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ATOMIC ENERGY OF CANADA LIMITED

L'ENERGIE ATOMIQUE DU CANADA, LIMITEE

FAILURE MAPS FOR INTERNALLY PRESSURIZED Zr-2.5% Nb PRESSURE TUBES WITH CIRCUMFERENTIAL TEMPERATURE VARIATIONS

CARTES DE RUPTURE POUR LES TUBES DE FORCE DE Zr-2,5% Nb SUBISSANT UNE PRESSION INTERIEURE ET DES VARIATIONS DE TEMPERATURE CIRCONFERENTIELLE

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RÉSUMÉ

Au cours de certains accidents de perte de caloporteur, il se pourrait que la température des tubes de force s'élève avant que la pression intérieure ne baisse et qu'il en résulte un gonflement de ces tubes. La température règnant sur la circonférence des tubes serait probablement uniforme et produirait une déformation localisée pouvant peut-être entraîner la rupture. On s'est servi du programme d'ordinateur GRAD pour déterminer la distribution de température circonférentielle nécessaire pour provoquer la rupture d'un tube de force de Zr-2,5% Nb subissant une pression intérieure avant qu'il n'entre en contact complet avec le tube de cuve correspondant. On a utilisé ces résultats pour établir des cartes de rupture.

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ABSTRACT

During some postulated loss-of-coolant accidents, the pressure tube temperature may rise before the internal pressure drops, causing the pressure tube to balloon. The temperature around the pressure tube circumference would likely be nonuniform, producing localized deformation that could possibly cause failure. The computer program, GRAD, was used to determine the circumferential temperature distribution required to cause an internally pressurized Zr-2.5% Nb pressure tube to fail before coming into full contact with its calandria tube. These results were used to construct failure maps.

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1. INTRODUCTION

In CANDU™ nuclear power reactors, pressure tubes are the primary heat-transport containment. During some postulated loss-of-coolant accidents, coolant flow through the pressure tubes would be reduced, causing the temperature of the fuel and pressure tubes to rise. As it is unlikely that the temperature would remain uniform around the pressure-tube circumference, any resulting deformation would be nonuniform. A computer program, GRAD, was developed to predict this nonuniform deformation [1], since any pressure-tube deformation will influence the heat transfer from the fuel to the moderator, which is a large heat sink [2]. This computer program uses transverse creep equations that were developed for cold-worked Zr-2.5% Nb pressure tubes [3]. Both the creep equations and GRAD have been thoroughly tested [4,5] and GRAD successfully predicted the nonuniform deformation and failure of sections of internally pressurized Zr-2.5% Nb pressure tubes with circumferential temperature variations.

In a CANDU nuclear reactor, the calandria tubes are concentric with the pressure tubes, and, under normal operation, garter springs maintain a gas insulation gap between the tubes. During a postulated loss-of-coolant accident, if the pressure-tube temperature rose sufficiently before the internal pressure dropped, the pressure tube would balloon. If the temperature around the pressure tube was uniform, the pressure tube would not rupture before reaching an average transverse creep strain of 0.18, at which point it would be in full contact with the calandria tube. But if there was a large temperature variation around the pressure tube causing the creep strain to be localized, the pressure tube could rupture before coming into full contact with the calandria tube. The sequence of events that would occur depends on whether or not the pressure tube fails before contacting the calandria tube. Thus, GRAD was used to determine the temperature distributions that would cause a ballooning pressure tube to rupture before reaching an average transverse creep strain of 0.18. These results were used to construct failure maps for Zr-2.5% Nb pressure tubes, which can be used as a guide in the analysis of postulated loss-of-coolant accident scenarios.

2. ANALYSIS

The temperature distribution around the pressure tube during a postulated loss-of-coolant accident is not well defined. Thus, the following equation for the temperature distribution is used:

$$T(t) = T_o + Rt + \Delta T \left(\frac{1 + \cos\theta}{2}\right)^m \tag{1}$$

where T_o is the initial temperature at the coldest point (°C), R is the temperature ramp rate (°C/s), t is the time (s), ΔT is the temperature difference across the tube (°C), θ is the angular distance from the hottest point, and m is an arbitrary integer. By varying m, the shape of the tem perature distribution around the tube can be varied, as shown in Figure 1. In this figure $\left(\frac{1 + \cos\theta}{2}\right)^m$ is plotted for m = 1 and m = 5. With m = 1 the temperature varies gradually from $T_o + Rt + \Delta T$ at $\theta = 0°$ to $T_o + Rt$ at $\theta = 180°$. But with m = 5, the temperature varies from $T_o + Rt + \Delta T$ at $\theta = 0°$ to $T_o + Rt$ at about $\theta = 120°$. Thus, increasing m decreases the width of the hot region. For this analysis, m = 1 or m = 5 were used for the temperature distribution. The value of T_o was taken to be $T_o = 500 - \Delta T$ (°C). This value of T_o was chosen so that the creep rate at the maximum initial temperature (500°C) was small, even at the largest internal pressure (10 MPa).

