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College of Engineering

Department of Mechanical Engineering

Cavitation and Multiphase Flow Laboratory

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EFFECTS OF PRESSURE AND TEMPERATURE VARIATION IN VIBRATORY CAVITATION DAMAGE TEST

BY: Frederick G. Hammitt

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ABSTRACT

Vibratory cavitation damage tests (20 kHz, 2 mil double amplitude) have been conducted in water on SAE-660 bronze, over the temperature range 55^{o}F to 250^{o} F and with 1 to 4 static NPSH supplied by variation in cover gas pressure. The effects upon damage of variation of temperature at constant static NPSH and variation of static NPSH at constant temperature are presented. Observations on the possible effects of gas content are included, and a full comparison with the existing literature is made in all respects.

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I. INTRODUCTION

Cavitation damage is encountered with almost any liquid pressure or temperature, and in many cases of present-day importance, with fluids other than water. Laboratory tests, however, must use experimental facilities which are usually standardized to their own most appropriate test conditions. In the case of the conventional vibratory facility, e.g., the test fluid is usually water at approximately room temperature. The pressure, when the horn is not operating, is usually one atmosphere, but the liquid pressure seen by cavitation bubbles during their life cycle is in the form of an approximately half sine wave giving a maximum collapse pressure of many atmospheres. The precise value differs according to the facility, since it depends upon frequency and amplitude. The gas content, another important parameter, is usually an equilibrium value characteristic of the vibrating horn in an open beaker, and somewhat less than the saturated content for one atmosphere at the water temperature. The gas content in field conditions can have any value depending upon many parameters.

In any laboratory test there are unavaidable minor variations of pressure, temperature, and gas content. Hence, to achieve precise and repeatable results from laboratory tests it is necessary to know the magnitude of the effect of such variations. A recent study conducted in various laboratories under the guidance of ASTM (1) has done much to help in this regard. However, even more important, in order to use laboratory data to predict field results, it is necessary to investigate effects upon cavitation damage of variations in pressure, temperature, and gas content from the test conditions. Such a study will also assist in increasing the basic understanding of cavitation damage mechanisms, and is important for this reason. The present paper concerns the effects upon damage of pressure and temperature variation in a relatively conventional vibratory facility, and will hopefully provide some of the still required information.

Very briefly, it is to be expected that the variation of pressure and temperature will affect cavitation damage through several mechanisms, which are more or less important in different cases, e.g.:

1. Change in fluid-dynamic behavior due to change in effective NPSH seen by bubbles.
2. "Thermodynamic" effects upon bubble growth and collapse due to the fact that the growth and collapse begin to vary significantly from isothermal behavior as the temperature is raised.
3. Change in dissolved gas content due to temperature variation.
4. Change in material properties due to temperature variation.

II. EXPERIMENTAL PROGRAM

A. Experimental Facility

The vibratory horn used for these tests is mounted by an "0" ring arrangement into a sealing flange so that the gas space between liquid surface and flange can be pressurized as desired. The tank containing the cavitating fluid is mounted into a heating tank in which cooking oil was used as a heat transfer fluid to maintain the cavitating fluid at the required temperature. The arrangement is shown schematically in Fig. 1. The horn, transducer, and driver are commercial units* providing a nominal 2 mil double amplitude at 20 kHz. The correlation between horn amplitude and power setting to the unit was frequently checked using a Fotonic Sensor.**

Distilled water was used for all the tests with pH $\sim$ 7.4. Typical measurements for cold water tests indicate a gas content somewhat less than saturation. No measurements were made in the hot water tests, but it is presumed from previous measurements on cold water tests that after a few minutes of cavitation, the gas content would be reduced to somewhat less than saturation for the test temperature. Thus the total gas in the high temperature tests would be substantially less than for the room temperature tests, though the entrained portion might be relatively greater due to dissolution effects during the heating process. This variation in gas content may have had some influence on the test results, though recent tests by Hobbs (2) indicates that at least for cold water the effect of total gas content variation over most of the subsaturated range is small. For future tests of this type a facility modification should be made so that tests at constant gas content over a range of temperature variation could be made.

All test specimens were of SAE 660 bronze. Its room temperature mechanical properties, as measured in our laboratory, are listed in Table I. The temperature range employed (55-250°F) is not enough to cause significant variation in these properties, and corrosion should be negligible. Hence no variation due to these factors need be considered.

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*Sonifier Converter Model J, Branson Instruments, Inc.

**Fotonic Sensor Model KD-38, Mechanical Technology, Inc.

Table I - Properties of Test Material (SAE 660 Bronze)

Yield Strength = 24.3×10^3 psi (Y.S.)

Tensile Strength = 45.2×10^3 psi (T. S.)

Hardness = 1890 BHN

Elastic Modulus = 12.8×10^6 psi (E)

Elongation = 23 %

Area Reduction = 25%

B. Tests Performed

The tests were divided into constant temperature sets for varying NPSH* and constant NPSH sets for varying temperature. Common parameter conditions were used in evaluating the effect of these two primary variables, but the matrix of conditions was not completely filled. Table II shows the conditions used. Four temperatures, ranging from 55 to 250°F and selected for approximately equal vapor differentials, and four NPSH values** (~35 -144 ft.) were used. A total of 9 separate parameter combinations was tested, using 17 specimens. Thus in most cases the results are the average of two specimens. All tests were continued to at least 60 minutes. MDP*** after 60 minutes was used in the curves to show effects of NPSH and temperature variation. In addition, maximum damage rates (MDPR****) were computed (Table 3) for each of the 9 parameter conditions. The individual curves are typical for our facility, showing an increasing weight loss rate up to a maximum which usually persists over a reasonable duration, followed by a falling rate. Fig. 2 is a typical weight loss and MDP vs. time curve.

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*NPSH = (pressure above vapor pressure)/density; horn static.

**Since suppression pressure was actually maintained constant for runs at different temperature, NPSH for these runs varies slightly due to slight changes in density.

***MDP = Mean depth of Penetration = (volume loss)/(specimen face area).

****MDPR = MDP rate.

No runs were made for pressures greater than that required for 4 atm NPSH at 250°F (73.9 psig) because of erratic horn operation at this condition, and limitations in vessel strength. It is likely that the horn will become power limited at sufficiently high NPSH. As NPSH is increased, cavitation occurs during a decreasing portion of the negative pressure part of the sine wave, so that a larger portion of the full ideal sine wave is realized. The power requirement is thus larger. It is not certain that this difficulty was responsible for the erratic behavior observed at 4 atm. NPSH.

For all tests the horn was operated at 2 mil double amplitude and 20 kHz. A power meter was used for measuring amplitude, but it was frequently checked with the Fotonic Sensor.

C. Experimental Results

Fig. 3 shows weight loss (and MDP) vs. duration with the 4 temperatures as curve parameters at 1 atm (nominal) NPSH. The 55 and 250° F curves are nearly identical, as are the 150 and 230°F curves, although the terminal MDP for the intermediate temperatures are about twice those for the extreme temperatures. Fig. 4 is similar with nominal NPSH as curve parameter; all tests at 150°F. Fig. 5 is analogous to Fig. 4, but for 250°F. For both of these figures, there is a strong increase in terminal MDP, and rate, for increase in NPSH. However, the rate of increase is reduced between 3 and 4 atm. NPSH at 250°F (4 atm. data was not obtained at 150°F).

The same results can be consolidated in a manner more suitable for showing the overall pattern if 60 min. MDP values (i.e. average MDPR for a one hour test) are used rather than complete MDP vs. time curves. The maximum rates could be used as well, although for practical purposes the average rate may be more meaningful. Fig. 6-9 are plots of this type. Fig. 6 is a composite curve showing average one hour MDPR as a function of temperature (vapor pressure also shown as abscissa) with nominal NPSH as curve parameter. An open-beaker curve is included for comparison. The shape of this curve was taken from data previously generated in our laboratory using a 304 stainless steel specimen (Fig. 10). The stainless steel data was normalized to coincide with that from the 1 atm. NPSH SAE-660 test of the present series at the maximum damage temperature of the open beaker test (about 120 ^{o}F). This is reasonable, assuming the specimen material does not affect the curve shape, since at this temperature the vapor pressure is almost negligibly small. Thus NPSH values for the two tests are about the same (34 vs. 30.4 ft.). A comparison of the open-beaker test with that for 1 atm. nominal NPSH (for which the curve is reasonably well defined with 4 data points) shows that the open-beaker and constant NPSH curves are of similar shape, with the maximum damage point occurring at a higher temperature for the constant 1 atm. NPSH curve (about 190 ^{o}F vs. 120 ^{o}F). Although only 2 data points each exist for the 2 and 3 atm. nominal NPSH curves, and one point for the 4 atm. curve, it is assumed that their shapes are similar. The curves are drawn to indicate an increasing maximum damage temperature for increasing NPSH. This assumption is made on the theoretical grounds that the thermodynamic restraints, which increase with temperature, would become relatively less important as the collapsing head seen by the bubbles (increases with NPSH) is increased. This curve shape is also consistent with our available data points, as well as most of the curves of Peters and Rightmire (9) at constant pressure.

