THE UNIVERSITY OF MICHIGAN

College of Engineering

Department of Mechanical Engineering

Laboratory of Cavitation and Multiphase Flow

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CAVITATION DAMAGE TESTS OF SAE-660 BRONZE AT WATER TEMPERATURES AND PRESSURES

F. G. Hammitt
D. J. Kemppainen
D. O. Rogers

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ACKNOWLEDGEMENTS

Mr. Edward E. Timm, Research Assistant, was mainly responsible for the continued calibration and maintenance of the vibratory facility as well as its original modifications to the increased pressure and temperature operation here required.

Most of the tests were actually performed by Mr. G. Ogranowski, Mr. B. Anderson, and Mr. D. Getz.

ABSTRACT

The results of vibratory cavitation damage tests on SAE-660 bronze over a range of water temperatures from 55°F to 250°F and for static NPSH ranging from sub-atmospheric to 4 atm. is reported. It is found that specimen weight loss rate increases approximately linearly with NPSH over the range tested, with a somewhat decreasing rate of increase between 3 and 4 atm. NPSH. Increasing NPSH also of course reduces the "degree of cavitation" so that the damaged area decreases, leaving a broader undamaged ring around the specimen O. D. for higher NPSH, and thus substantially reducing the actual damaged area. If a mean depth of penetration is computed based on the actual damaged area, then the rate of MDP so computed increases approximately as NPSH, i. e., a linear increase.

It was further found that for all NPSH values tested, the damage cumulative increases (for constant NPSH) as temperature is raised from a "cold water" condition, passes through a maximum, and decreases drastically for temperatures in excess of 200°F in the present tests. The low damage at the cold water end of the curves may be explicable in terms of a larger dissolved gas content, but further tests are necessary. The decrease at high temperature for the constant NPSH tests is primarily due, presumably, to the "thermodynamic effect". These results indicate the practical points that "hot water" is much less damaging than that at moderate temperature (about 150 - 200°F), and cavitation damage may very possibly be reduced substantially by assuring high gas contents.

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I. INTRODUCTION

This is a final report for the second research contract between the Worthington Corp. and the Cavitation and Multiphase Flow Laboratory* of the Mechanical Engineering Department of the University of Michigan. The first contract concerned the investigation of the cavitation resistance of various materials suitable for use in water lubricated bearings where cavitation damage problems might be expected. A final report on this work, our Report 07985-3-T, "Cavitation Erosion Characteristics for Bearing Materials in Water at 150°F", by C. Chao, F. G. Hammitt, and D. O. Rogers, June 1968, has already been submitted. These tests encompassed a variety of material of interest, but were all done using the standard type of vibratory horn test wherein the water sample is maintained under a pressure of one atmosphere in an open vessel. Tests were made at 55°F and 150°F. However, the actual fluid in bearings will exist under various pressures both above and below the standard test pressure of one atmosphere, and of course cavitation in turbomachines, etc., can well occur over a large range of pressures. A consideration of basic bubble dynamics, as well as field and laboratory experience, suggests that cavitation damage rates are likely to be strongly affected by pressure.

Consequently, a second contract for which this is the final report was initiated to investigate the effect of pressure and tempera ture over the range attainable with the existing laboratory equipment, using a standard test material, SAE-660 bronze. The effect of temperature has been investigated up to 250°F and the effect of

*Formerly Laboratory for Fluid Flow and Heat Transport Phenomena, Nuclear Engineering Department, University of Michigan pressure up to a suppression pressure of 4 atmospheres, i.e., about 90 psia at 250°F.

There are two primary effects which might be expected:

1) NPSH* effect, i.e. the direct effect of suppression pressure (pressure above vapor pressure) in providing differing driving pressures to cause bubble collapse and thus differing collapse intensities; and the inverse effect that increased NPSH for a given vibratory horn amplitude and frequency should cause a reduction in the number and mean diameter for bubbles existing in each cycle and perhaps in their distribution.

2) Thermodynamic Effect. At constant NPSH for a fluid such as water at moderate temperature, as the temperature is increased, the vapor pressure increases by a very large ratio compared to the absolute temperature increase, so that the vapor density increases by a proportionately large ratio also. Thus the mass of vapor in a cavitation bubble of given diameter also increases by a large ratio. When the bubble collapses, the latent heat of this mass of vapor must be conducted or convected away from the bubble wall into the liquid if the liquid and vapor temperatures in and around the bubble are not to increase greatly. In any case, the local temperatures must increase slightly above the bulk liquid temperature. If the vapor density and mass are high, the corresponding local temperature rise will also be great, so that the vapor pressure will be increased within the bubble, and the collapse intensity of the bubble under the influence of the driving pressure in the liquid at large distances, will be reduced. Thus according to the

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*NPSH (Net Positive Suction Head) as used for this type of facility refers to the difference between static liquid pressure head (horn not vibrating) and vapor pressure head. The vibrating horn imposes a roughly sinusoidal pressure variation on this static base, which must then dip below vapor pressure if cavitation is to occur in the negative pressure portion of the cycle. If the NPSH is raised, the generated underpressure for a given horn frequency and amplitude is reduced in duration and amount.

thermodynamic effect mechanism, the bubble collapse will be moderated and the cavitation damage rate reduced.

There is still another mechanism which might be expected to affect cavitation damage rates if the liquid temperature is made very high (depending on the material), i.e., the mechanical properties of the material as strength, hardness, etc. will be reduced. However, this mechanism is not important for the temperature range and material here used (up to 250°F with bronze). In addition there are other, probably minor, effects such as change in fluid viscosity, surface tension, fluid compressibility, etc. In the present case, however, it appears reasonably certain that the NPSH and "Thermodynamic" effects will be predominant. For this reason, the test program was planned to investigate each of these singly, i.e., to generate curves of damage rate vs. NPSH at constant temperature and damage rate vs. temperature at constant NPSH. The results in these terms are presented and discussed in the body of the report.

Most previous tests with vibratory cavitation damage facilities to investigate temperature effects here(1) and elsewhere(2, 3) have demonstrated the importance of the thermodynamic effect, but under conditions of constant total liquid pressure rather than constant NPSH. Peters and Rightmire(4) do investigate the effects of variations in both temperature and pressure, but with results differing from those obtained here, as discussed later. It was shown in our tests (Fig. 26 is an example from our laboratory for type 304 stainless steel) that damage reachaed a maximum at about 120°F in a 1 atmosphere test, and decreased very rapidly as the temperature was raised only slightly, presumably becoming zero at 212°F since there is then no collapsing pressure. This reduction is presumably due to both the decrease in NPSH and the thermodynamic effect. To separate these effects it is necessary to perform tests such as those discussed here.

The decrease in damage for temperatures below 120°F occurs at very nearly constant NPSH, since the vapor pressure is essentially negligible in this range. It has been previously assumed to be due to an increase in gas content within the liquid, since the solubility for gas increases as temperature is reduced.* Thus the gas content effect is another which needs further investigation, but is not included within the scope of the present contract.

*Reference 3 shows the interesting result of a difference in the damage vs. temperature curve depending upon whether it was generated during heating or cooling. The heating curve is conventional, but the cooling curve (generated after a heating cycle) shows an increase in damage at low temperature after a previous minimum. This may be due to degassing effects which occured during the heating cycle. This result is reproduced in Fig. 27.

II. EXPERIMENTAL PROGRAM

A. Experimental Facility

The tests were performed in the Ultrasonic Vibratory Facility of this laboratory. This facility and our operating procedures for measuring cavitation damage have been described in a previous report to Worthington (5). All the present tests were accomplished with the "new" Branson transducer* (20 Khz, 2 mil double amplitude), and hence there is no problem of comparing results obtained with slightly differing facilities as was encountered in our bearing material evaluation program (6). For the high temperature portion of the present tests the test vessel was submerged in a constant temperature bath using ordinary cooking oil as the heat transfer medium. The correlation between amplitude of horn tip and power setting to the Branson unit was monitored frequently with a Fotonic Sensor** to be certain that an actual amplitude of 2.0 mils was used.

B. Tests Performed

The tests were divided into constant temperature sets for varying NPSH, and constant NPSH sets for varying temperature for the reasons explained in the Introduction. Temperatures used were 55°F, 150°F, 230°F and 250°F (p_v=29.8 psia for the last); and NPSH values were 1, 2, 3, and 4 atmospheres. Common points were of course used to evaluate the effect of the two major parameters, but the complete matrix of combinations was not completed, since it had been judged that this would not be necessary when specifying the contract. Though it was not known to ourselves until these tests, it was found that 4 atmospheres NPSH is the maximum feasible for our transducer. This limit is due presumably to

*Sonifier Converter Model J, Branson Sonic Power Division, Branson Instruments, Inc.

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

overloading effects encountered as the degree of cavitation is reduced for higher NPSH so that the horn is operating more nearly in liquid water than in a vapor-liquid mixture. Higher pressures could be obtained if desired by either reducing the specimen diameter or increasing the transducer power. High temperatures could also be used if it is desired. The temperature connotes a corresponding increase in vapor pressure. It is believed that a maximum vessel pressure of 100 psig would be feasible. A maximum pressure of approximately 74 psig was used in these tests (Table I).

TABLE I - TEST CONDITIONS

Temperature T (^{o}F)	Vapor Pressure p_v (psi)	Vessel Pressure p (psi)	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.