The computer model, GRAD, has lower and upper bound failure criteria. For the lower bound failure criterion, it is assumed that the pressure tube initially had an axial scratch at the position of maximum creep strain (usually the hottest point), and failure occurred by necking to zero wall thickness at this scratch. The local transverse creep strain at which failure occurs is [1,4,6]

$$\varepsilon_f = -\frac{1}{n}\left\{\ln 1 - \left[\frac{W_o - d}{W_o}\right]^n\right\} \qquad (2)$$

where W_o is the initial wall thickness, d is the depth of the defect, and n is the stress exponent for creep. For this analysis it was assumed that the scratch depth, d, was 0.075 mm, which is the maximum allowable scratch depth in an as-received Zr-2.5% Nb pressure tube [7]. For the upper bound failure criterion, it is assumed that there were initially no defects, and failure occurred when the tube necked down to zero wall thickness at the point of maximum creep strain [1].

For the temperature distribution given by Equation (1), failure maps were constructed. The internal pressure was held constant, and GRAD was used to determine the required ΔT for the lower and upper bound failure criteria to occur at an average transverse creep strain of 0.18. As the maximum temperature ramp rate of a pressure tube during a loss-of-coolant accident is about 50°C/s, ramp rates of 1°C/s, 10°C/s and 50°C/s were used. Internal pressures were varied from 1 MPa to 10 MPa.

3. FAILURE MAPS

Failure maps with m = 1 and temperature ramp rates of 1°C/s, 10°C/s and 50°C/s are given in Figures 2-4, and failure maps with m = 5 and the same temperature ramp rates are given in Figure 5-7. The bottom line gives the conditions when the lower bound failure criterion occurs, when the average transverse creep strain is 0.18. Thus, for any point below this line, the pressure tube is unlikely to fail before coming into full contact with the calandria tube. The top line gives the conditions when the upper bound failure criterion occurs, when the average transverse creep strain is 0.18. Thus, for any point above this line, the pressure tube will probably fail before coming into full contact with the calandria tube.

The lower bound failure criterion assumes there is a scratch at exactly the same position as the maximum creep strain. Unless the pressure tube becomes badly scratched in service, it is unlikely that there would be a scratch at the position of maximum creep strain. Thus, the lower bound failure criterion is extremely conservative. In all the experiments, in which internally pressurized sections of Zr-2.5% Nb pressure tube with a circumferential temperature gradient ruptured, the failure occurred close to the upper bound failure criterion [5]. Thus, the top curve (the upper bound failure criterion) is the most likely dividing line between failure and no failure of pressure tubes, before reaching an average transverse creep strain of 0.18, and the bottom line is a conservative lower bound.

The creep rate of Zr-2.5% Nb varies exponentially with temperature. Thus, when the temperature of an internally pressurized Zr-2.5% Nb pressure tube, with a temperature gradient, is ramped, very little creep strain occurs until just before failure. Then the creep rate in the hottest region accelerates rapidly and most of the deformation occurs in the hottest region near the temperature at which the failure occurs. Thus, to rupture an internally pressurized pressure tube that has a constant temperature ramp rate, the temperature of the hottest point must be high enough to cause the tube to neck down to zero wall thickness. Because of this second requirement for rupture, the temperature at the hottest point when failure occurs at an average transverse creep strain of 0.18 is also plotted in Figures 2-7. This temperature is for the upper bound failure criterion, but there is little difference in temperature at failure, for the two failure criteria. Thus, if the temperature ramp of an internally pressurized Zr-2.5% Nb pressure tube is stopped before the temperature at the hottest point reaches this critical temperature for failure, and the tube is cooled quickly, the tube will not fail.

Consider a pressure tube that, according to the failure maps, has a temperature distribution that is severe enough to cause failure before reaching an average transverse creep strain of 0.18, but the temperature ramp is stopped before the hottest point reaches the critical temperature for failure. If the temperature distribution then remains constant, the tube will continue deforming, and it will eventually fail before reaching an average transverse creep strain of 0.18. The time to failure depends only on the temperature of the hottest point and the internal pressure. The times to failure for a tube with a constant temperature distribution were calculated, and the results are plotted in Figure 8. This figure can be used to analyze scenarios in which a pressure tube has a severe temperature gradient but the temperature ramp stops before the hottest point reaches the critical temperature for failure.

The failure maps (Figure 2 to 7) show a number of interesting facts. First, as expected, with $m = 5$ the ΔT required for failure before reaching an average transverse strain of 0.18 is much lower than with $m = 1$. With $m = 5$ the hot region is much narrower, causing the creep strain to be more localized, and causing failure to occur with a smaller ΔT. Secondly, the ΔT required for failure increases with decreasing pressure. A lower pressure causes the stress exponent, n, ($n = (\partial\varepsilon/\partial\sigma)_T$) to decrease, because the stress exponent decreases with both decreasing stress and increasing temperature. A lower value of the stress exponent causes less strain localization when there are temperature gradients, and consequently increases the ΔT required for failure. Thirdly, the ΔT required for failure increases with increasing temperature ramp rate. With higher temperature ramp rates, the creep strain and failure occur at higher temperatures, which causes the creep strain to occur with a lower stress exponent increasing the ΔT required for failure.

In the extreme case, when the temperature ramp rate is high and the internal pressure is low, the maximum temperature could rise to well above 850°C. This would cause a change in the creep mechanism at the hot spot due to a phase change [3], and the creep rate actually would decrease at the hottest point, even though the temperature would still be increasing. This would cause a very large ΔT required for failure.