Fig. 7 is entirely analogous to Fig. 6 except that the abscissa is proportional to vapor pressure instead of temperature (which is also shown along the abscissa). Since the bubble collapse pressures and velocities are a direct function of pressure rather than temperature, this seems a logical method of presentation. The curves do indeed appear better behaved when plotted in this fashion, giving a better basis for extrapolation to higher vapor pressures and temperatures.

Fig. 8 shows average MDPR as a function of nominal NPSH (suppression pressure also shown on abscissa) for 150^{o} and 250^{o}F, the two temperatures for which sufficient data points were available. The open-beaker test point (Fig. 6 and 7) is included at its own NPSH at 150^{o}F, as part of that curve. The increase of average MDPR with increase in NPSH is approximately linear at 150^{o}F, but the rate of increase decreases somewhat as NPSH is increased. For 250^{o}F, over the whole range from 1 to 4 atm. $\Delta MDPR \propto \Delta NPSH^{1.18}$. However, the rate of increase decreases at higher NPSH. From 1 to 2 atm. the exponent is 1.62, from 1 to 3 atm., n= 1.37, and from 2 to 4 atm., it is 0.745. In all cases there appears to be a threshold NPSH of 1/4 to 1/2 atm. below which damage would be close to zero.

Fig. 9 is entirely analogous to Fig. 8 except that the average MDPR is based on the actual damaged area which decreases for increasing NPSH as discussed later. In this case the increase of damage with NPSH is more than linear in all cases. For 150^{o}F, $\Delta MDPR \propto \Delta NPSH^{1.15}$ over the whole range, and the exponent at 250^{o}F is approximately 1.27 throughout.

The changing damage patterns with NPSH and temperature are shown in Fig. 11 and 12 which are low-magnification photographs of the damaged surfaces for 150 and 250^{o}F respectively.

III. DISCUSSION OF RESULTS

A. Comparison with Previous Pertinent Results

The present paper, with the exception of Peters and Rightmire (9), is to the writer's knowledge the first publication of the results of a combined investigation of temperature and pressure effects upon cavitation damage. However, there have been several previous studies reporting upon effects of the variation of either separately.

The effect of temperature variation in an open-beaker test, i.e. constant pressure rather than constant NPSH, has been included in several papers (e.g., 3, 4, 5, 6, 7, 8, 9). Generally a curve very similar to Fig. 10 results showing a maximum damage rate at about 120 °F and monotonically decreasing damage for either higher or lower temperatures (Fig. 10 from ref. 6 is included for convenience). Two recent Russian publications (4, 5) have shown a minimum rate at a relatively low temperature (105 °F), and then an increasing rate for lower temperatures. There is a continuous decrease in damage as temperature is increased beyond the maximum damage temperature, (140 °F), as is usual. Fig. 11 shows the shape of this curve (4). A third Russian paper (8) reports a monotonic decrease in damage with temperature from about 70-200 °F. No results on temperature effect for constant NPSH (rather than constant pressure) have been previously reported to the writer's knowledge. The results of Peters and Rightmire (9) for temperature variation at constant pressure appear to show rather conflicting results.

The effect of pressure variation at a single temperature has been reported by several (e.g. 2, 9, 10, 11). With the exception of the first reported investigation of this sort, Peters and Rightmire (9), all studies have shown a strong increase of damage rate with increased pressure. In their test at 100 °C they found a complex curve which increased to a maximum, as NPSH was increased, at about 1 atm. NPSH, a minimum (factor of ~2) at 1-1/3 atm. NPSH, a second maximum (about same magnitude as first) at 2 atm., and thereafter a decrease by a factor of ~10 at 2-1/2 atm. Their facility was of the low frequency type (6.5 kHz, 3.65 mils), and hence differed substantially from the others for which results are reported (ranging from 15 to 25 kHz). No explanation for their unusual result is apparent other than through a changing balance between the countering mechanisms of increased bubble collapse intensity at higher pressures along with reduced number and size of bubbles. With a given unit it is obvious that cavitation damage will disappear for high enough pressure since no cavitation bubbles will be formed.

The present tests show that the change in MDPR is approximately proportional to the corresponding change in NPSH over the range of 1 to 4 atm. NPSH. On the other hand the tests of Hobbs (2), Plesset (10) in cold water, and Young and Johnson (11) in 800°F sodium show that damage variation is proportional to about the square of NPSH variation. This is a relatively accurate description of the Hobbs and Plesset data. However, the exponent in the Young-Johnston tests varies between about 1.0 and 2.7 depending upon the material and interval selected. In the Peters-Rightmire test (9) with 100°C water there was very little damage increase with pressure increase, but rather a decrease in a portion of the pressure range.

Another parameter which may importantly influence damage rate is gas content. It is the entrained gas portion which is presumably important, but this may in general be expected to vary with total content. Extreme range effects seem obvious. Near-zero gas would appreciably increase liquid tensile strength and reduce the number and size of cavitation bubbles, though increasing the collapse violence for those bubbles which were formed. At the other extreme, large amounts of gas would increase the number of bubbles but cushion their collapse so that little damage would be done. The above hypotheses are consistent with Hobbs tests (2) where a substantial dimunition of damage for a gas content below about 20% saturation, and a gradual dimunition as gas content is increased above about 70% saturation is indicated. Quite similar results were also found by Hansen and Rasmusssen (12) using a rotating disk apparatus.

Somewhat different results are shown in papers by Bebchuk and Rozenberg (8) and Sirotyuk(13). Tests are reported by Bebchuk using a 8 kHz magnetostrictive horn in cold water. He reports a more than ten-fold monotonic decrease in damage as gas content in increased from 10% to 100% saturation. Sirotyuk compares the damage rates for "degassed" and "ordinary" water as a function of temperature. The degassed water is always most damaging, but the ratio decreases from 4 to about 3 as temperature is raised from 20 to 80°C. In his experiment, the specimens are placed in a cavitation field generated by a 28.5 kHz transducer.

As already mentioned it is believed that the gas content in the present tests remains a fairly constant portion of saturation ($\sim$70%) at the test water temperature, which differs in the various tests. Since the solubility of gas in water decreases with increasing water temperature, the total gas content in the higher temperature tests is probably less than in those at lower temperature, though the entrained gas portion may conceivably vary inthe opposite direction. However, it is impossible to isolate the effect of gas content on damage in the present tests.

B. Additional Points Concerning Present Test Results

In the vibratory test, an increase in NPSH affects the fluid-dynamics of the cavitating regime in two ways. It decreases the extent of the bubble cloud, concentrating it toward the center of the specimen, since the pressure oscillation induced by the horn is reduced near the specimen outer radius. It also increases the driving head for bubble collapse, rendering individual collapses more damaging. The present results show a somewhat decreasingly strong increase in MDP as NPSH is increased. However, it is obvious for an individual horn that this trend could not continue to very high NPSH, since eventually the horn oscillation would not be sufficient to cavitate the fluid at all.

Fig. 11 and 12, consistent with the sodium data of Young and Johnston (11), show the increasing extent of the outer undamaged annular region as NPSH is increased in the present water tests. Additional radial damage striations, with annular regions of relatively light damage succeeding heavier damaged regions at larger radius are also shown. This feature, and the relatively periodic nature of the circumferential damage pattern, are suggestive of a very short sonic wave-length in the two phase mixture in this region.

In the present tests an increase in NPSH was brought about by an increase in pressure. In previous tests in this laboratory, the effects of NPSH variation were investigated through a change of fluid density with pressure maintained constant. For this purpose tests were conducted on fluids ranging from mercury (13.6 g/cc) to molten lithium (0.5 g/cc). As NPSH was increased in this fashion (Fig. 14) by a factor of about 27, the same effect of a concentration of damage toward the center was observed. Thus the range of NPSH variation in the density-varying tests was much greater than in the present tests, where the effective range of NPSH is really quite moderate, although its precise definition is complex. The variation in static pressure which was used (3 atm.), is only $\sim$7% of the half sine wave pressure amplitude for the 2 mil ,20 kHz operating condition ($\sim$ 43 atm.). Note that if NPSH is changed by density change, both static and oscillating portions are affected in equal proportion.

IV. CONCLUSIONS

For a typical 20 kHz, 2 mil conventional vibratory cavitation damage test in water at 150 and 250°F, it has been shown that damage rate increases about in proportion to the corresponding increase of static NPSH (measured with horn stationary) from 1 to 4 atm. NPSH. A more rapid increase of damage with increase in NPSH has been shown by Young and Johnston (11) for molten sodium, and Hobbs (2) and Plesset (10) for cold water. They show a damage increase roughly with the square of NPSH increase. This exponent varies considerably with material and NPSH interval for the sodium tests (11). In the present tests there appears to be a threshold NPSH of 1/4 to 1/2 atm., below which damage would be nearly zero. This observation is consistent with the other tests reported (2, 10, 11).

It has also been demonstrated that an increase in NPSH, brought about either by pressure increase or density decrease, causes a decrease in the radial extent of the undamaged outer rim and an accumulation of damage toward the center.

The effect of temperature increase at pressures above one atmosphere has been shown to be similar to that at one atmosphere, i.e. maximum damage at an intermediate temperature, and damage decreasing monotonically as temperature is either increased or decreased from this value. The decrease at high temperature is ascribed to the increasing importance of thermodynamic restraints on bubble collapse, but the mechanism for the decrease at low temperature is not clear. It may involve an increasing gas content at low temperature. The general existence of a monotonically decreasing damage rate for temperatures below the maximum damage temperature is disputed by two recent papers (4, 5).