It can be seen from the test conditions in Table I, that the effect of temperature (or vapor pressure) variation at constant NPSH can be most completely evaluated at 1 atm. NPSH, though some data is also provided for temperature effect at 2 and 3 atm. NPSH. The effect of varying NPSH at constant temperature can be evaluated at both 150 and 250°F.

C. Test Results

The basic test results are presented in Fig. 1-9, showing curves of weight loss vs. duration for the various test conditions used, all at 2 mils, 20 kHz. As indicated by the individual data points, in most cases more than one specimen was used. For these curves as well as all others used in this report, a scale of Mean Depth of Penetration (MDP), i.e. volume loss divided by specimen bottom surface area, is shown opposite the weight loss scale. Since all specimens are of the same material (SAE-660 bronze) and of the same dimensions, the scales differ only by a constant factor. The MDP scale is presented for easy comparison with other results, since many cavitation damage results are presented in these terms.

Most tests are carried out to 90 minute duration so that this may be used as a common point of comparison, as may also 60 minutes. The accumulated weight losses at 60 minutes were used for the cross-plots, discussed later, showing the effects of parameter variations. In one case the test was carried to 300 minutes (specimen 2301 at 230°F and 1 atmosphere NPSH) to observe any possible unexpected trends at longer duration, but there were none. The curves are typical for this type of material and test with our facility, showing an increasing weight loss rate at first and then a decreasing value. The maximum rates as taken from the cumulative weight loss curves are listed in Table II for each condition.

TABLE II - MAXIMUM DAMAGE RATES

Condition			Peak Wt. Loss Rate	Peak MDPR
55°F	1 atm.	(Fig. 1)	.73 mg/min	1.28 mil/min
150	1	(Fig. 2)	1.60	2.80
150	2	(Fig. 3)	3.95	6.94
150	3	(Fig. 4)	7.20	12.62
230	1	(Fig. 5)	1.14	1.98
250	1	(Fig. 6)	.85	1.49
250	2	(Fig. 7)	1.76	3.09
250	3	(Fig. 8)	5.43	9.51
250	4	(Fig. 9)	8.59	15.05

Fig. 10-18 are photographs of the damaged surfaces, arranged in the corresponding order to the weight loss curves, Fig. 1-9. Since each photo was taken at the conclusion of the test, they correspond to differing quantities of weight loss, but nevertheless very interesting trends in weight loss distribution, as will be discussed later, are evident.

Fig. 19, 20 and 21 show the effects of temperature variation at 1 atm. NPSH, and the effects of NPSH variation at 150 and 250°F respectively as weight loss vs. test duration out to 90 minutes.

Fig. 22, 23, and 24 summarize the effect on accumulated damage (at 60 minutes) of temperature variation at all NPSH values and the effect of NPSH variation at the two temperatures for which sufficient data was available respectively. These are the key figures of the report in summarizing the trends in accumulated damage created by temperature, vapor pressure, and NPSH variation when considered separately.

III. DISCUSSION OF RESULTS

A. General

Fig. 19 - 21 show the detailed curves of weight loss (or MDP) vs. duration for either constant NPSH conditions with varying temperature, or constant temperature with varying NPSH. That the curves showing lower total weight loss are often concave upward while those for high weight loss are concave downward is indicative of the fact that there is essentially a "universal damage curve" for a given facility at given operating conditions, if MDP rate is plotted against MDP as previously suggested by the first author [7]. The low weight loss curves represnt an earlier portion of their own "universal" curve*, where the MDP rate is still increasing with increased MDP, while the high loss specimens are beyond the peak of MDP rate and in a region where it decreases for increasing MDP.

Fig. 22 - 24 summarize the overall results of the investigation. Fig. 22 shows the effect of temperature on weight loss (or MDP) at various NPSH from approximately 1 to 4 atmospheres (34 to 144 ft.). Also included in Fig. 22 is an open-beaker test where the total over-pressure is always 1 atmosphere, so that the NPSH is less by the amount of the vapor pressure. At the temperature for which comparison with the other tests can be made (150°F), the NPSH is then about 3/4 atmospheres. The open-beaker test data here is that of Fig. 26 for which the test specimen was type 304 stainless steel [1]. At least approximately the curve shape with temperature should be independent of material. Thus it is possible to establish a factor between the damage rate in

*A single "universal curve" cannot be considered here because the operating conditions (i.e., NPSH and temperature) differ. For lower NPSH the collapsing violence is less so that damage may be slower to develop and a longer "incubation period" found.

this test and the present test at low temperature (90°F was used for this purpose) where the vapor pressure effect on NPSH is negligible. The factor so derived is then used to plot the rest of the data, in order to approximate the results which would have been achieved had the test been run with SAE-660 rather than stainless steel.

It appears from Fig. 22 that the increase in the damage rate with NPSH is nearly linear for small NPSH but tends to become much less than linear for the higher values. This is especially true for the jump between 3 and 4 atm. NPSH, although even at this point, damage rate is still increasing with NPSH. This same trend is shown more clearly in Fig. 24 and will be discussed in more detail in connection with that figure.

A somewhat similar test by Peters and Rightmire[4] in 1938 shows an entirely different result. Their test, for water at 100°C, showed a peak of damage at about 1 atmosphere NPSH, a local minimum (by a factor of about 2) at about 1 1/3 atmospheres NPSH, and a second maximum (about the same damage rate as the first) at about 2 atmospheres NPSH. Thereafter the damage decreased by a factor of about 10 to about 2 1/2 atmospheres NPSH. Their unit was of the standard low frequency type (6.5 kHz, 3.65 mils), thus differing markedly from our own. Unfortunately their detailed weight loss curves are not shown. The specific reasons for the substantial difference between their results and our own cannot be detailed at this point.

B. Variable Temperature at Constant NPSH

Fig. 22 also shows that for any NPSH, and also for the open-beaker test where NPSH is decreasing as temperature is increased, damage rate passes through a maximum at an intermediate temperature and then decreases very rapidly at high temperatures. The decrease at high temperature for the constant NPSH curves must result primarily from the "thermodynamic effect" previously discussed, and is of great practical significance in indicating that, other things being equal, "hot" water is apparently much less damaging than cold water. Presumably the same would be true for other fluids in a temperature range where the thermodynamic effects would be important. This has been indicated to be the case in our own tests with liquid metals [1] and in work with liquid metals by NASA [8] and Hydronautics, Inc. [9], though in none of these cases were the tests actually made with constant NPSH. Rather total pressure was held constant.

A further point with respect to Fig. 22 is that the temperature for maximum damage appears to increase with NPSH. It seems intuitively likely that this would be the case, though the present data is not sufficiently comprehensive to definitely verify this point.

In all cases in Fig. 22, the damage rate decreases at low temperatures. As previously mentioned this may be the result of increased gas content at low temperature, or perhaps partially the result of decreased viscosity and other fluid property effects. Tests in which gas content is controlled are required to further investigate this region of the curve.

A somewhat different result is reported by Makarov and Kortnev [3]. They performed the conventional open-beaker vibratory test with water with the usual damage rate maximum at an intermediate temperature (about 60°C in their case). When the curve was generated by incremental increases in temperature between damage rate measurements, the low temperature result was also conventional. However, when additional damage rate points were generated by reducing temperature from the highest value reached the damage maximum at 60°C was reproduced, but a minimum was found at about 40°C and then a new maximum at 20° C (the lowest temperature tested), which in some cases was of a magnitude similar to that of the 60°C maximum. It is suggested that this "hysteresis effect" is confirmation of the importance of gas content at low temperature, since the prior heating cycle would have reduced the gas content over that in the water during the initial set of low temperature tests. They also report the effect of variation of gas content at 20°C, 40°C and 80°C, and in all cases find maximum damage in the range 0.010 to 0.015 volume percent gas (saturation at room temperature is about 1.8%).

A more recent Russian paper[10] also reports the existence of a secondary damage maximum at about 40°C in an open beaker test, but it is not clear whether this is restricted to a heating or cooling cycle.

The decrease in damage for the open-beaker curve on Fig. 22 at high temperature is a result of the thermodynamic effects combined with a significant decrease in NPSH as temperature is raised. With data taken in this fashion it is not possible to separate these effects.

C. Vapor Pressure at Constant NPSH

Fig. 23 is a replot of the data from Fig. 22 with vapor pressure rather than temperature as the abscissa. This form of plotting has the effect of spreading out the curves horizontally, since the vapor pressure increases much more rapidly than temperature. No new trends can be shown in this fashion, since the present data is only with water so that there is a unique relationship between temperature and vapor pressure. It is possible to conclude by extrapolation, since the abscissa is expanded at the high temperature end, that damage will be essentially nil at 280 °F. However, a consideration of the mechanism of the thermodynamic effect indicates that pressure is a more basic variable than temperature in this respect, since it is almost proportional to vapor density which is very basically involved in the thermodynamic effect. Hence plots of this form should be more useful if tests with different fluids were to be compared.

D. NPSH at Constant Temperature

Fig. 24 shows directly the effect on damage rate of NPSH variations up to 4 atmospheres. The 3/4 atmosphere open-beaker point at 150°F (previously discussed) and the fact that the damage becomes approximately zero in the open-beaker test at 180°F (1/2 atm. NPSH) is used in plotting Fig. 24. While the rate of damage increase at low NPSH is more than linear, it is approximately linear in the mid-range (as also observed by Young and Johnston at NASA with Sodium[8]), and the rate of increase appears to reduce considerably between 3 and 4 atmospheres*. (According to Young and Johnston, the linear range continued at least to 4 atmospheres total pressure, their maximum pressure point). This is of course of considerable practical interest in indicating that increasing pressure in a given installation may well have the effect of increasing cavitation damage, contrary to the usual expectation.