Lastly, the maximum temperature at failure increases with increasing temperature ramp rate. But, with the same temperature ramp rate, the maximum temperature at failure is the same with $m = 1$ and $m = 5$. Thus, the maximum temperature at failure depends on the temperature ramp rate, but not on the temperature distribution.

4. CONCLUSIONS

Failure maps were constructed for two different temperature distributions, and three different temperature ramp rates. It was assumed that the internal pressure and temperature ramp rates were constant. These maps can be used as an aid to determine whether a ballooning pressure tube, with a circumferential temperature gradient, would fail during a postulated loss-of-coolant accident.

During some postulated loss-of-coolant accidents, the pressure tube may have a temperature distribution that is severe enough to cause the pressure tube to rupture before coming into full contact with its calandria tube, but the temperature rise is stopped before the hottest spot reaches the critical temperature for rupture. The time to failure for this case was determined as a function of the temperature of the hottest spot and the internal pressure.

ACKNOWLEDGEMENTS

The computer program GRAD was developed using creep data for Zr-2.5% Nb pressure tubes that were obtained under a CANDEV funded program.

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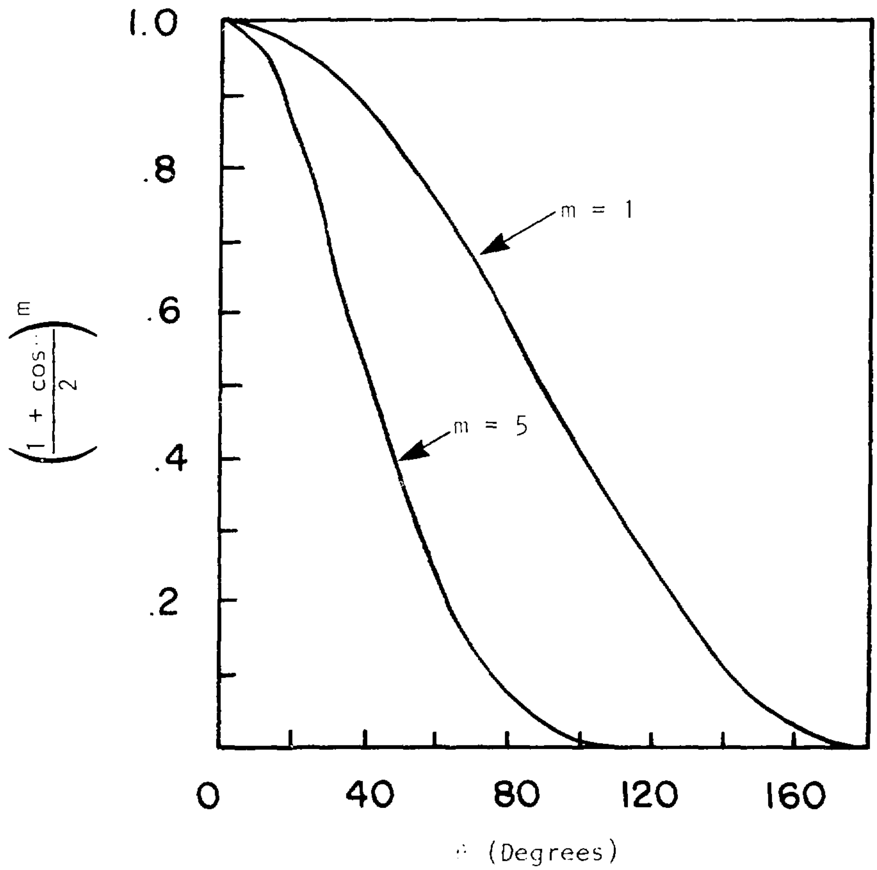