An examination of previous literature indicates in general that damage decreases significantly in an atmospheric test for an increase in total gas content in the range of 70 - 100% saturation at standard temperature and pressure. There is some evidence that it also decreases for very low gas contents (2, 12), which the present writer ascribes to the increased water tensile strength under these conditions and the resulting dimunition in size and number of bubbles. The decrease at low gas content is disputed by two previous investigators (8, 13). The present tests cannot isolate gas content variations from temperature and NPSH changes.

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TABLE II - TEST CONDITIONS

Temperature T ($^\circ F$)	Vapor Pressure p_v (psi)	Vessel Pressure p (psig)	Suppression Pressure $p - p_v$ (atm)	NPSH* $\frac{p - p_v}{\gamma(T)}$ (ft.)
55	0.21	0.2	1	34.0
150	3.72	3.7	1	34.6
		18.4	2	69.3
		33.1	3	104.0
230	20.78	20.8	1	35.6
250	29.82	29.8	1	36.0
		44.5	2	72.0
		59.2	3	108.0
		73.9	4	144.0

*Suppression pressure (pressure above vapor pressure) and NPSH are different only by the factor of specific weight, $\gamma(T)$. Because the specific weight varies somewhat with temperature a constant suppression pressure does not necessarily indicate constant NPSH. It can be seen from Table I, however, that the variation is very small; and for this analysis it is ignored. The terms suppression pressure and NPSH are used interchangeably, i.e., NPSH may be given in atmospheres or feet.

TABLE III - MAXIMUM DAMAGE RATES

Condition			Peak Wt. Loss Rate	Peak MDPR
55°F	1 atm.		.73 mg/min	1.28 mil/min
150	1	(Fig. 11)	1.60	2.80
150	2	(Fig. 11)	3.95	6.94
150	3	(Fig. 11)	7.20	12.62
230	1		1.14	1.98
250	1	(Fig. 12)	.85	1.49
250	2		1.76	3.09
250	3	(Fig. 12)	5.43	9.51
250	4	(Fig. 12)	8.59	15.05