In the present tests, increasing NPSH has the effect of increasing bubble collapse intensities by increased collapsing pressure differential, but also of reducing the "degree of cavitation",

*The horn operation is marginal at 4 atm. NPSH being power-limited. As a result portions of the 4 atm. tests were at slightly reduced amplitude. The data was corrected to a 2 mil base assuming that damage varies as amplitude to the 1.7 power as taken from ASTM sponsored tests[11]. Both original and corrected points are shown in Fig. 9. Since the correction is relatively minor, a proportionally large error in it would not significantly affect the overall trend.

i.e. the number and mean diameter of bubbles. These are opposing effect. Clearly a sufficient increase of NPSH, to the point where cavitation ceases completely, would reduce cavitation damage to zero. Hence it would be expected that the rate of increase of damage with NPSH would fall off for higher NPSH as is shown by the present data. The practical question of interest is to what NPSH value the damage will continue to increase. This cannot unfortunately be determined with the present facility without modification, as was previously mentioned.

Increasing NPSH should reduce the degree of cavitation. Since the pressure oscillation created by the vibrating horn is a maximum near the axial centerline and decreases to zero near the specimen O. D. it would be expected that an increase in NPSH would create a broader band around the O. D. where damage is minimal, since there is insufficient pressure oscillation to cause cavitation. An examination of the photographs of the damaged specimens, even though they represent varying quantities of MDP (being taken at the test termination) shows that this is the case. A comparison of Fig. 15 and 18 showing the specimens from the 1 atm. and 4 atm. at 250°F tests is illustrative in this respect. While the volume loss from the 4 atm. specimen is more than 5 times that of the 1 atm. specimen, the relatively undamaged ring is more than 1 1/2 times as broad on the 4 atm. specimen, and the heavily damaged area of the 4 atm. specimen is about 0.8 that of the 1 atm. specimen. (Estimates of the damaged diameter and areas are given in Table III). Thus MDP, if computed on the area actually damaged, would increase much more than the MDP over the total area. This is perhaps a more appropriate measure of the actual severity of the attack. The data in this form is shown in Fig. 25, otherwise analogous to Fig. 24, from which can be estimated that MDP is approximately proportional to

NPSH for the entire range. That is, the relationship in linear over the range tested.

TABLE III - ESTIMATED DAMAGED AREA CORRECTIONS

Fig. No.	Specimen Temp.	NPSH	Estimated Damaged Diameter	Estimated Damaged Area	Corrected MDP at 60 min.
10	55°F	1 atm.	.510 in.	.2050 in.	.99
11	150	1	.490	.1885	2.175
12	150	2	.475	.1775	4.85
13	150	3	.455	.1625	7.54
14	230	1	.482	.1825	2.12
15	250	1	.467	.1720	1.19
16	250	2	.455	.1625	3.67
17	250	3	.460	.1660	5.29
18	250	4	.425	.1420	7.03

It is interesting to note that the same changes in damage patterns were also observed in previous tests in this laboratory when NPSH was changed by varying fluid density (specific gravity range of 0.5 to 13.5 was used) at constant total pressure(1). Similar results were noted in the NASA work with Sodium(8).

E. Desirable Further Work

The investigation to this point has shown major trends of high practical interest, but has been limited in scope by time and funding so that these could not be resolved in complete detail. The following highly importnat points remain to be investigated further.

1. Effect of high NPSH on damage beyond range of present investigation. It has been shown that damage increases strongly in the vibratory test as NPSH is increased up to at least 4 atm. for the present data, which terminates at 4 atm. because of facility limitation. However, there is no indication of the attainment of a

maximum to this point. Higher NPSH could be investigated by either using specimens of reduced diameter (since a facility power limitation has been encountered) or by increasing the available power. The first alternative would involve rerunning some of the already tested conditions to establish the effect of specimen diameter itself, while the second alternative would probably involve the purchase of new equipment.

2. Effect of reducing temperature and increasing gas content on damage. It has been shown that for all NPSH's investigated, damage rate reaches a maximum at an intermediate temperature and then decreases rapidly for lower temperatures. It has been speculated that this is due to increased gas content, but this point cannot be verified, since gas content cannot be controlled without a facility modification which was not within the scope of the present contract. The extent to which increased gas content can reduce damage is of practical importance, since this may offer a method for reducing damage in certain types of machines, and is in fact sometimes used for this purpose now.

3. Temperature for maximum damage at elevated NPSH. The present data is not sufficiently comprehensive to locate these maxima with precision. Hence, additional data is required.

IV. CONCLUSIONS

The present investigation has established the following major conclusions:

1. With the vibratory-type test facility used in this laboratory (2 mil, 20 kHz), cavitation damage rate generally increases with NPSH from a sub-atmospheric range up to at least 4 atm. Due to facility power limitations it has not been possible to explore the region above 4 atm. The increase in MDP as averaged over the entire specimen bottom surface is less than linear with NPSH in this range. However, if MDP is based only on the damaged area, which itself decreases with increased NPSH due to decreasing "degree of cavitation", the increase in damage is proportional to NPSH over this range (approximately linear relationship).

2. At constant NPSH, damage rate first increases with temperature and then decreases. For 1 NPSH the maximum occurs at about 190^{o}F as opposed to about 120^{o}F for an open-beaker 1 atm. test. The termperature for maximum damage rate appears to increase slightly for higher NPSH, perhaps to 210^{o}F, though the data is not sufficiently comprehensive to locate with precision the curve maxima. The decrease at high temperature for all NPSH is presumably a result of thermodynamic effects, and is of practical importance in indicating that hot water may be much less damaging than cold water, other things being equal. The same is true of other fluids in regions where vapor density becomes significant.

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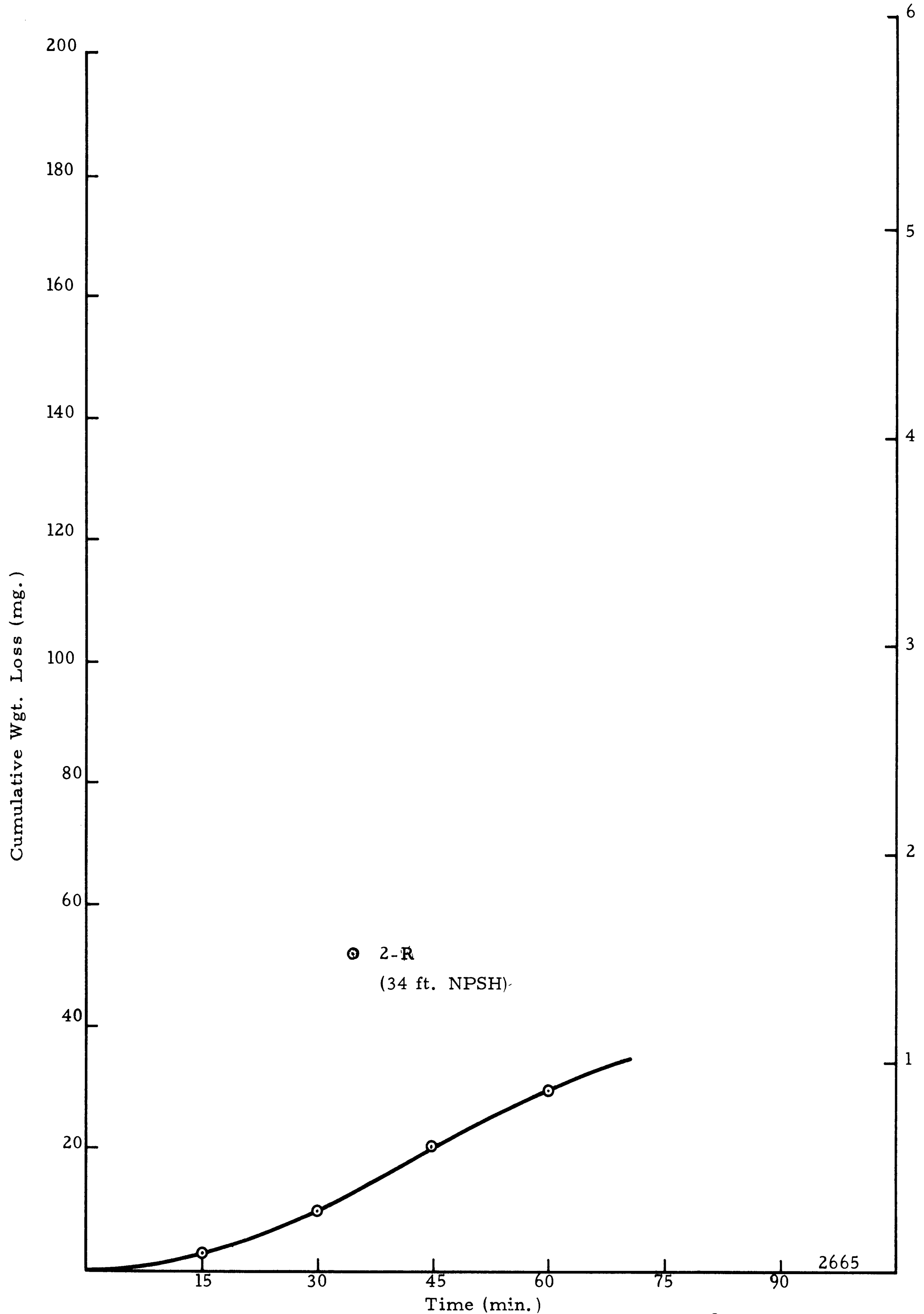