FIGURE 1: Temperature Distribution with m = 1 and m = 5

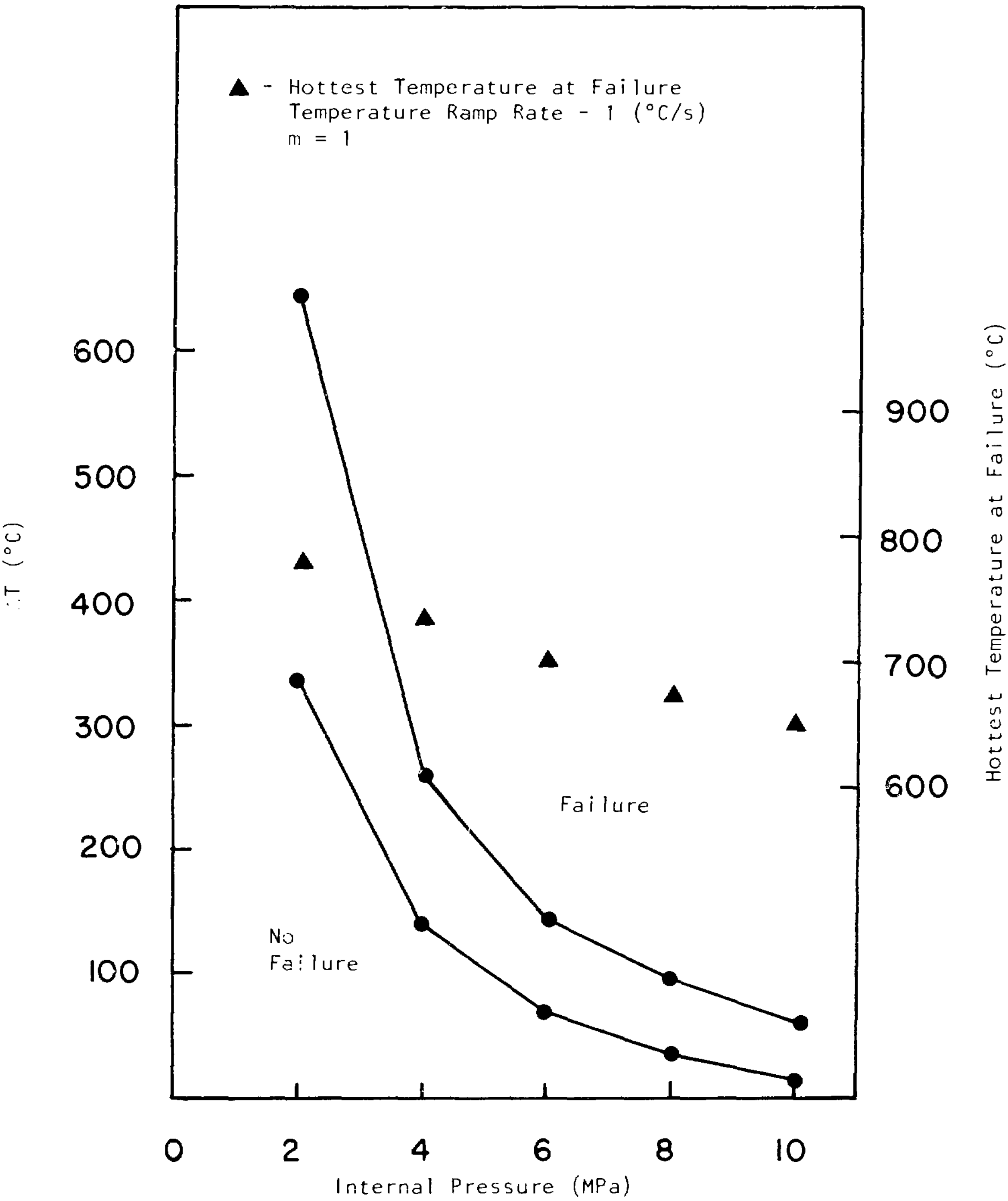

FIGURE 2: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 1°C/s and m = 1

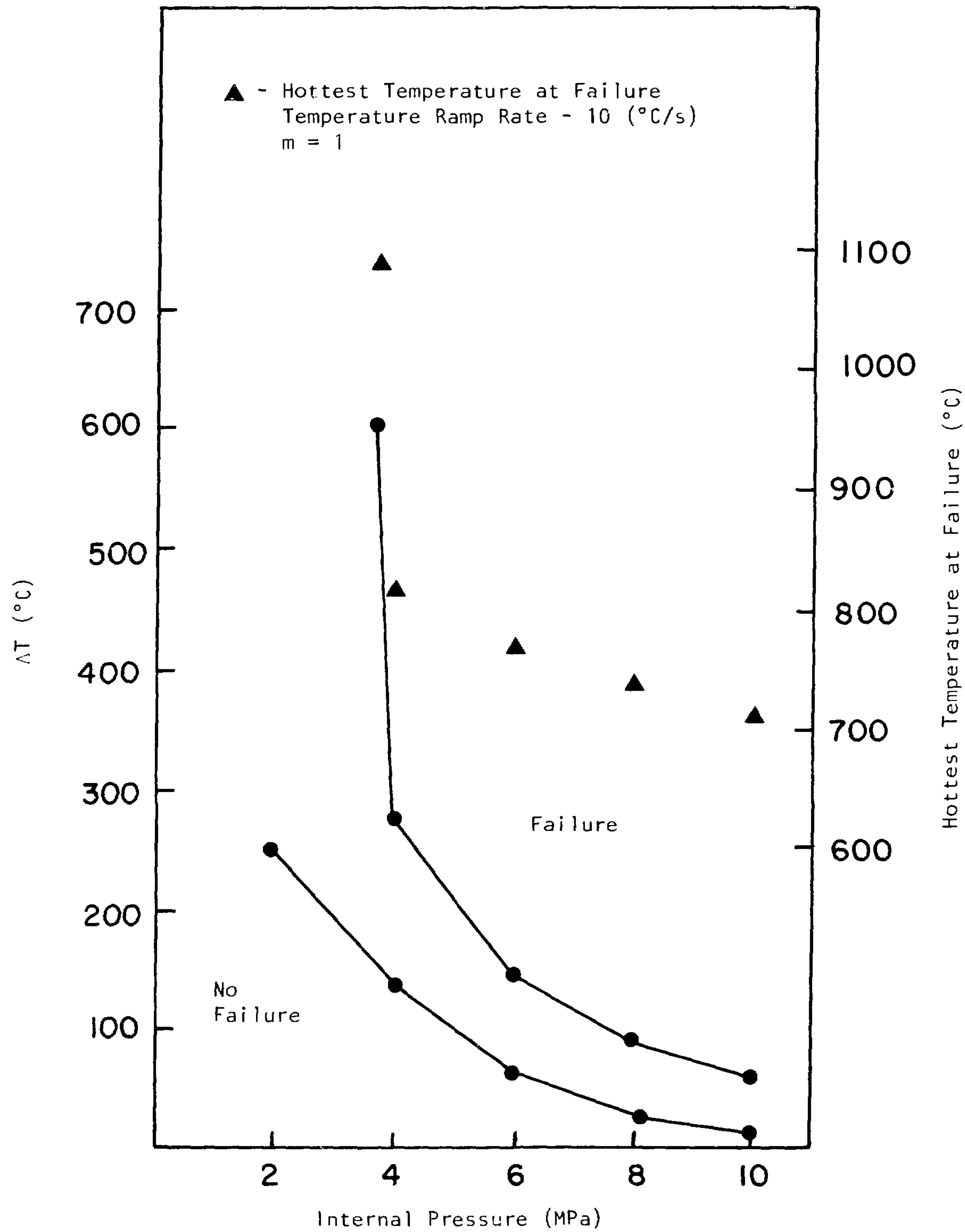