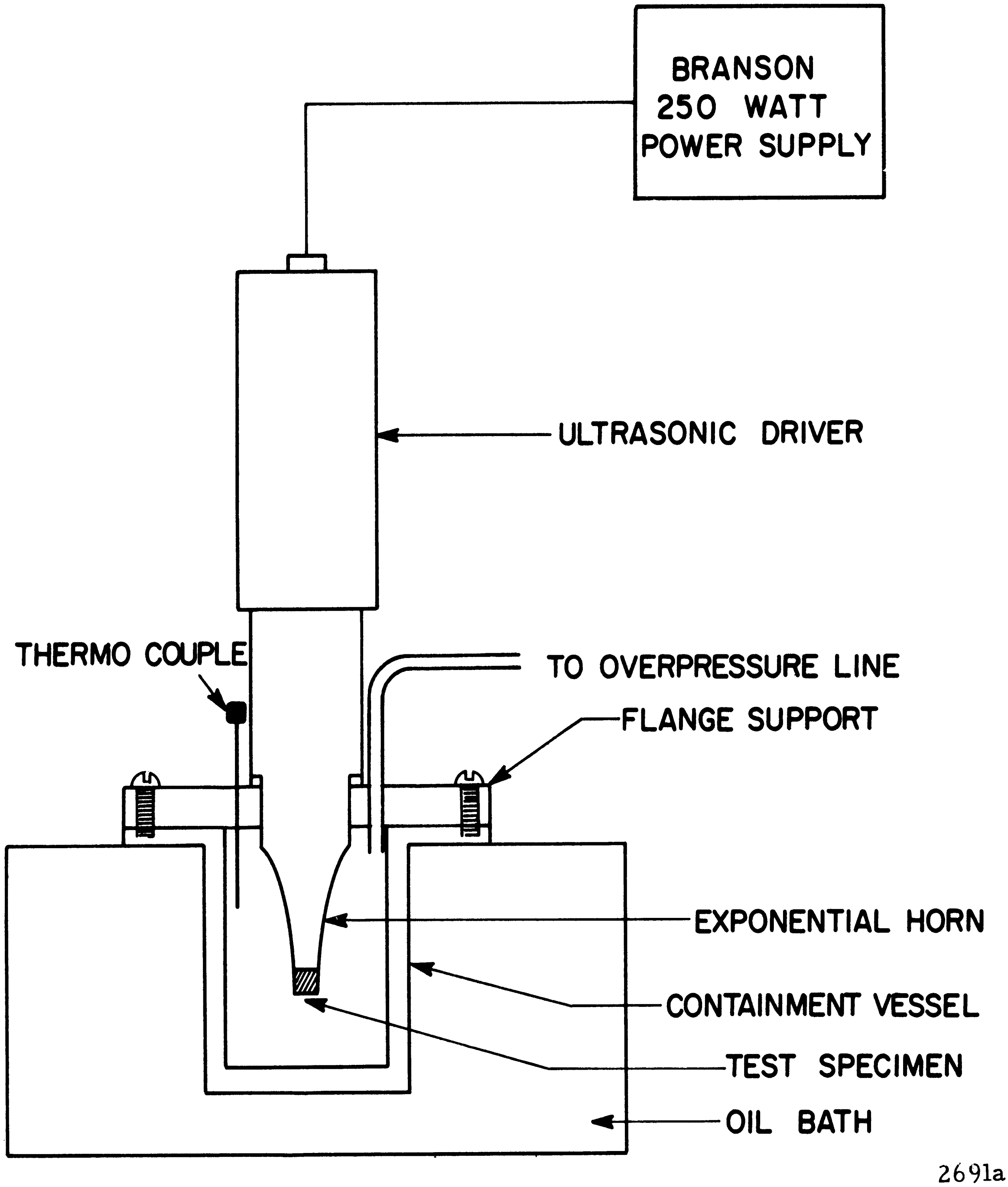


Fig. 1. Schematic of Ultrasonic vibratory horn

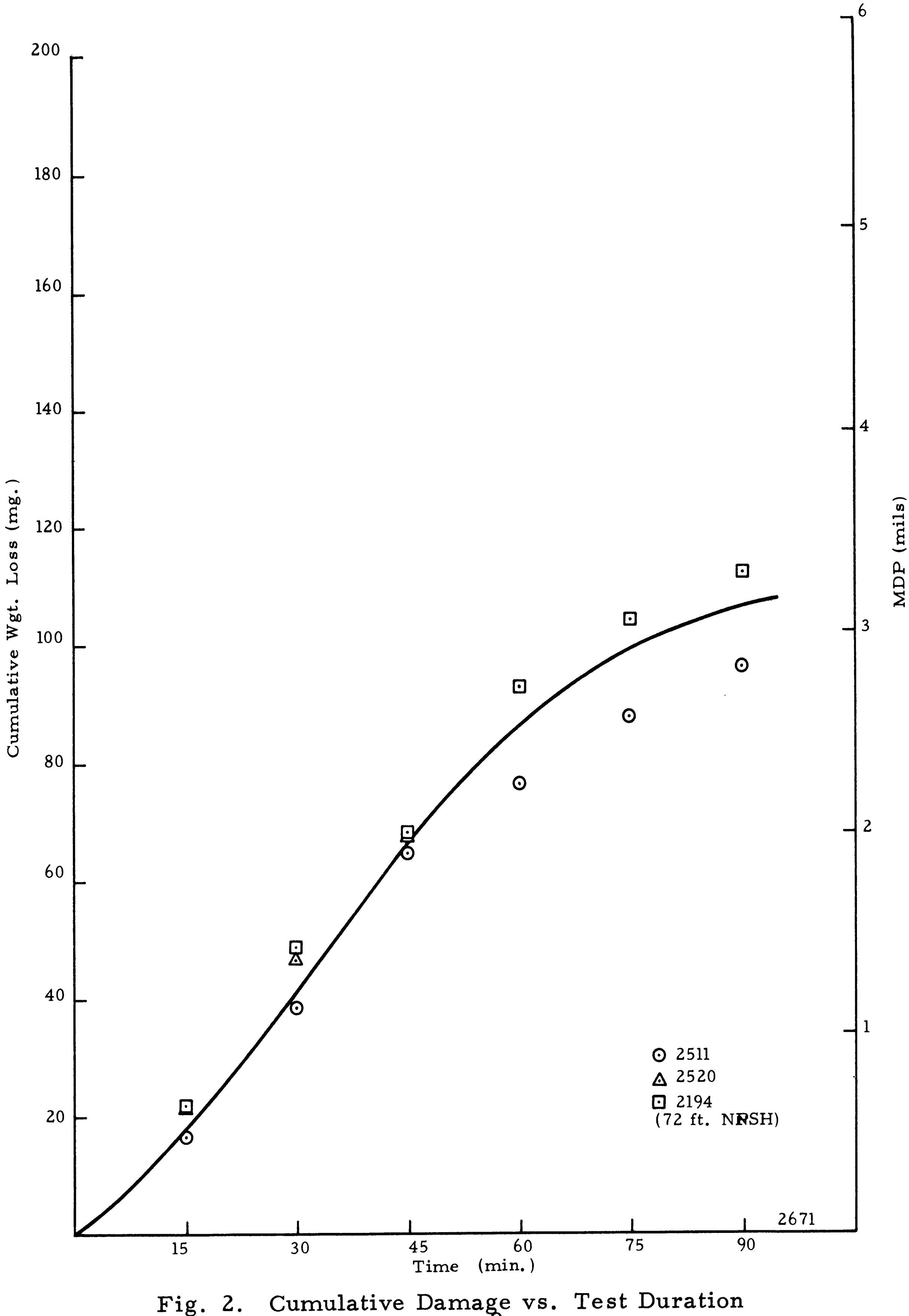


Fig. 2. Cumulative Damage vs. Test Duration of SAE-660 at 250°F and 2 atm. NPSH

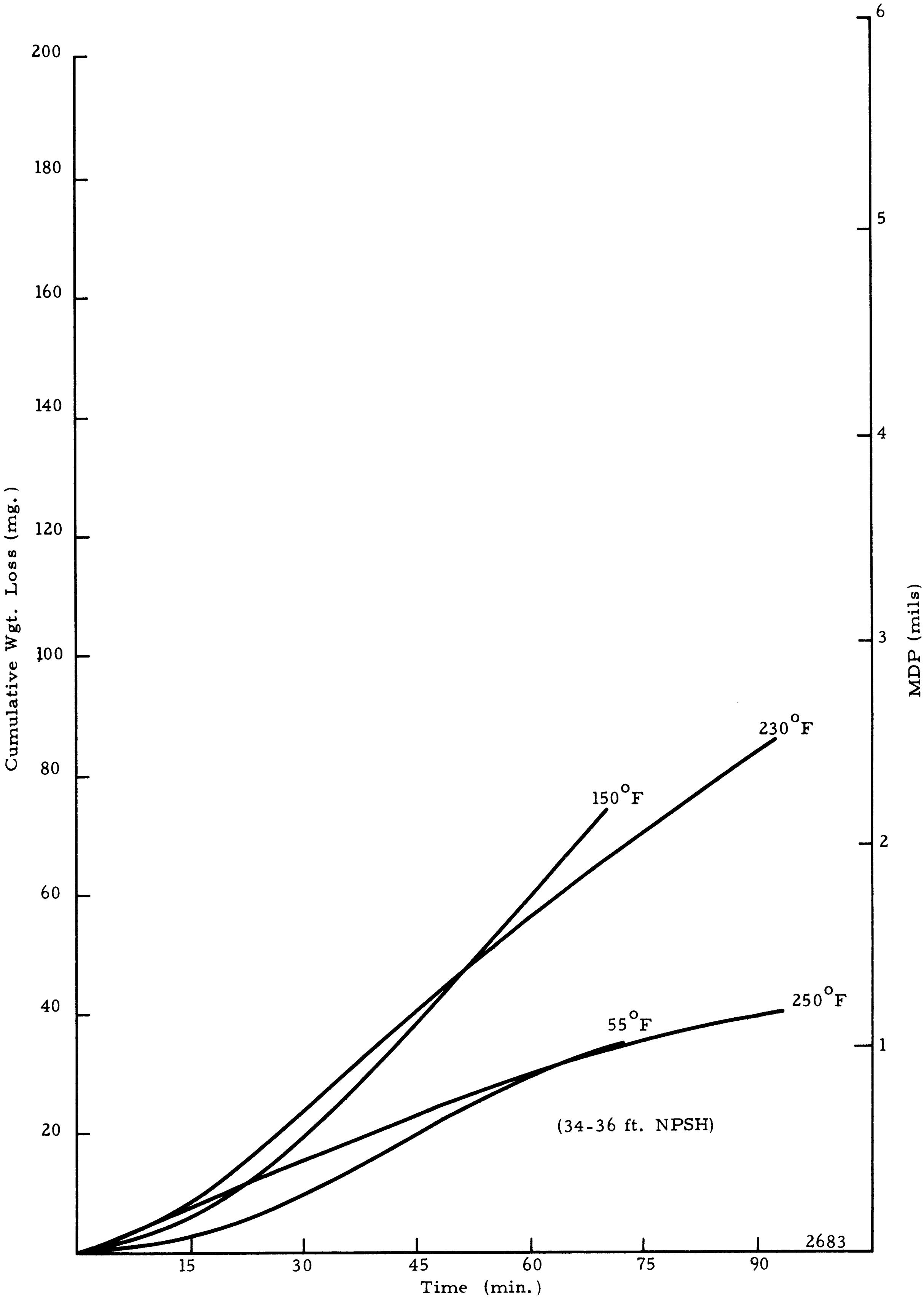


Fig. 3. Effect of Temperature at 1 atm. NPSH

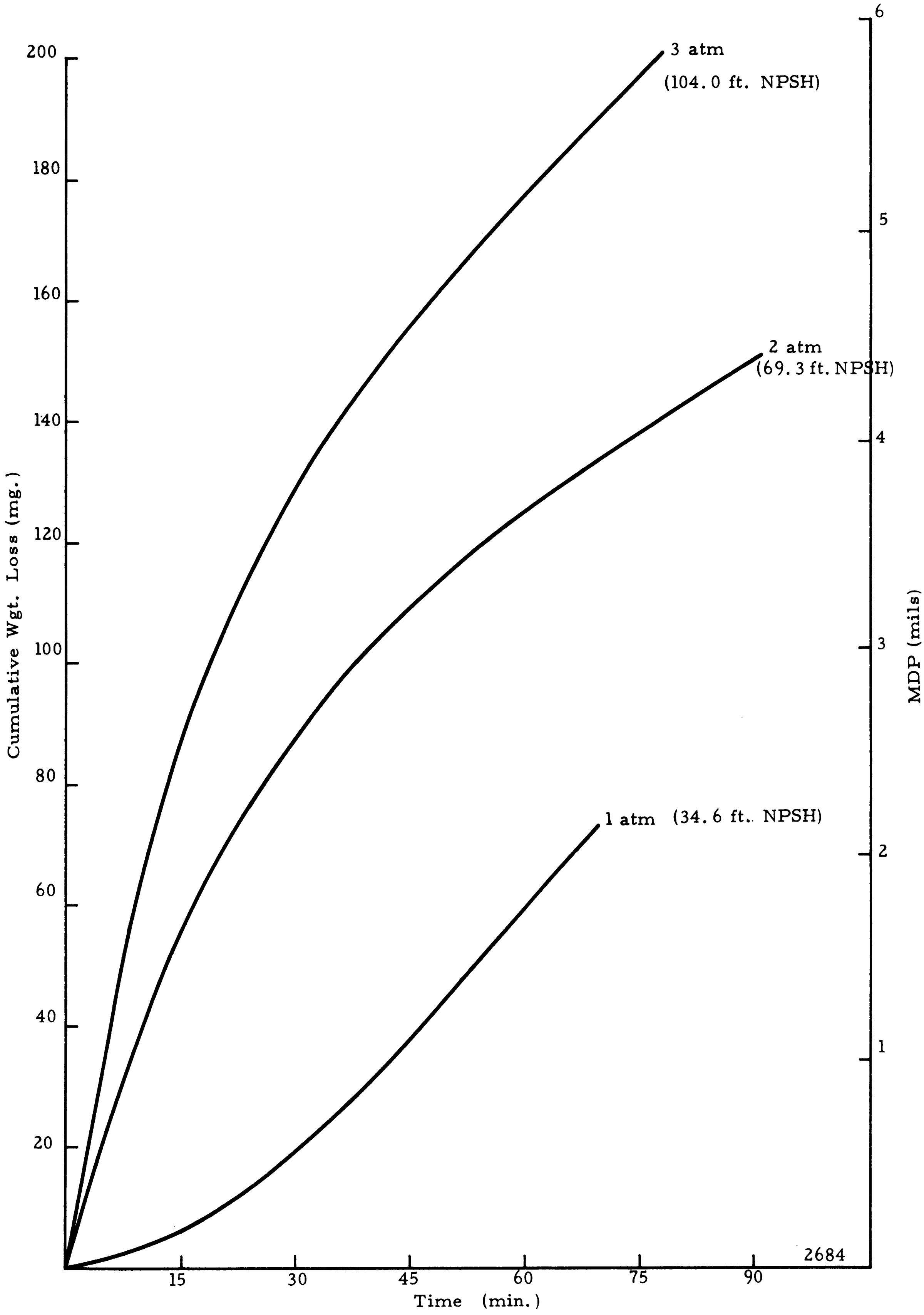