Fig. 1. Cumulative Damage vs. Test Duration of SAE-660 at 55°F and 1 atm. NPSH

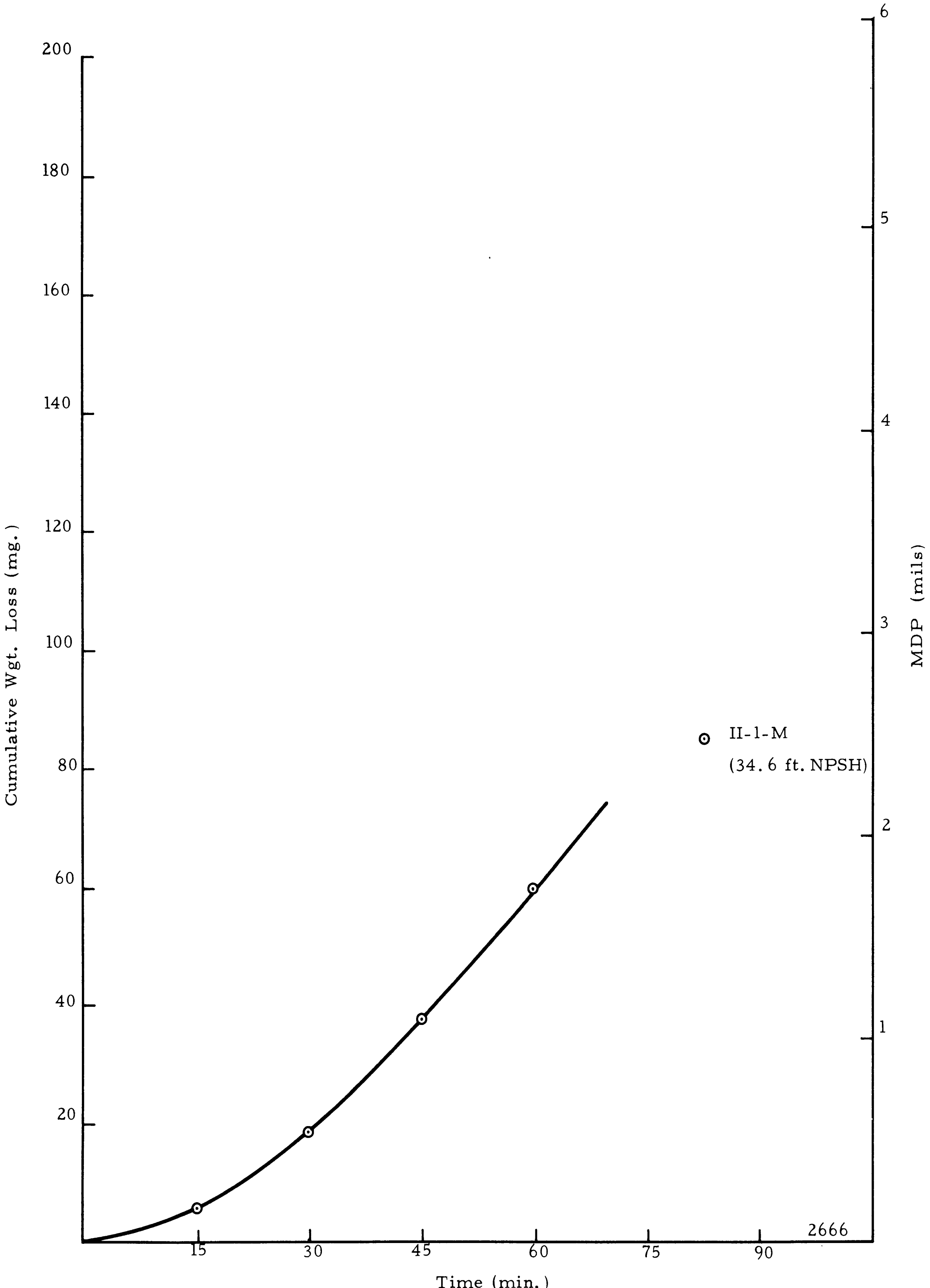


Fig. 2. Cumulative Damage vs. Test Duration of SAE-660 at 150°F and 1 atm. NPSH

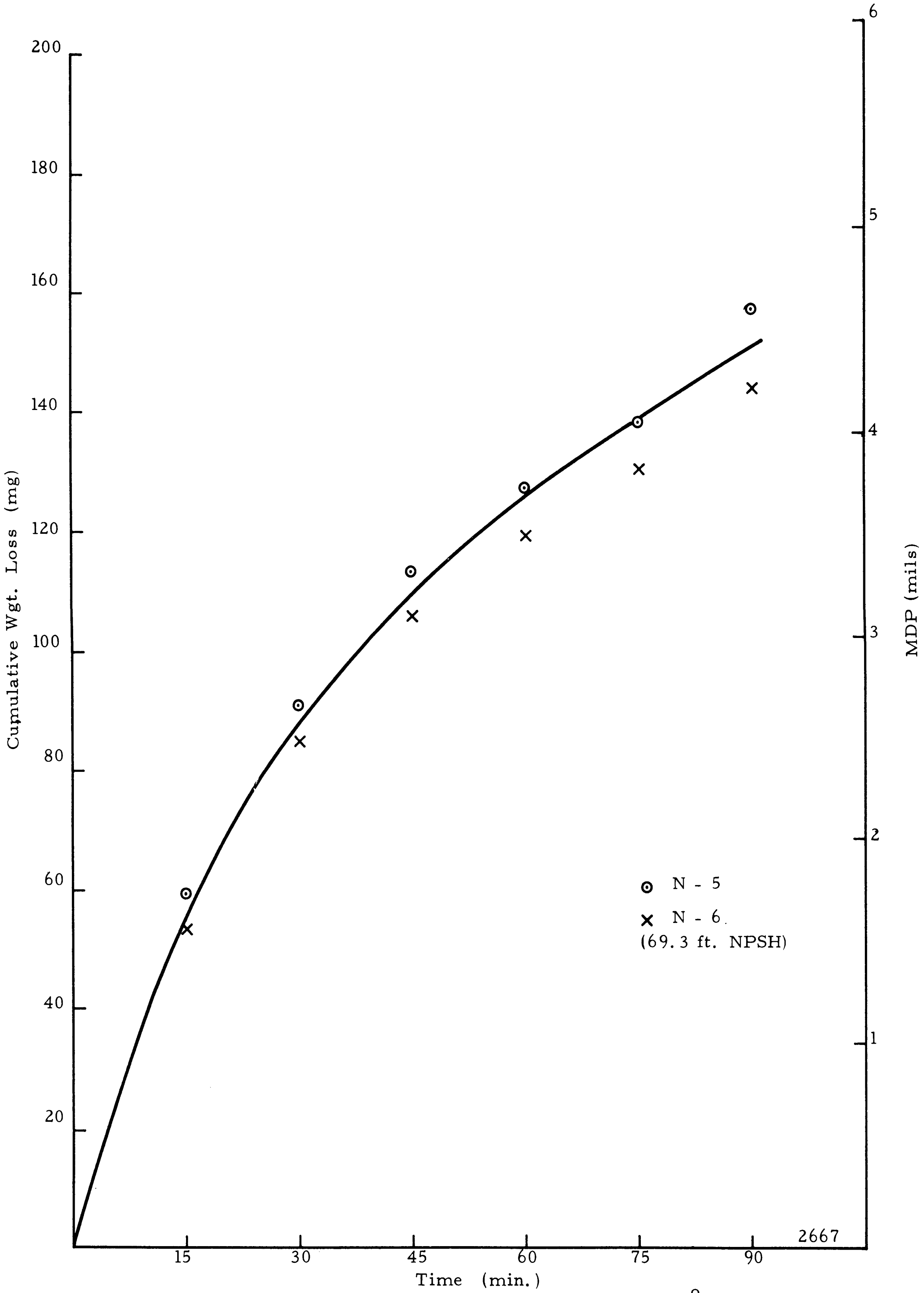


Fig. 3. Cumulative Damage vs. Test Duration of SAE-660 at 150°F and 2 atm. NPSH