FIGURE 3: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 10°C/s and m = 1

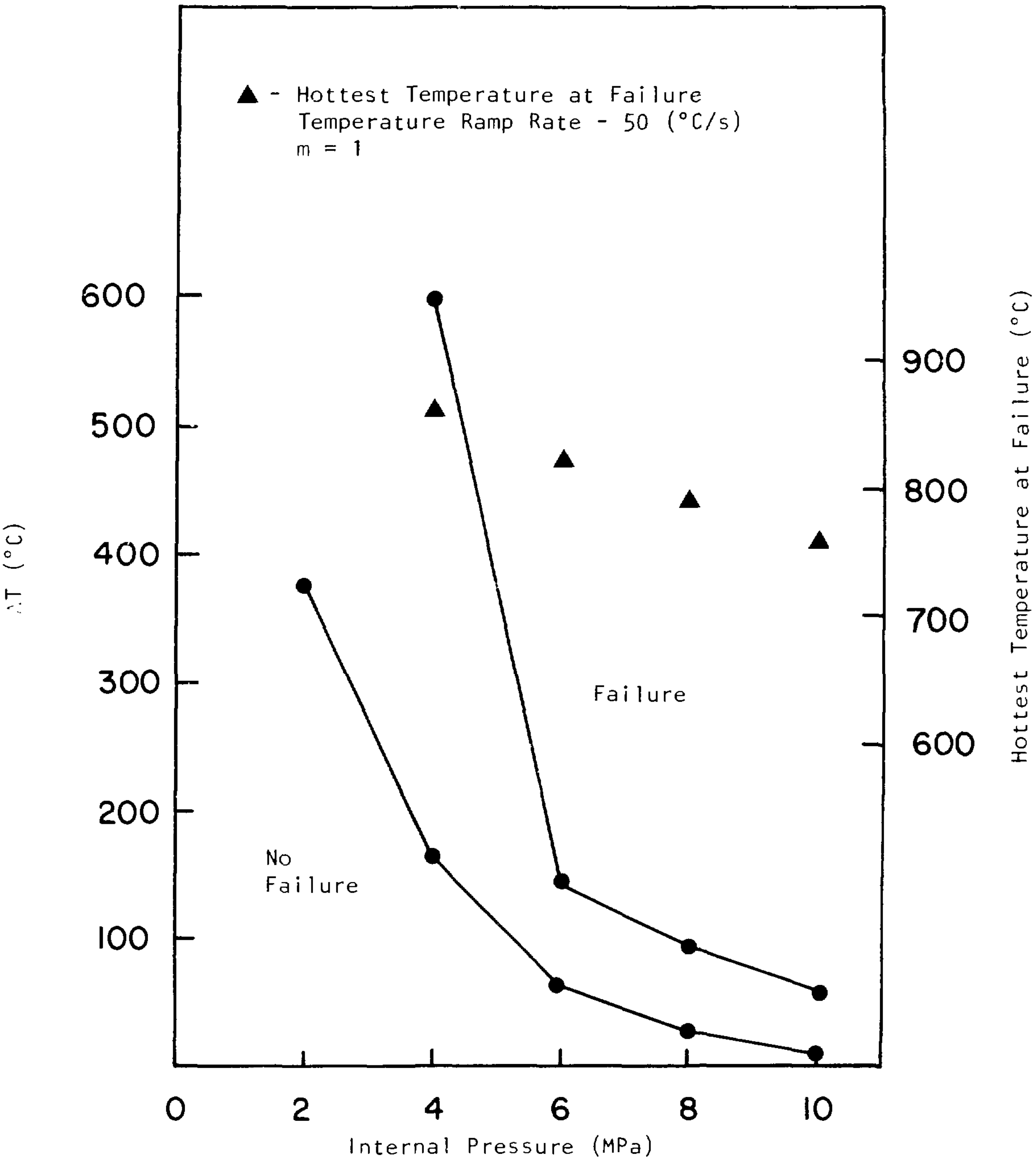

FIGURE 4: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 50°C/s and m = 1

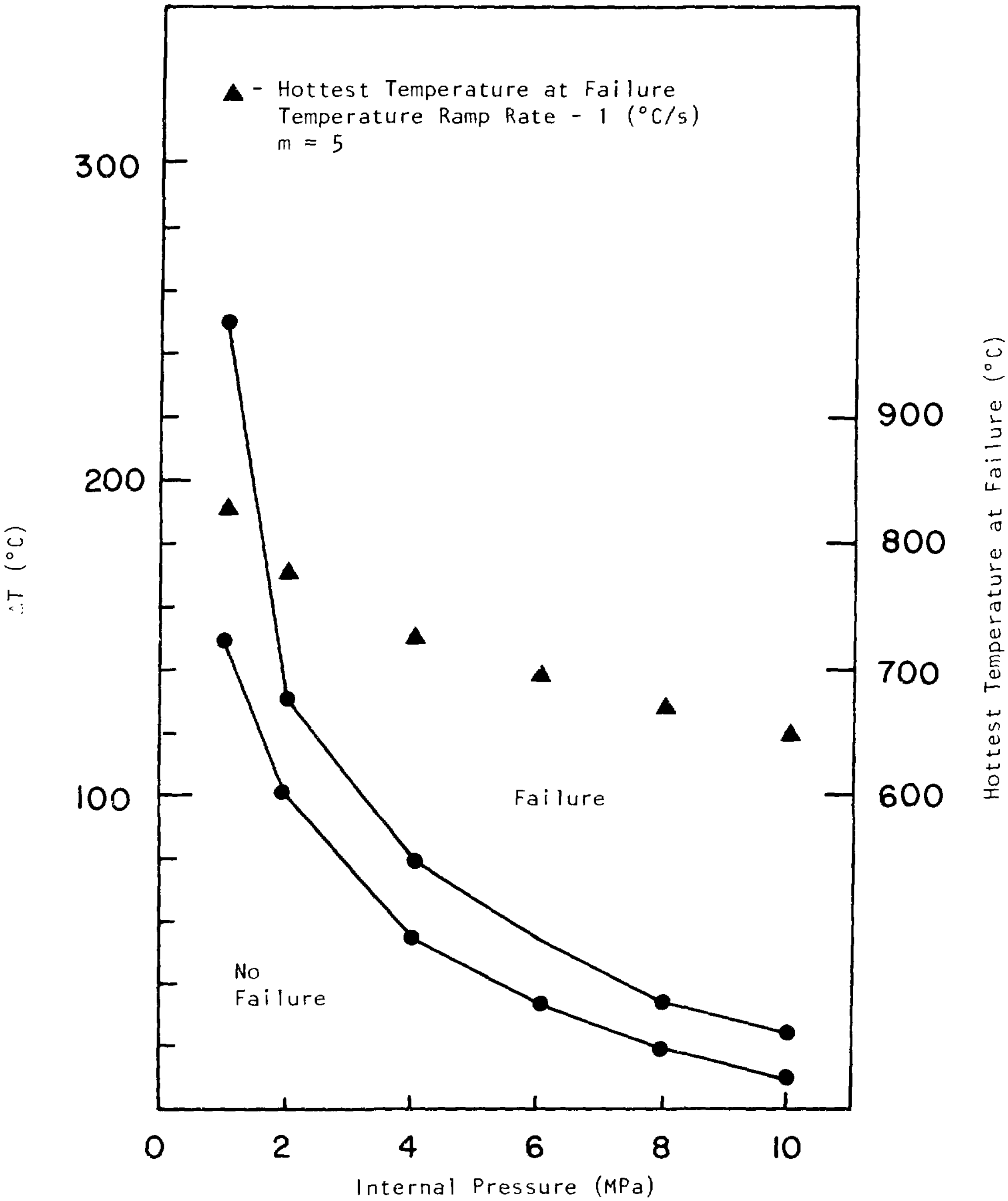