Fig. 4. Effect of NPSH at 150°F

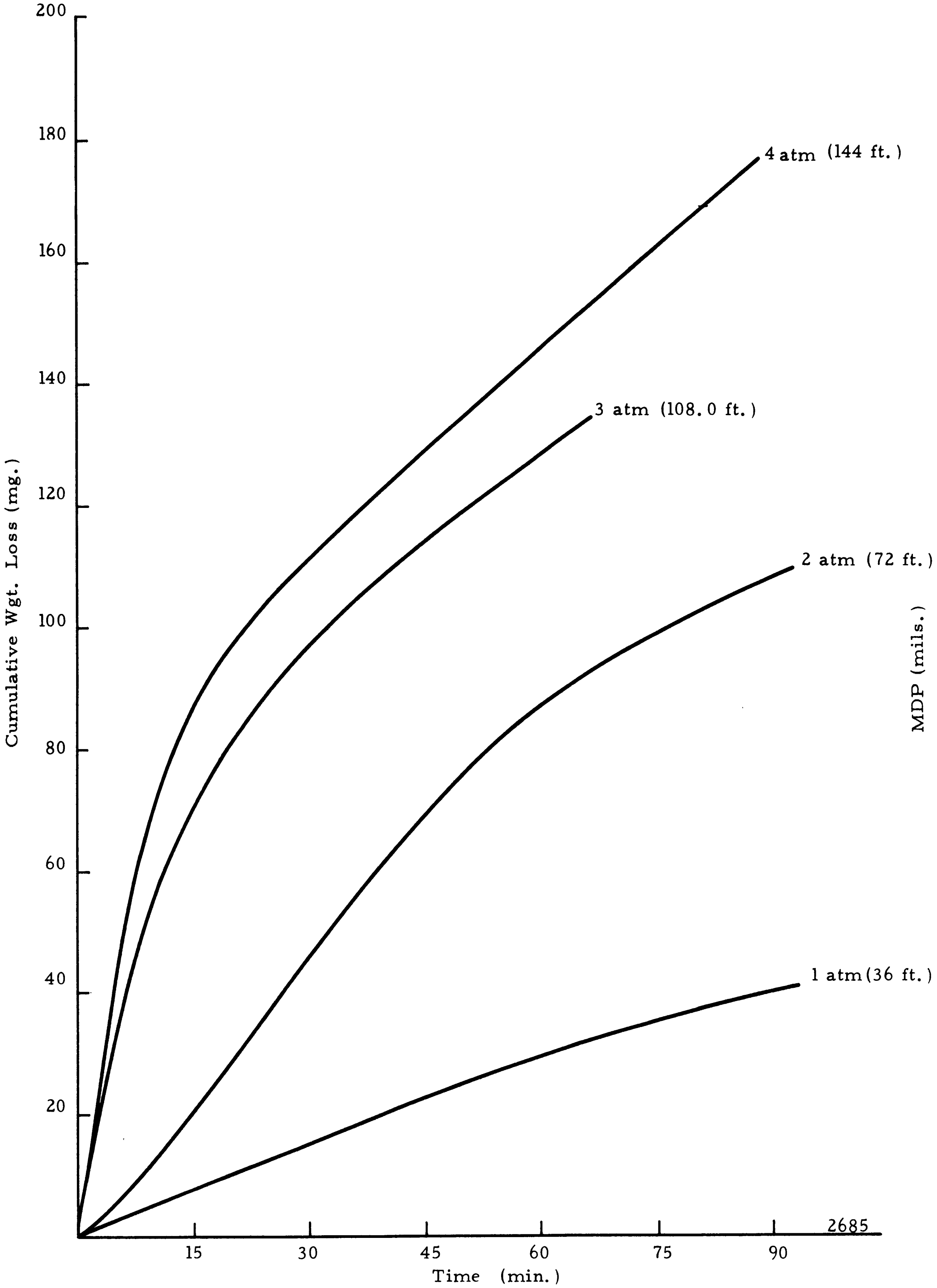


Fig. 5. Effect of NPSH at 250°F

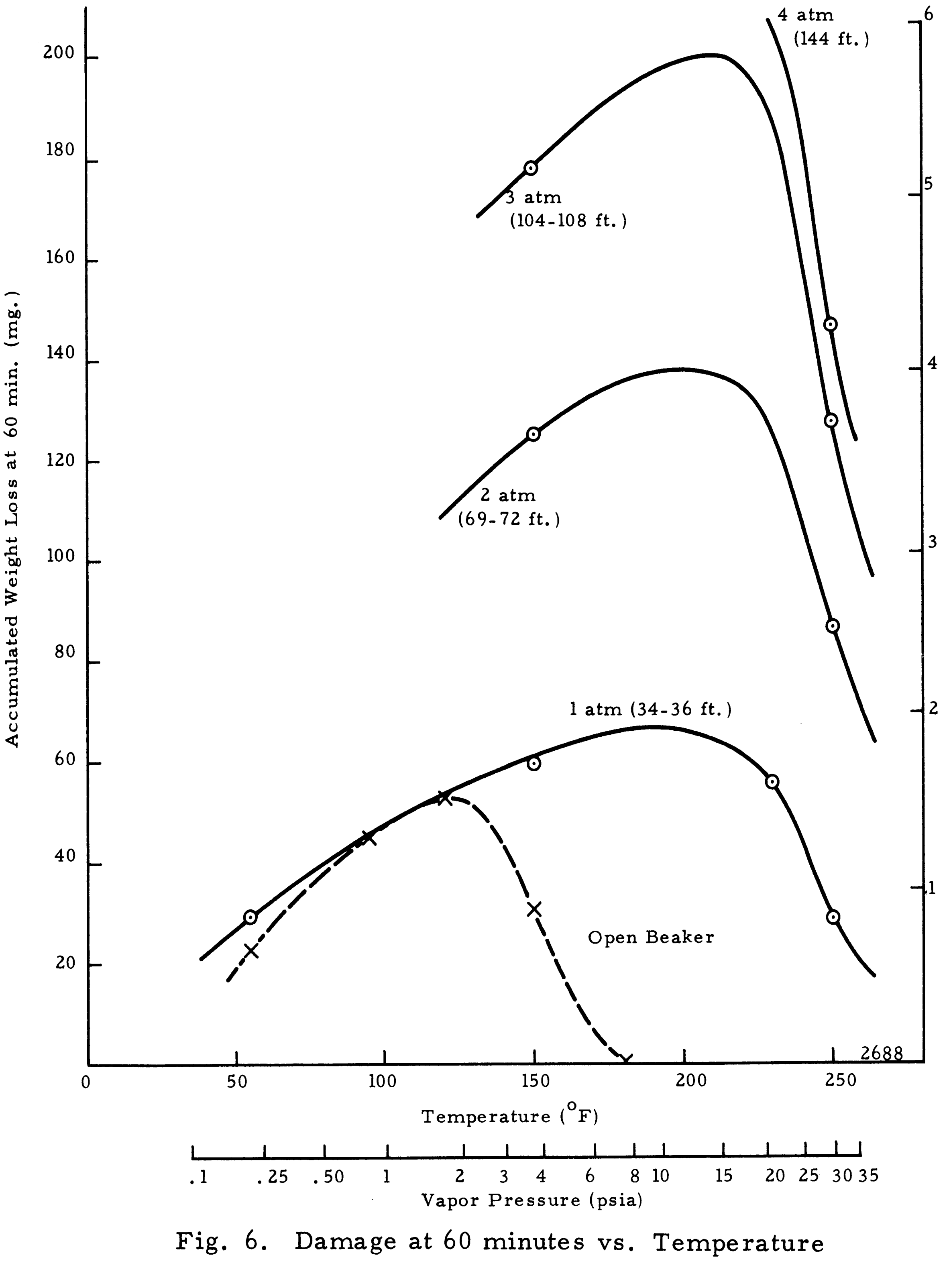


Fig. 6. Damage at 60 minutes vs. Temperature

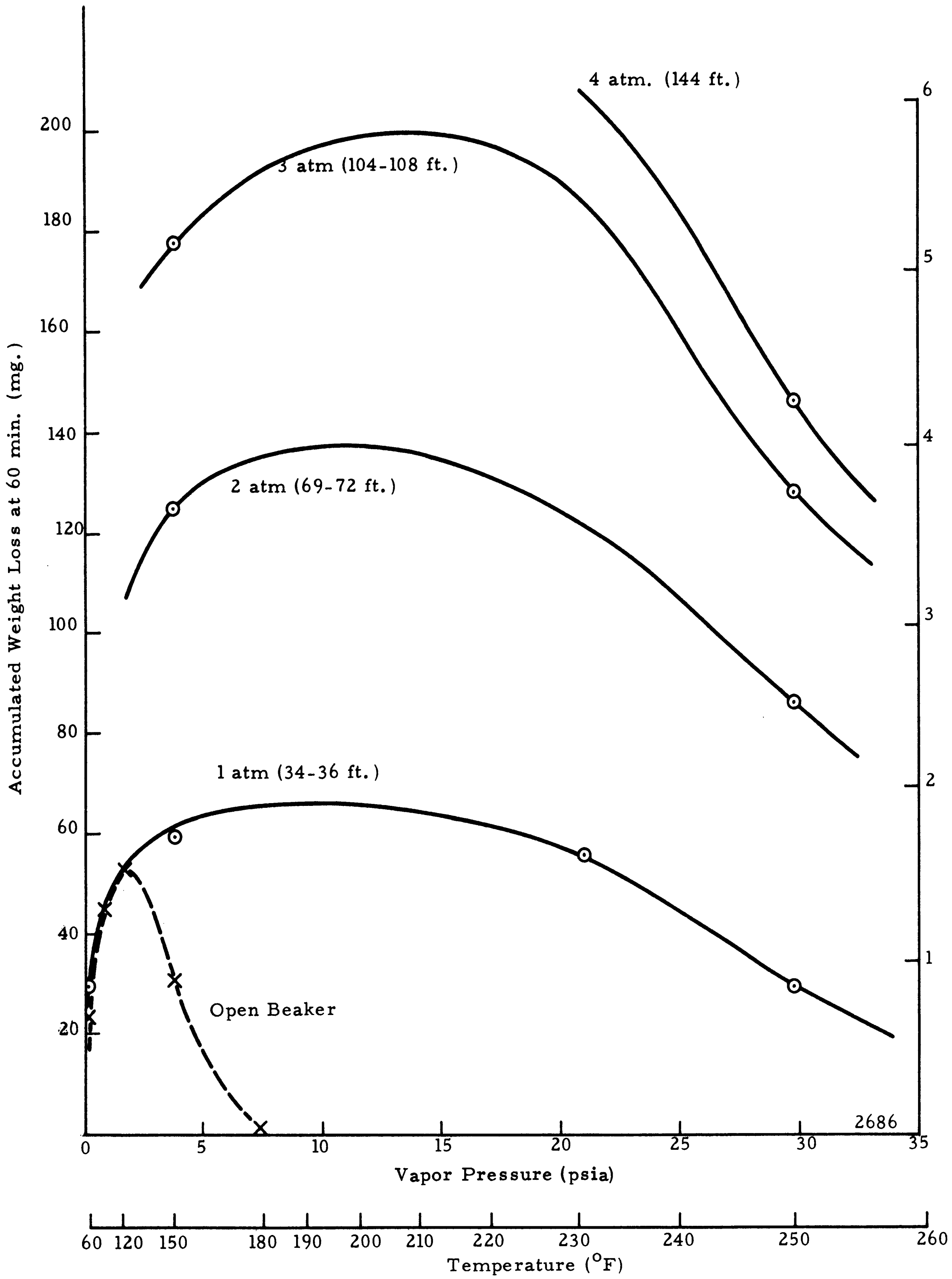


Fig. 7. Damage at 60 min. vs. Vapor Pressure

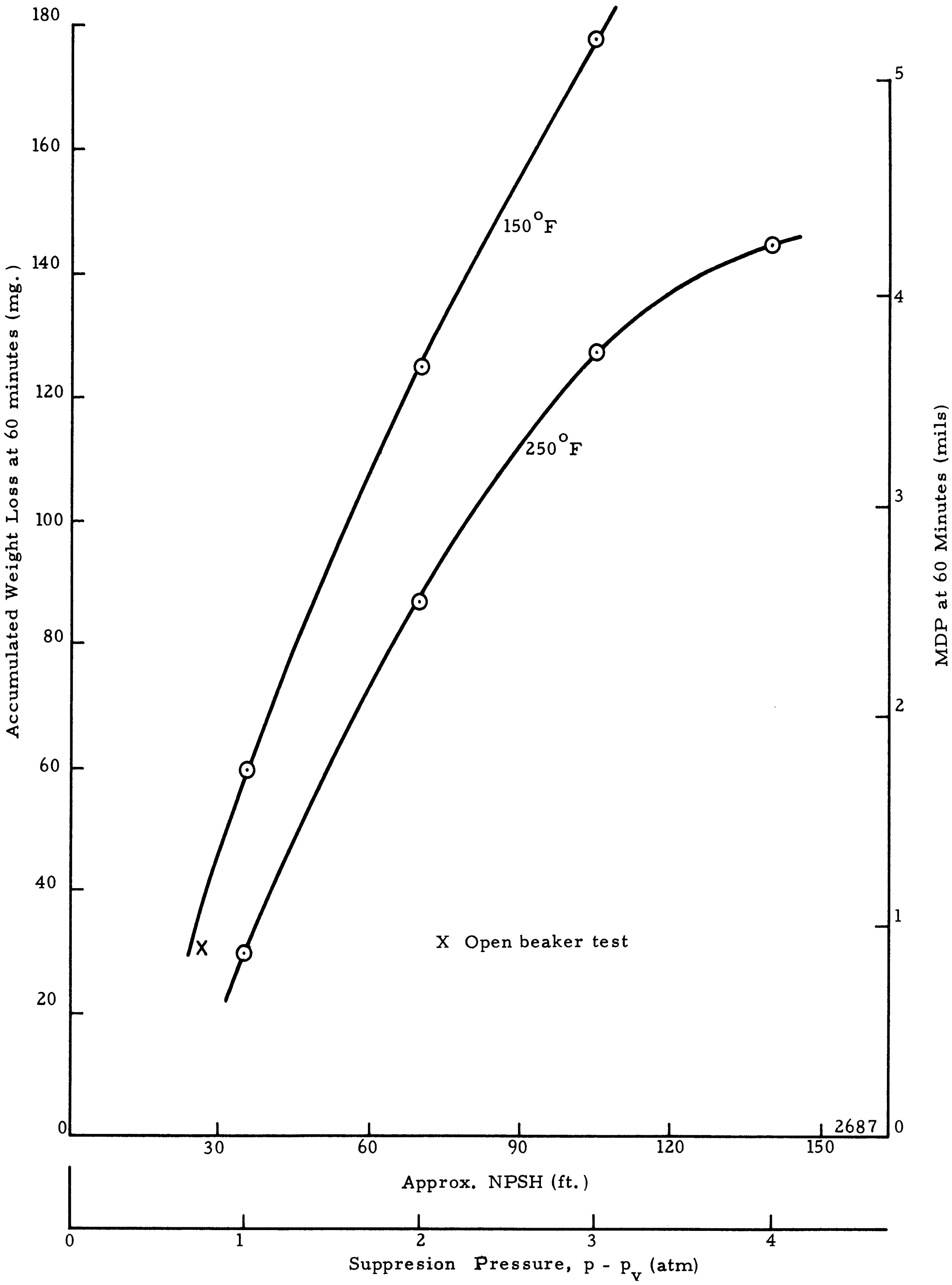