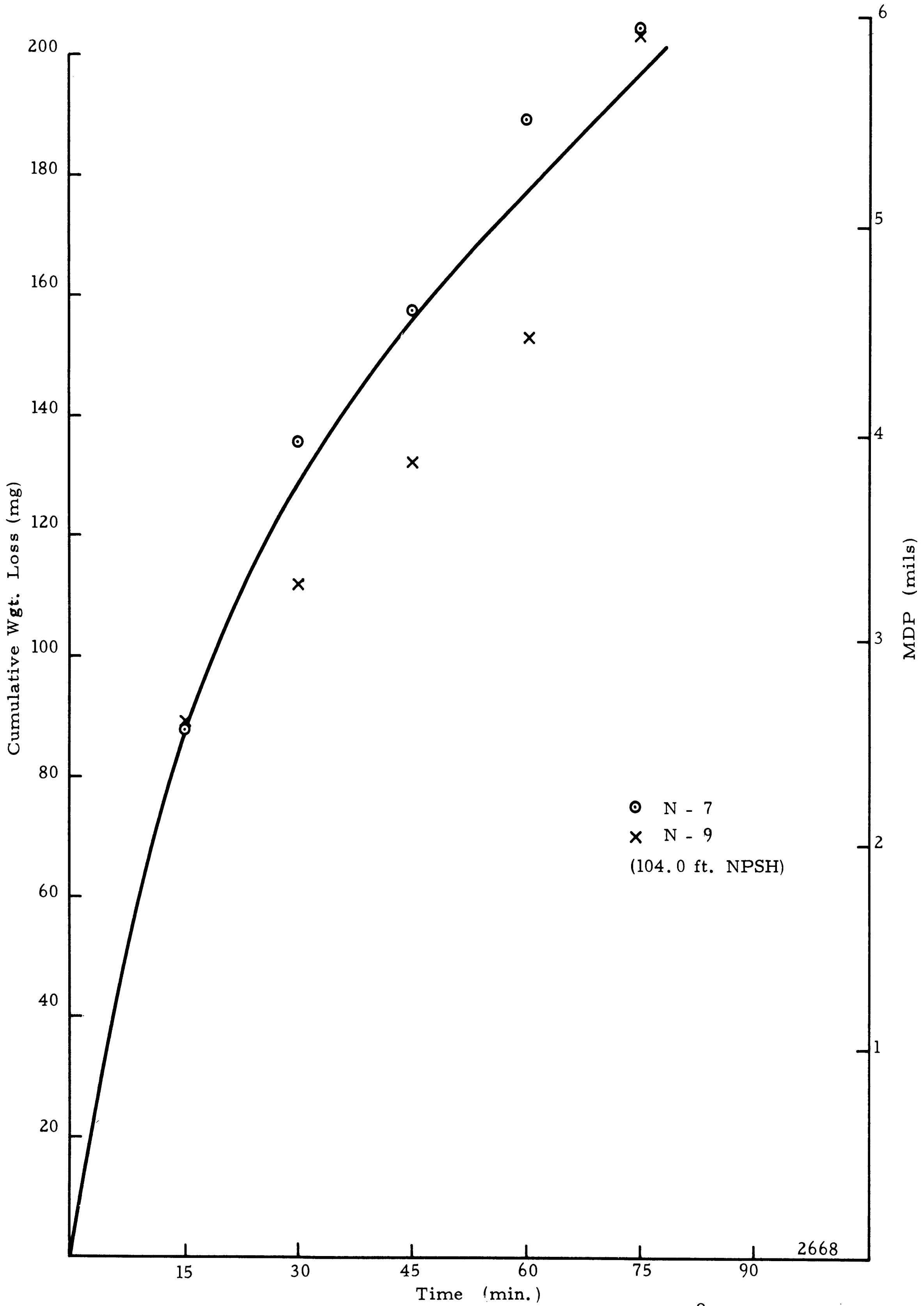


Fig. 4. Cumulative Damage vs. Test Duration of SAE-660 at 150°F and 3 atm. NPSH

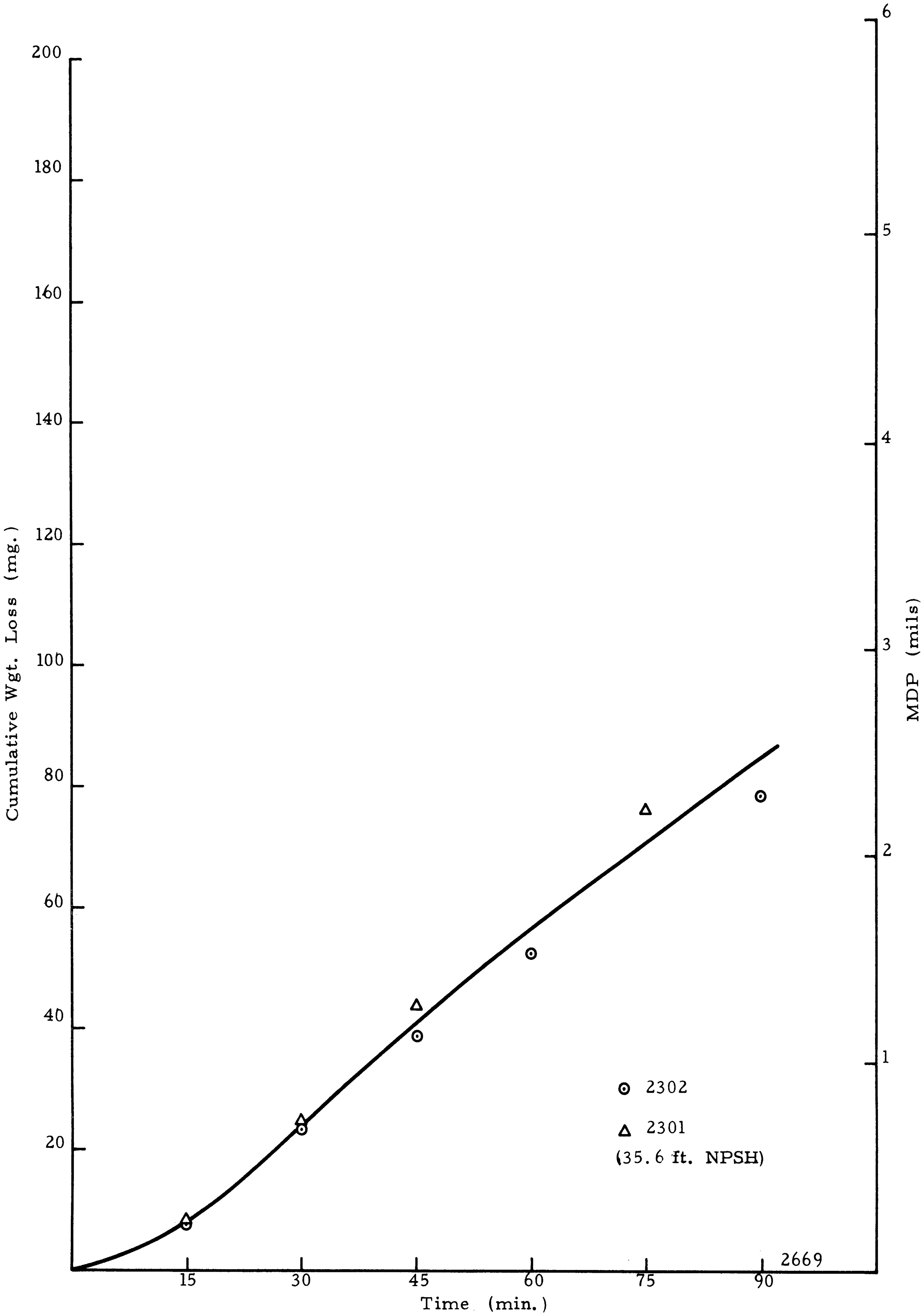


Fig. 5. Cumulative Damage vs. Test Duration of SAE-660 at 230°F and 1 atm. NPSH

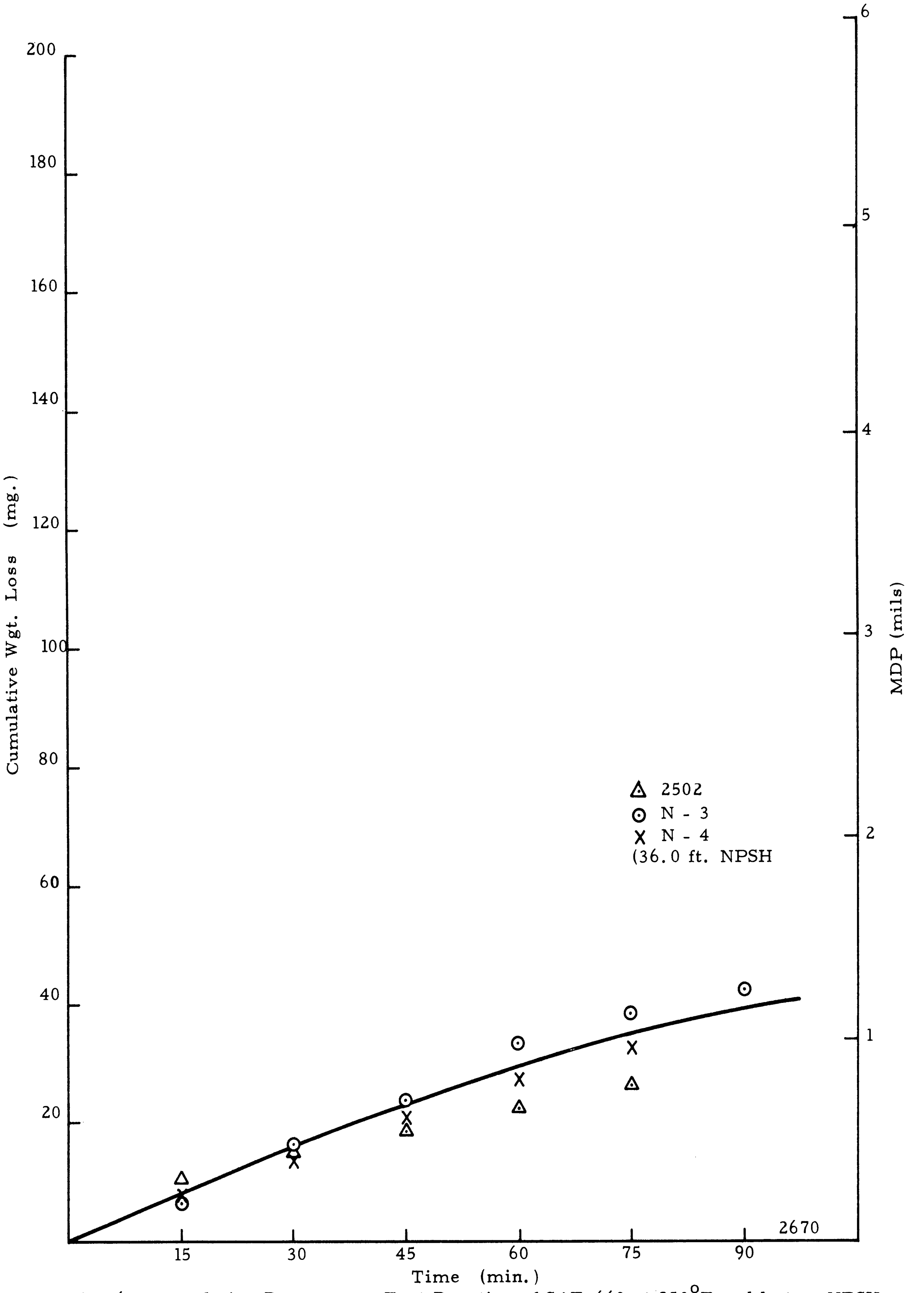


Fig. 6. Cumulative Damage vs. Test Duration of SAE-660 at 250°F and 1 atm. NPSH