FIGURE 5: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 1°C/s and m = 5

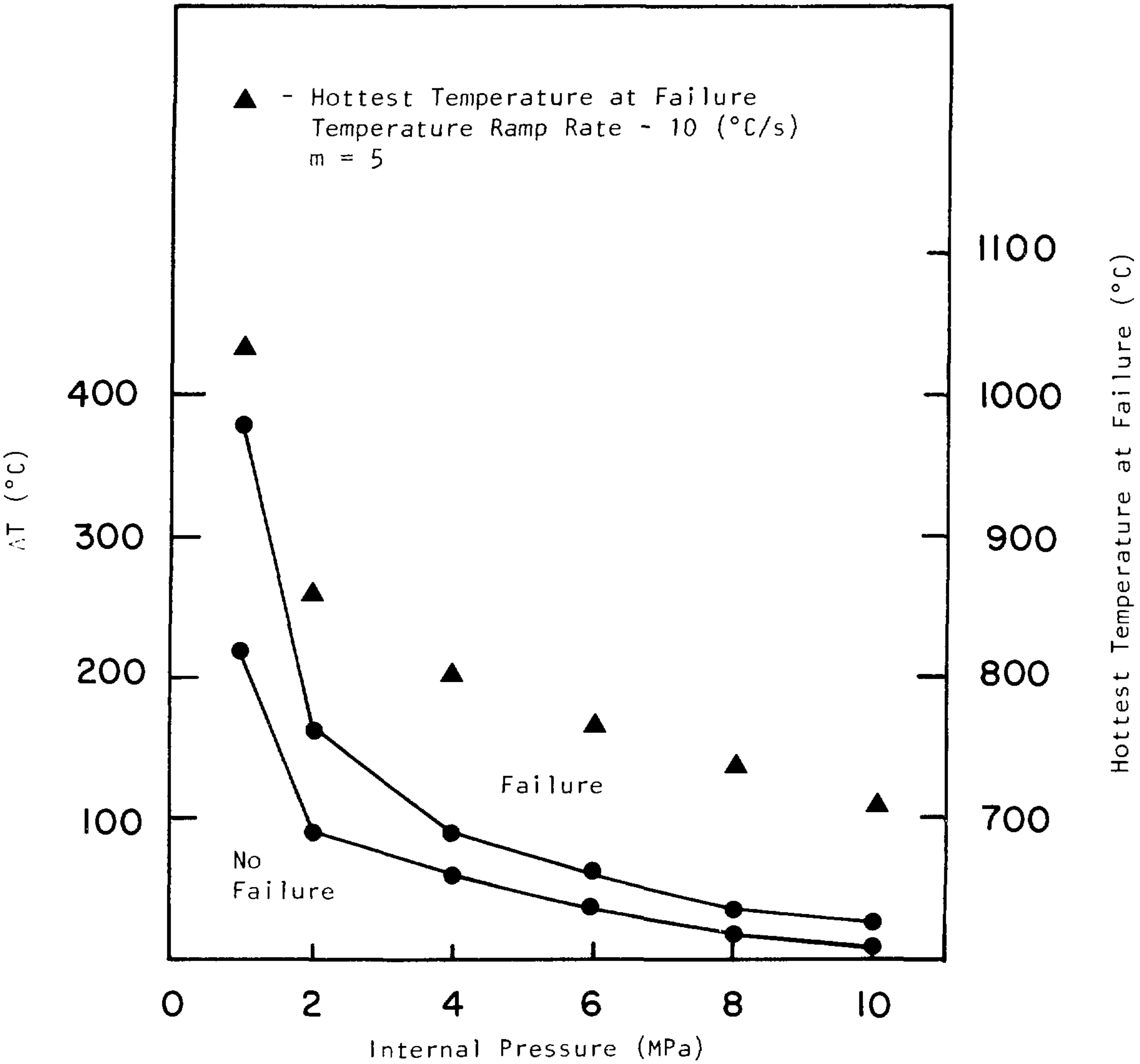

FIGURE 6: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 10°C/s and m = 5

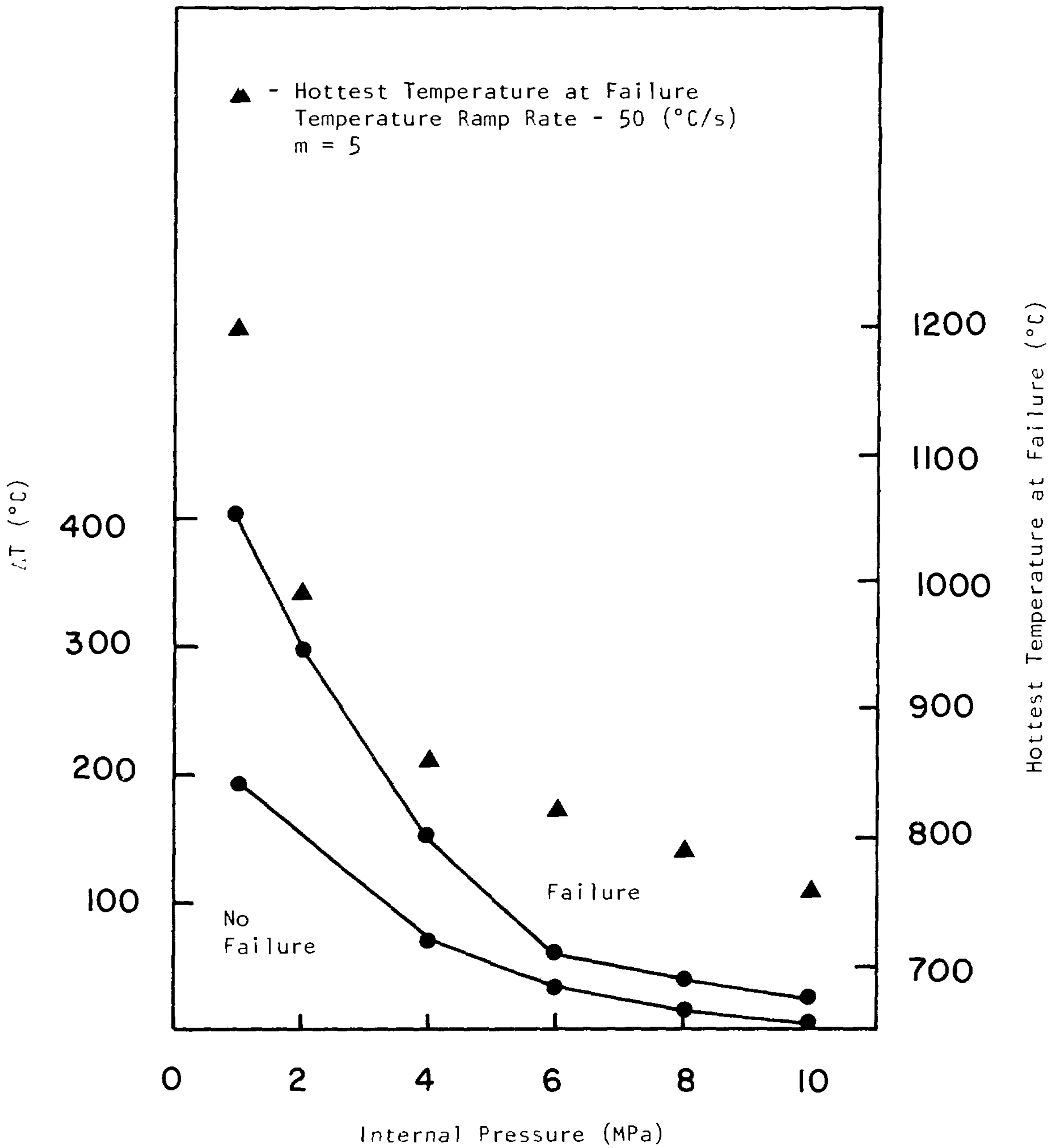