Fig. 8. Damage at 60 minutes vs. NPSH

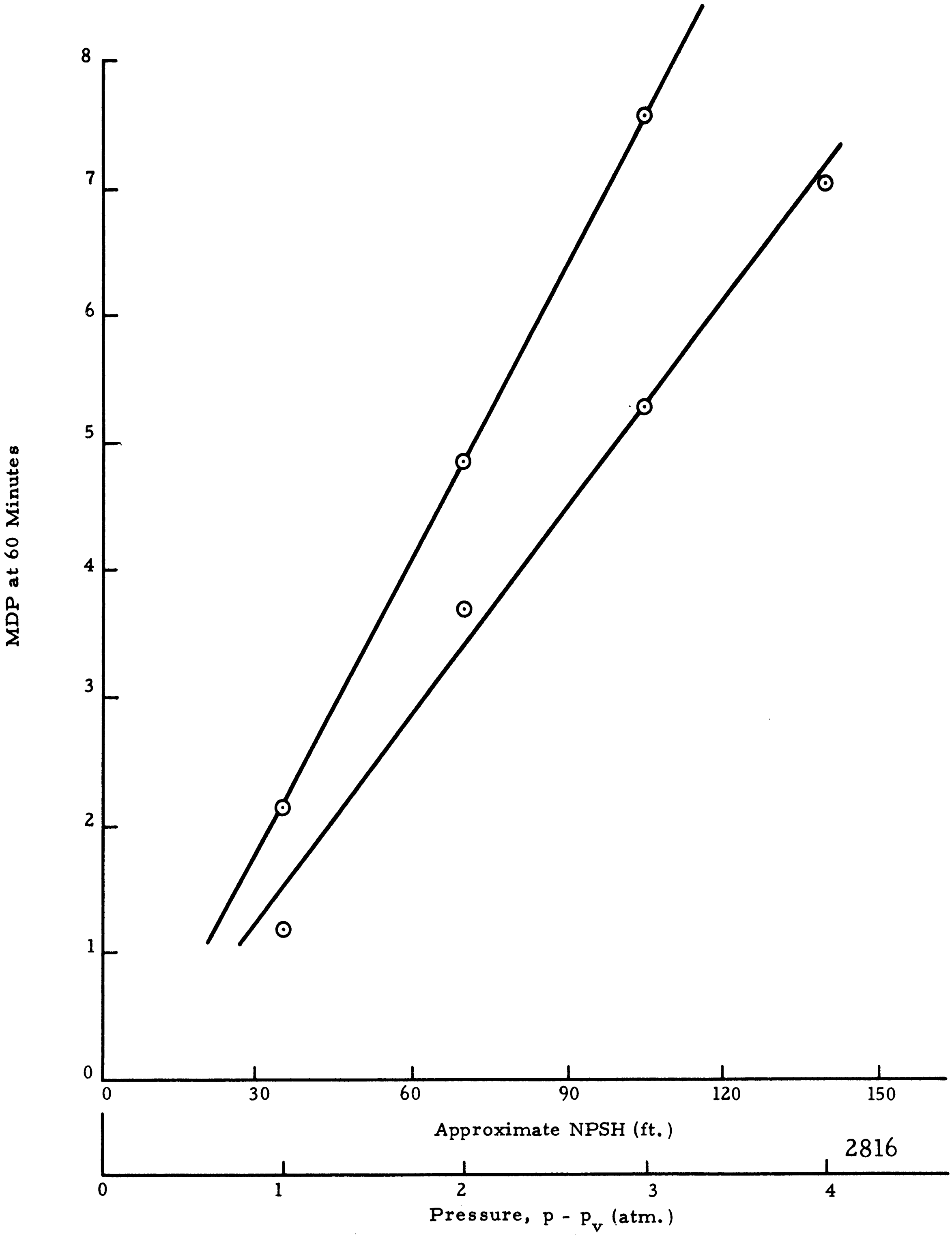


Fig. 9. Damage at 60 minutes versus NPSH based on Actually Damaged Area

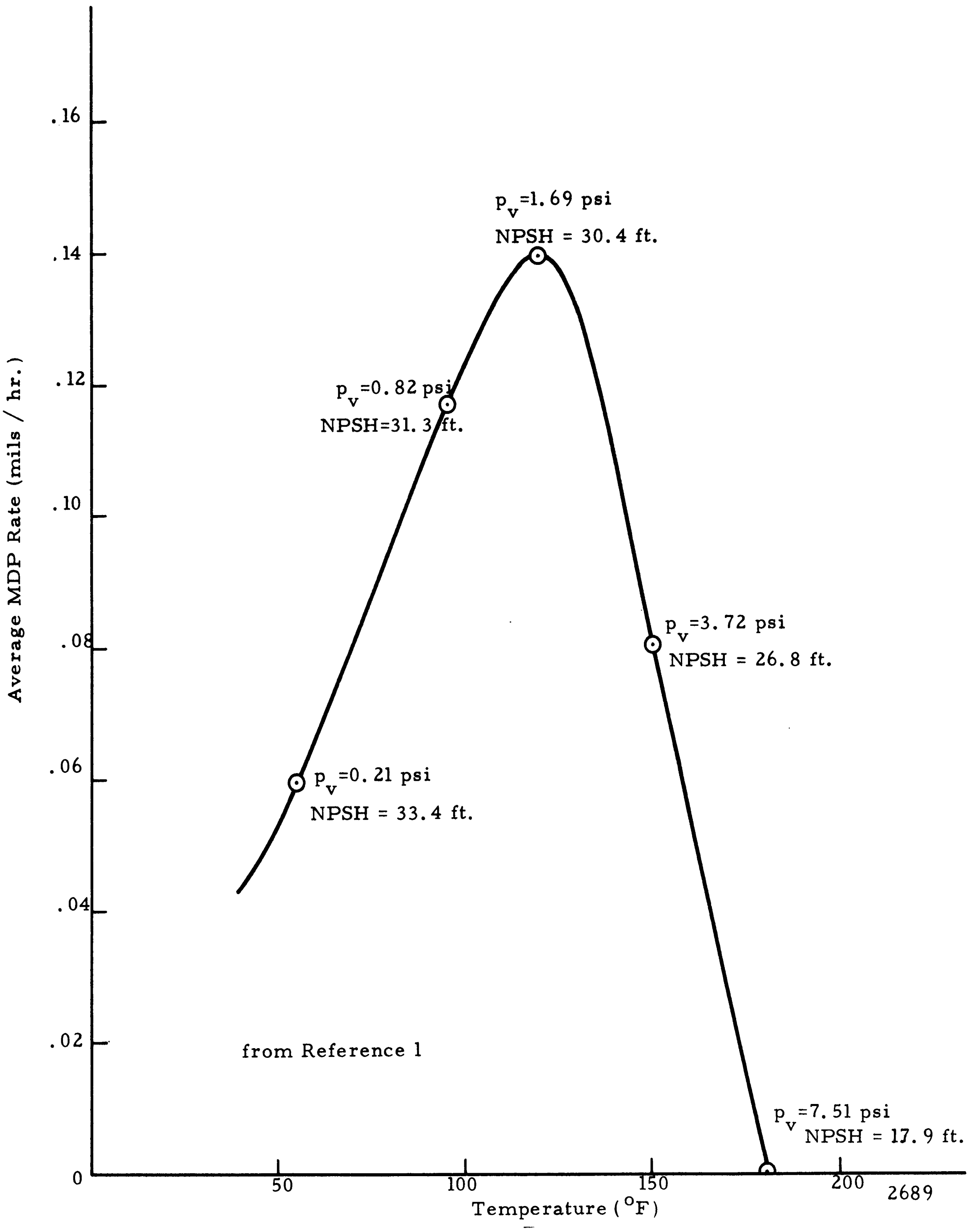
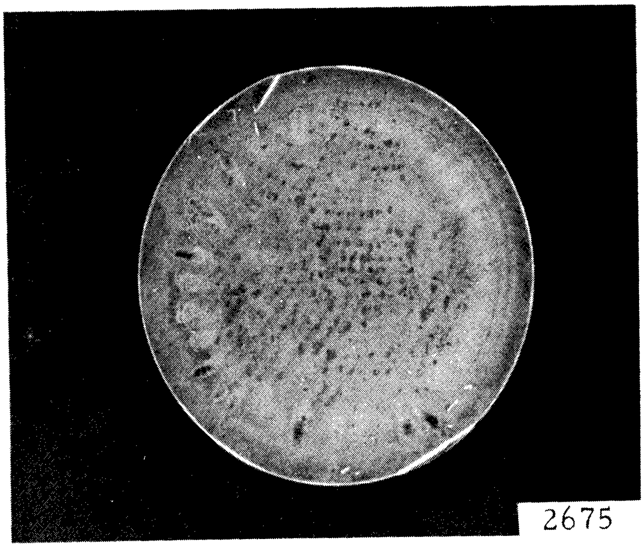


Fig. 10. Damage Rate vs. Temperature for 304 SS in Open Beaker Test

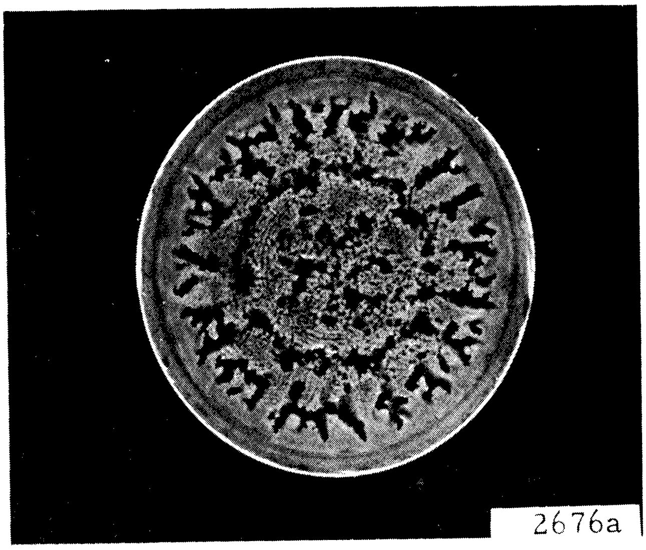


