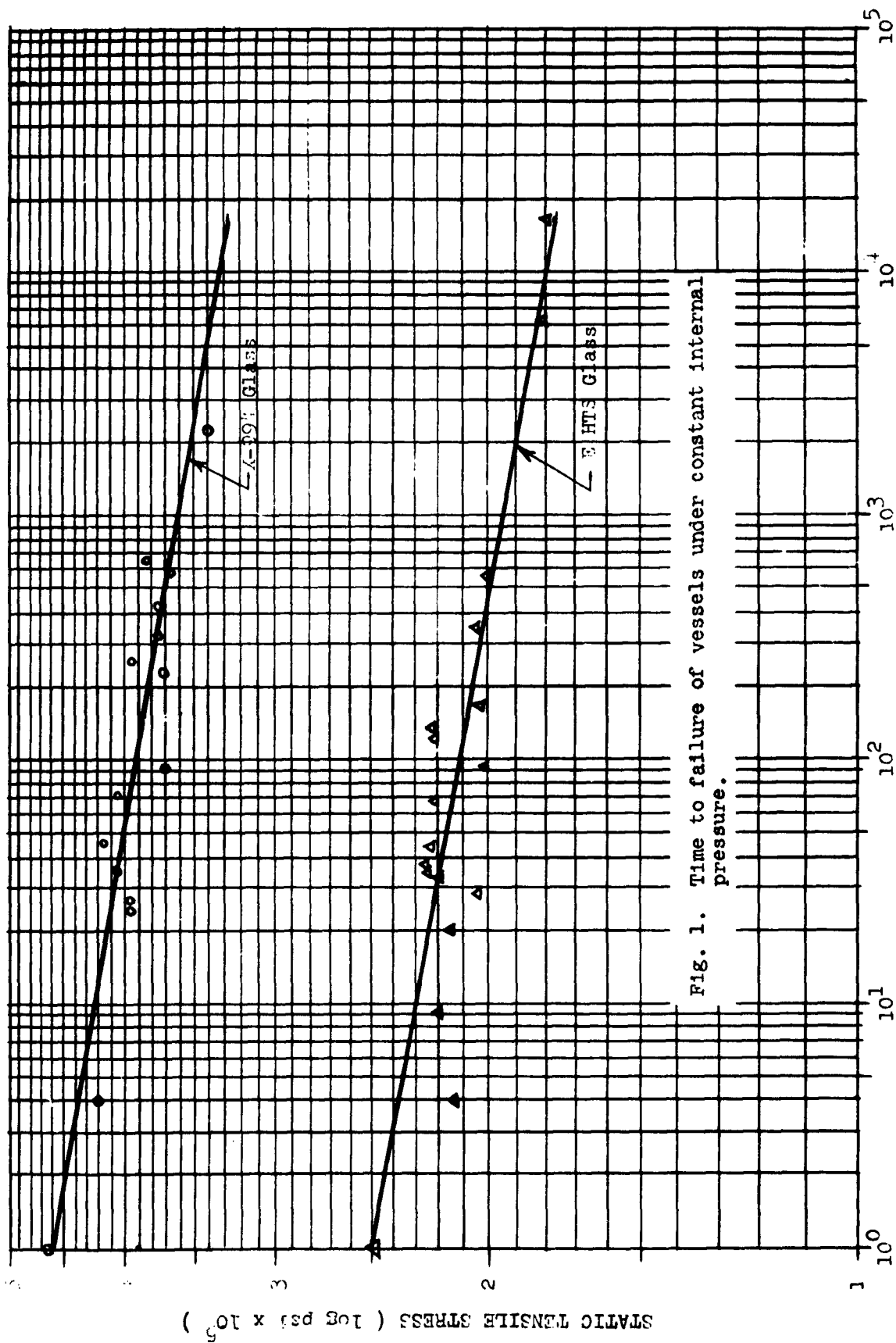


Fig. 1. Time to failure of vessels under constant internal pressure.