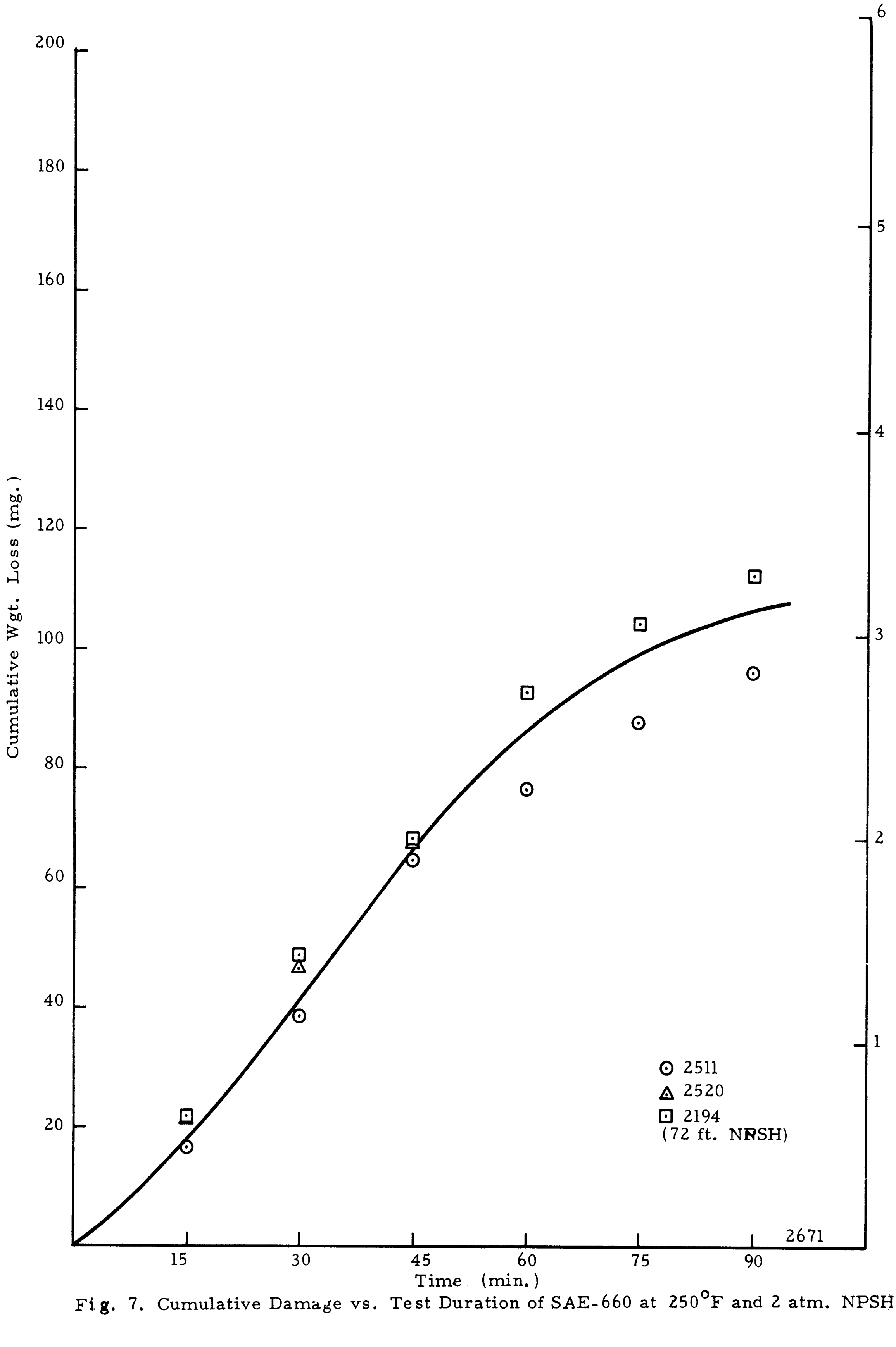


Fig. 7. Cumulative Damage vs. Test Duration of SAE-660 at 250°F and 2 atm. NPSH

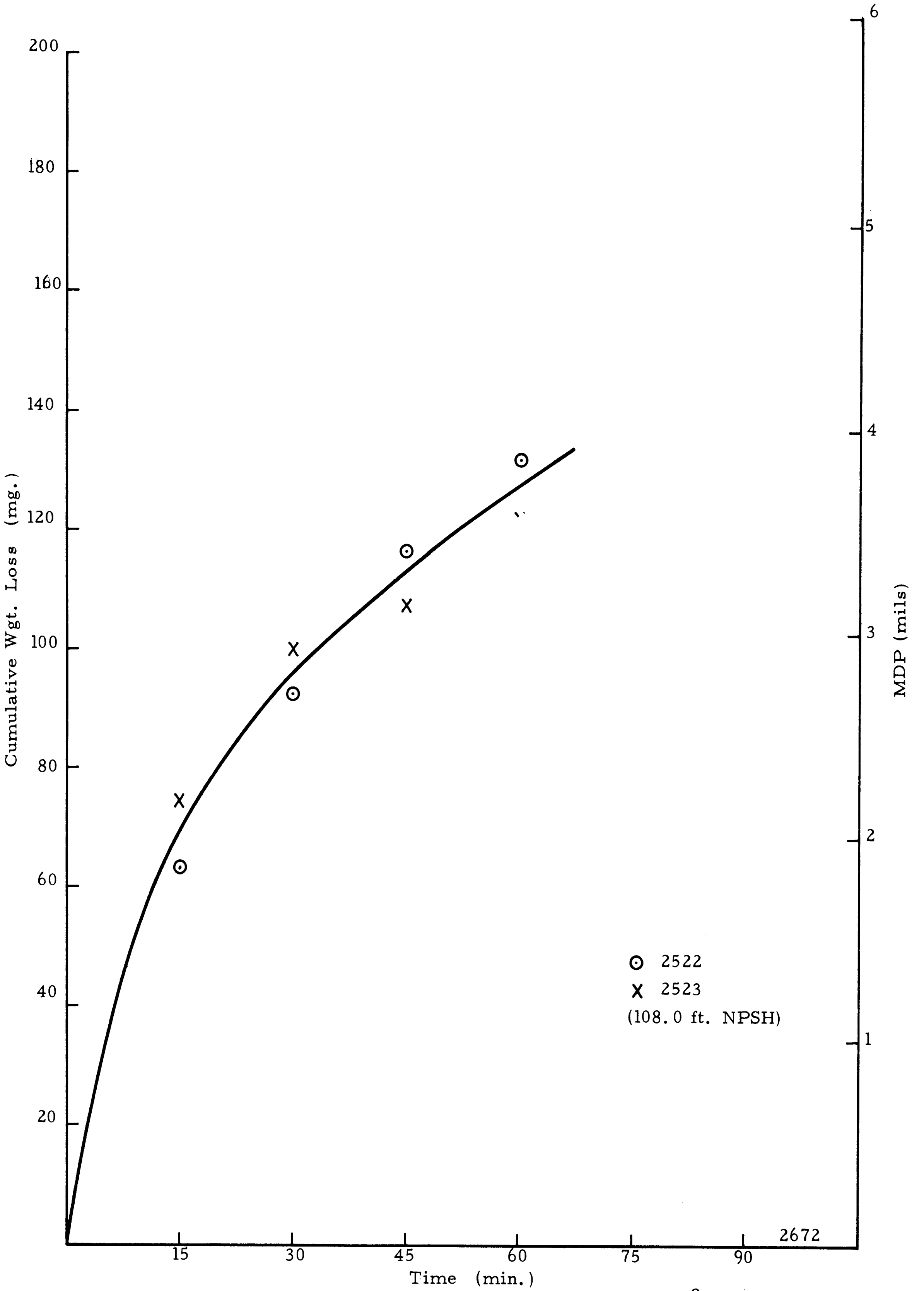


Fig. 8. Cumulative Damage vs. Test Duration of SAE-660 at 250°F and 3 atm. NPSH

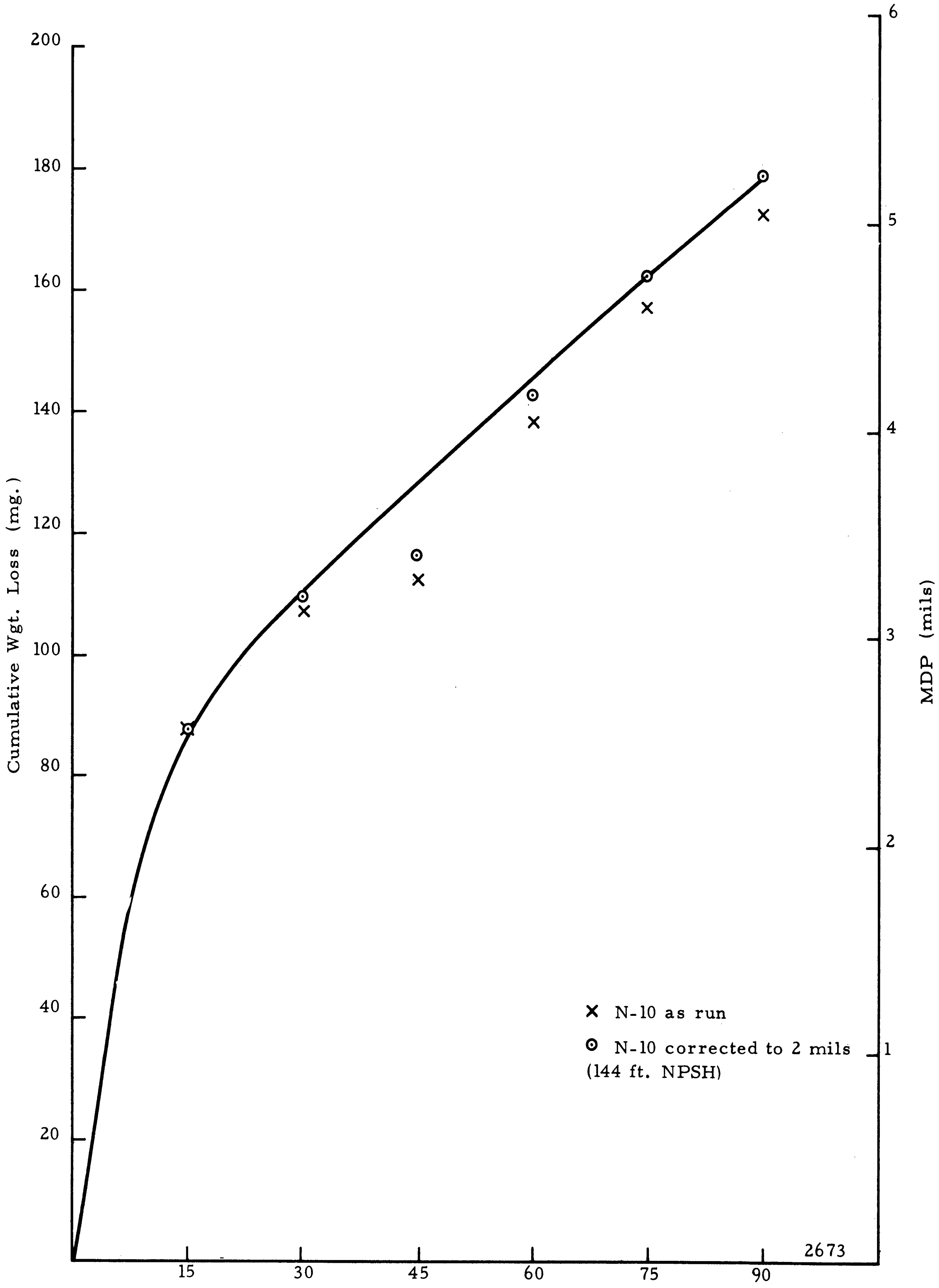
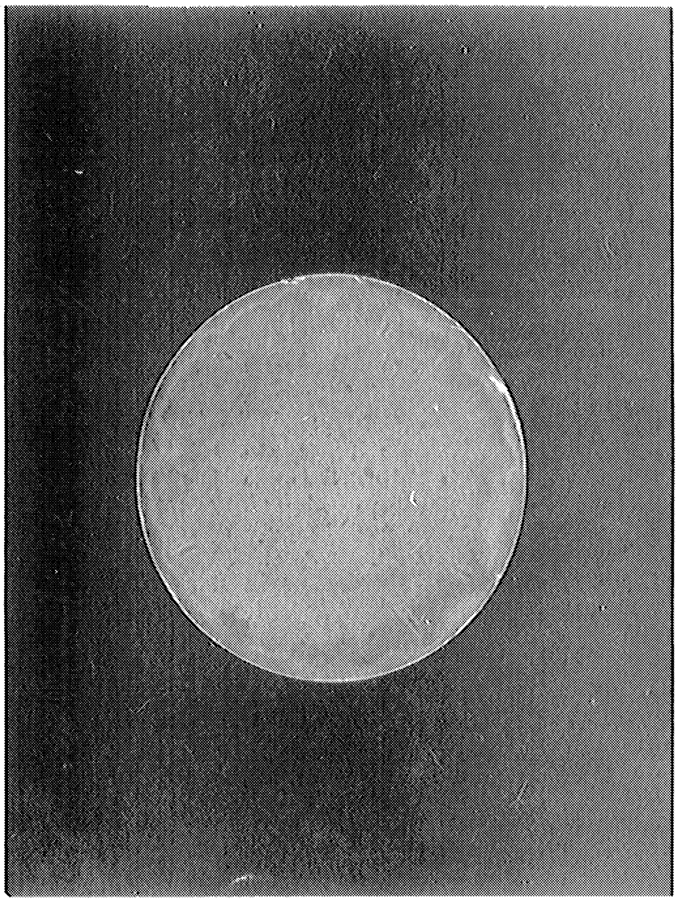