Specimen No. : II-1-M

Pressure: 1 atm. NPSH

Duration: 60 min.

Weight Loss: 59.5 mg.

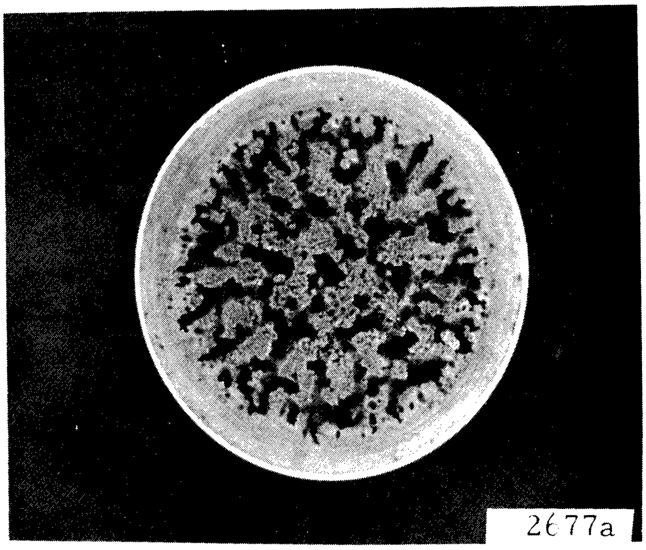


Specimen No. : N-5

Pressure: 2 atm. NPSH

Duration: 90 min.

Weight Loss: 144 mg.



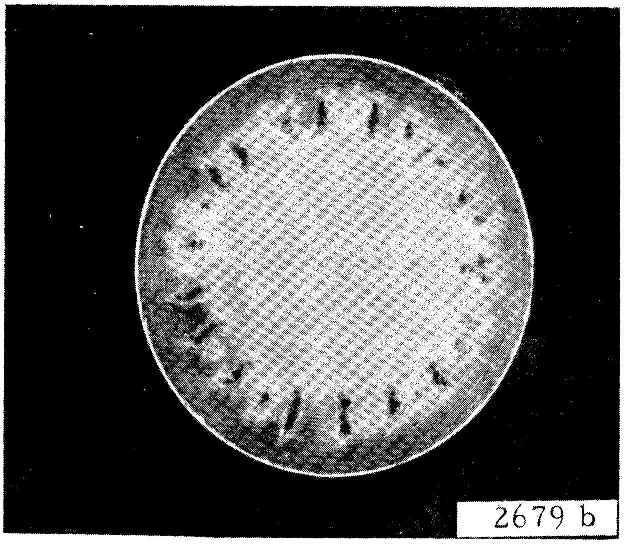
Specimen No. N-7

Pressure: 3 atm. NPSH

Duration: 90 min.