TIME TO FAILURE (log seconds)

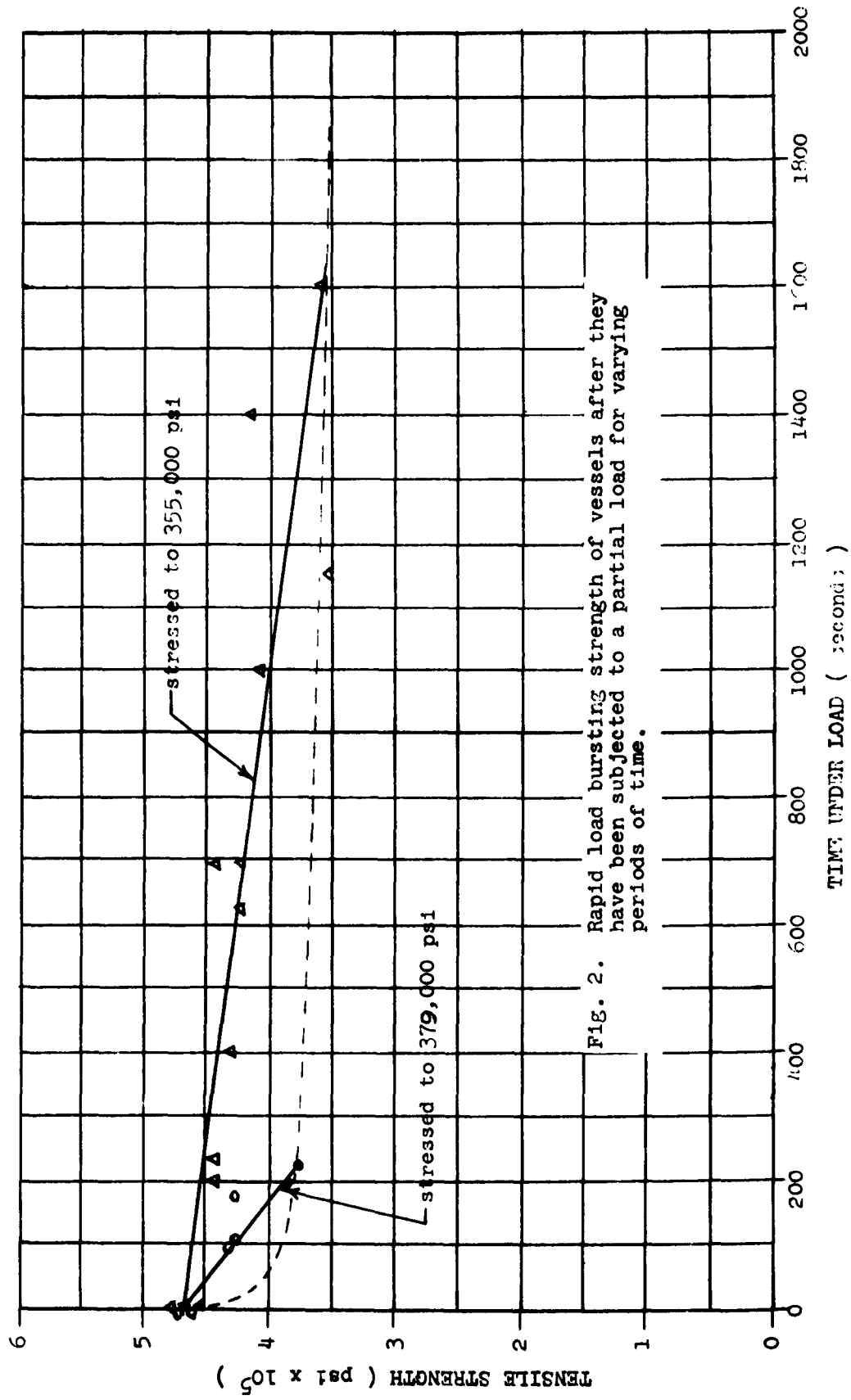


Fig. 2. Rapid load bursting strength of vessels after they have been subjected to a partial load for varying periods of time.