Fig. 9. Cumulative Damage vs. Test Duration of SAE-660 at 250°F and 4 atm. NPSH



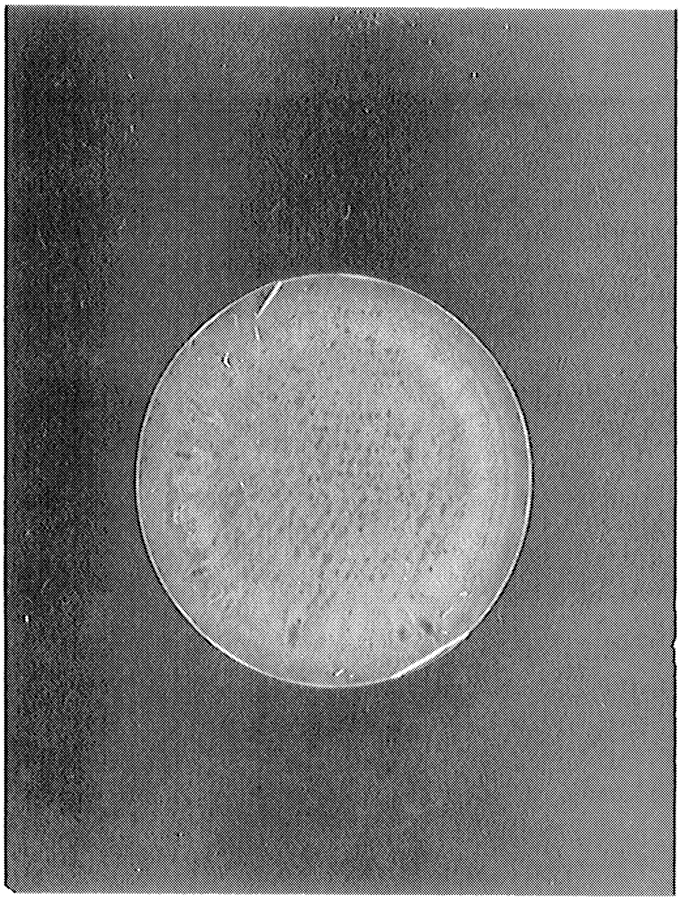
2674

Specimen 2 - R

Duration = 60 min.

Wgt. Loss = 30 mg.

Fig. 10. Specimen Tested at 55°F and 1 atm. NPSH



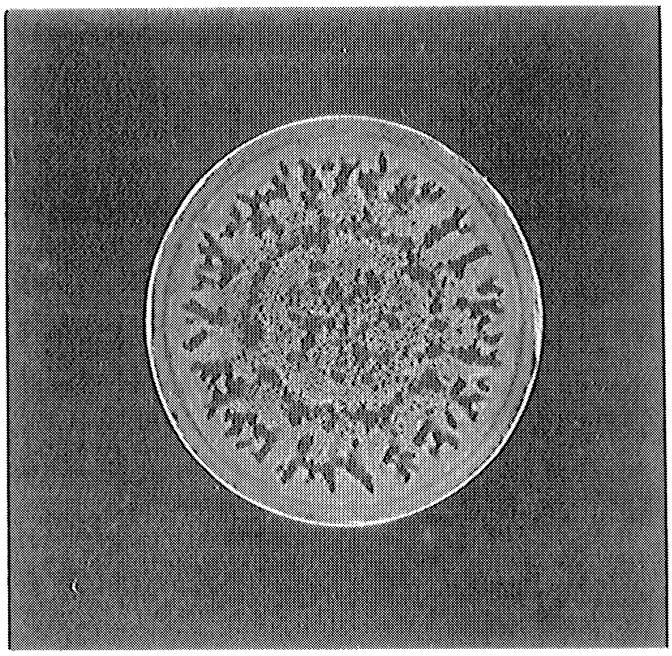
2675

Specimen II-1-M

Duration = 60 min.

Wgt. Loss = 59.5 mg.