Weight Loss: 219 mg.

Fig. 11. Effects of NPSH on specimen damage pattern for a water temperature of 150^{o}F.

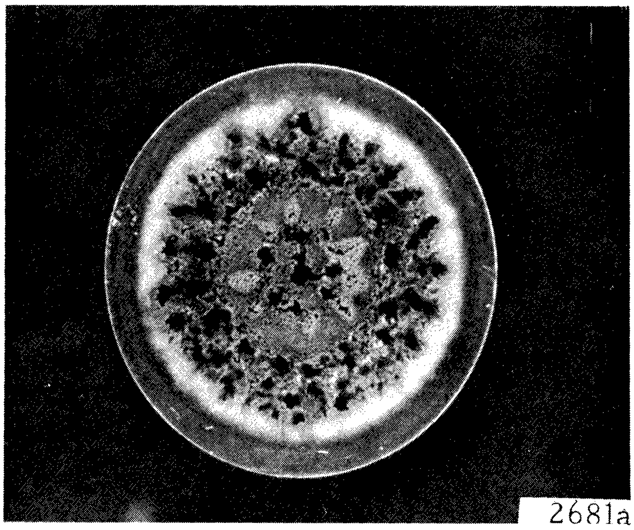


Specimen No.: N-3

Pressure: 1 atm. NPSH

Duration: 90 min.

Weight Loss: 42.5 mg.

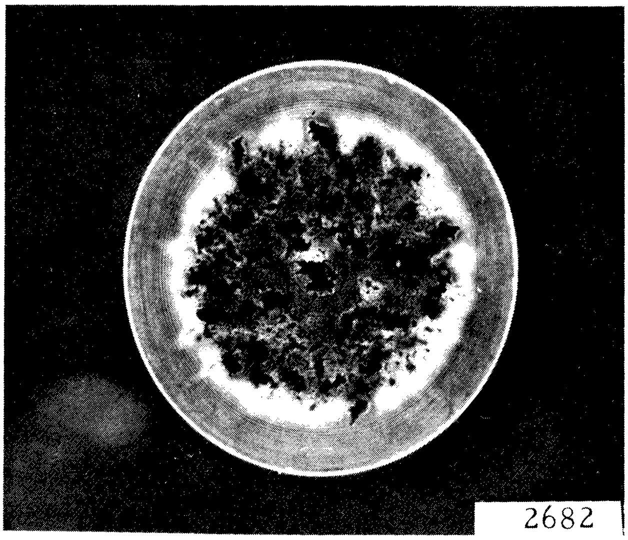


Specimen No. : 2522

Pressure: 3 atm. NPSH

Duration: 90 min.

Weight Loss: 130 mg.



Specimen No.: N-10

Pressure: 4 atm. NPSH

Duration: 90 min.

Weight Loss: 123 mg.

Fig. 12. Effect of NPSH on specimen damage pattern for a water temperature of 250^{o}F.

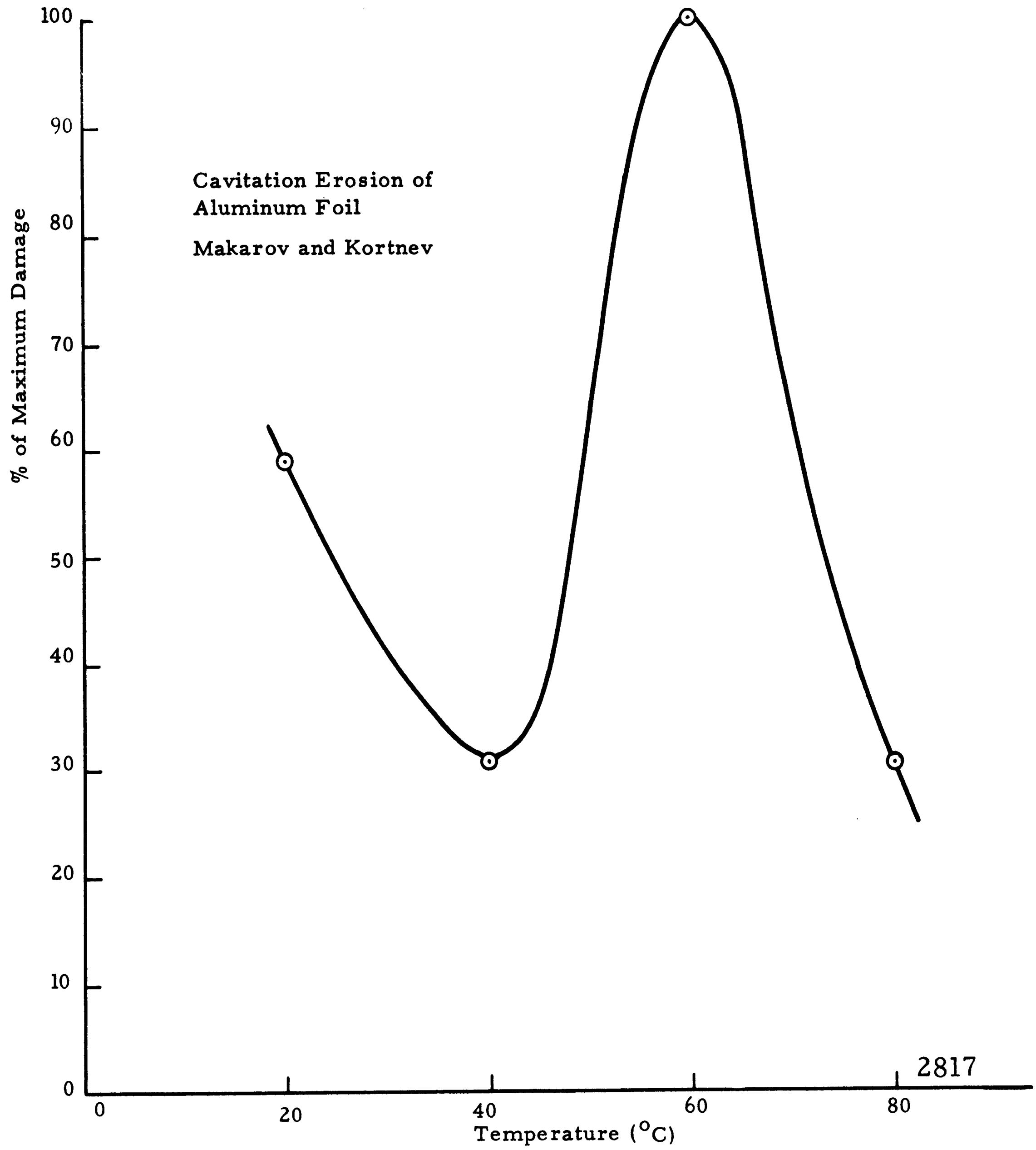
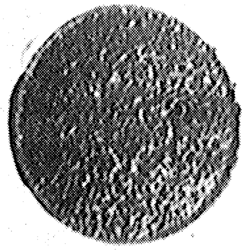
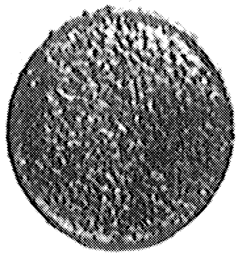


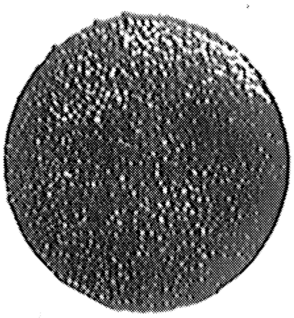
Fig. 13. Weight Loss versus Temperature for Cooling



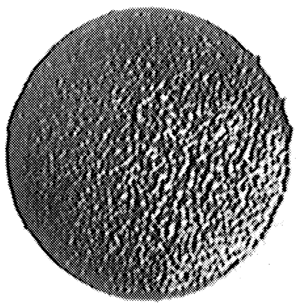
(1) 12 Hour Exposure
Pb-Bi at 500°F



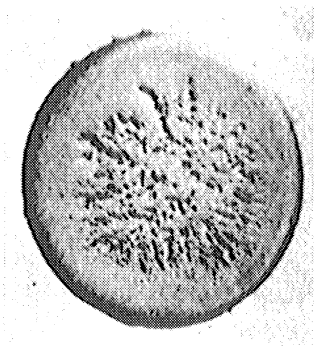
(2) 6 Hour Exposure
Pb-Bi at 1500°F



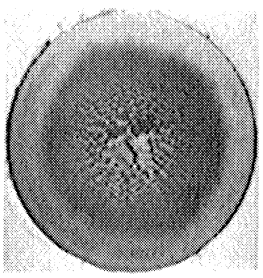
(3) 12 Hour Exposure
Mercury at 500°F



(4) 12 Hour Exposure
Mercury at 70°F



(5) 36 Hour Exposure
Water at 70°F



(6) 10 Hour Exposure
Lithium at 500 °F

Fig. 14. Effects of various fluids on specimen damage pattern for 316SS 2818