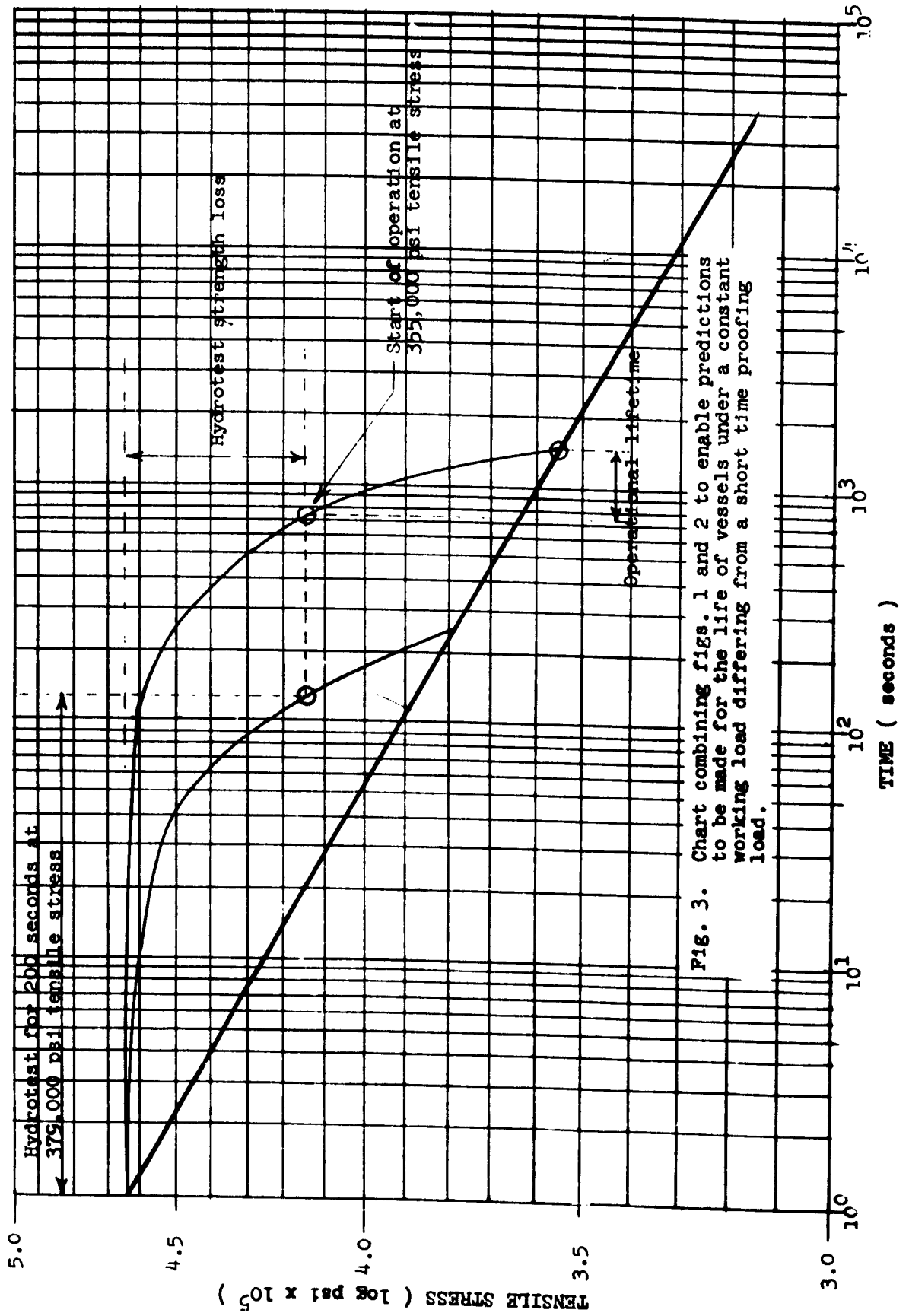


Fig. 3. Chart combining figs. 1 and 2 to enable predictions to be made for the life of vessels under a constant working load differing from a short time proofing load.