FIGURE 7: Failure Map for Zr-2.5% Nb Pressure Tubes with a Temperature Ramp Rate of 50°C/s and m = 5

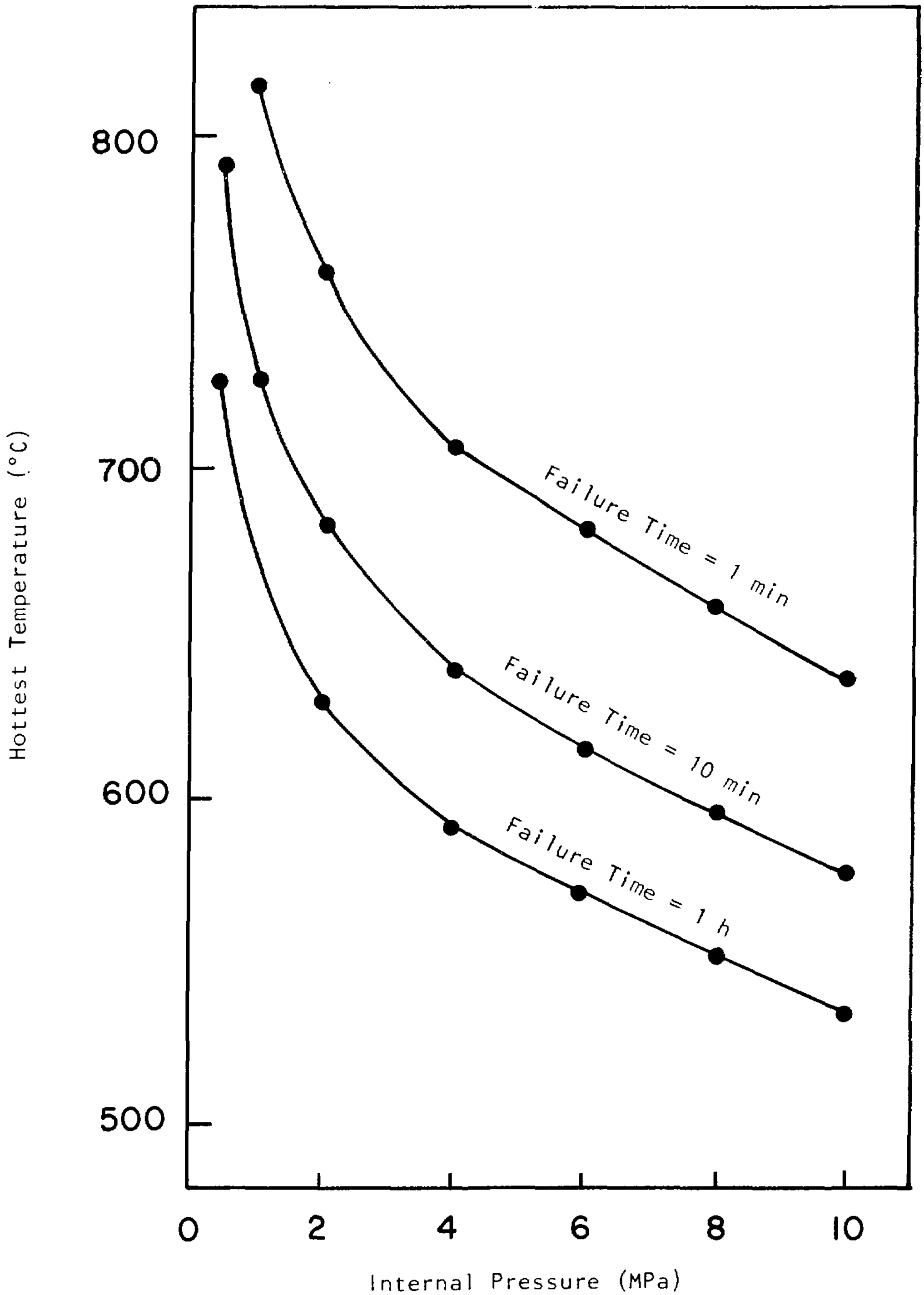

FIGURE 8: Failure Times for an Internally Pressurized Zr-2.5% Nb Pressure Tube with a Severe Temperature Distribution That Would Cause Failure Before an Average Transverse Strain of 0.18 is Reached. *The temperature distribution does not vary with time.*

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