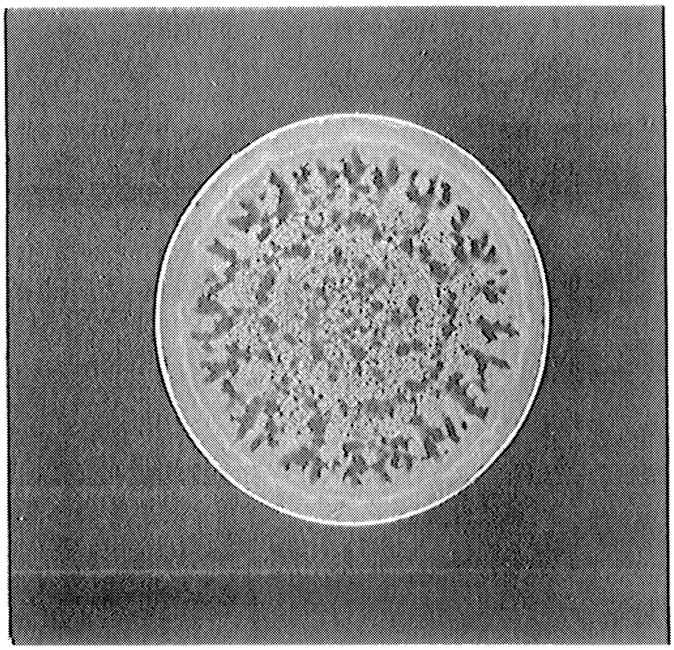
Fig. 11. Specimen Tested at 150°F and 1 atm. NPSH



Specimen N-S

Duration = 90 min.

Wgt. Loss = 144 mg.



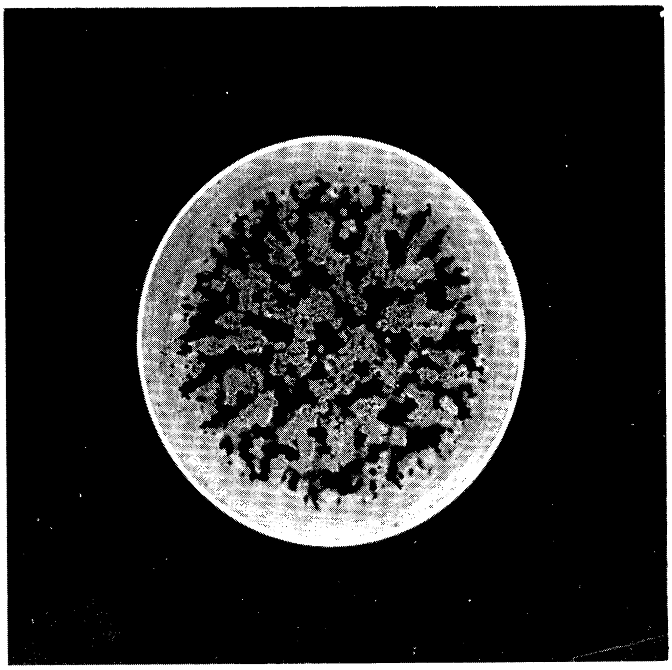
Specimen N-6

Duration = 90 min.

Wgt. Loss = 157 mg.

2676

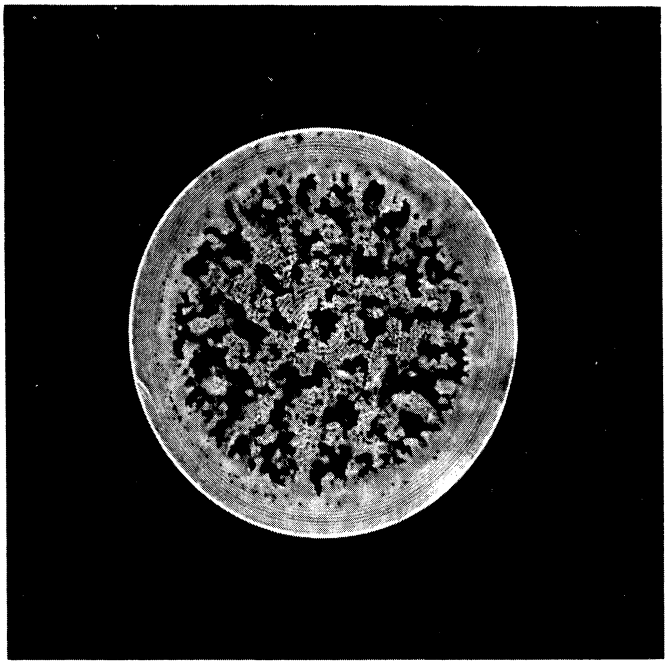
Fig. 12. Specimen Tested at 150°F and 2 atm. NPSH



Specimen N-7

Duration = 90 min.

Wgt. Loss = 219 mg.



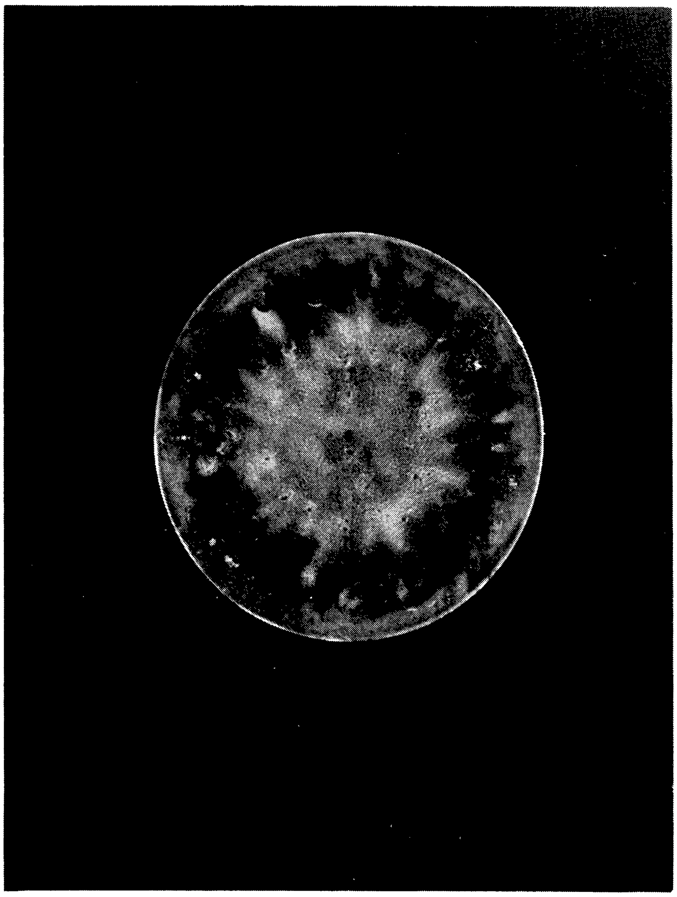
Specimen N-9

Duration = 90 min.

Wgt. Loss = 242.5 mg.

2677

Fig. 13. Specimens Tested at 150°F and 3 atm. NPSH



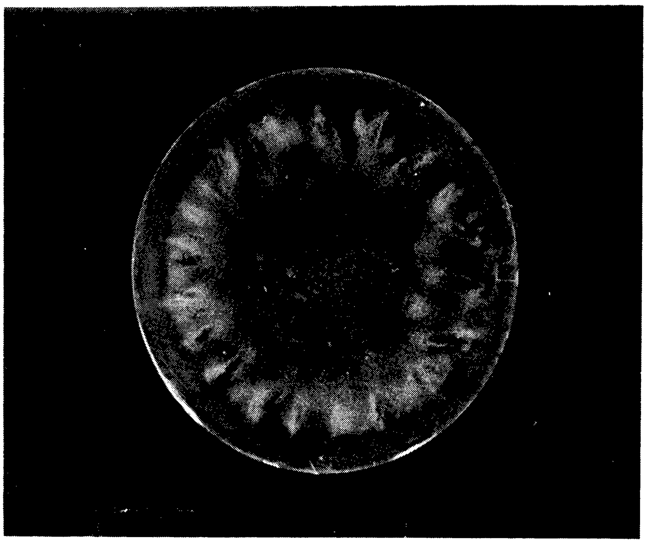
2678

Specimen 2302

Duration = 120 min.

Wgt. Loss = 96 mg.

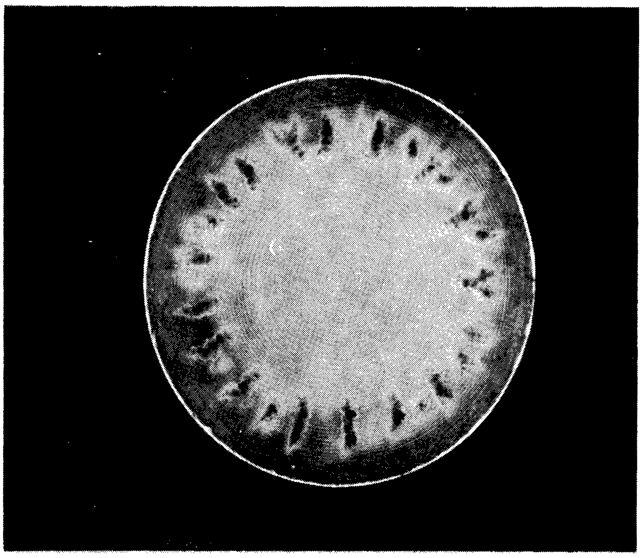
Fig. 14. Specimen Tested at 230°F and 1 atm. NPSH



Specimen 2502

Duration = 75 min.

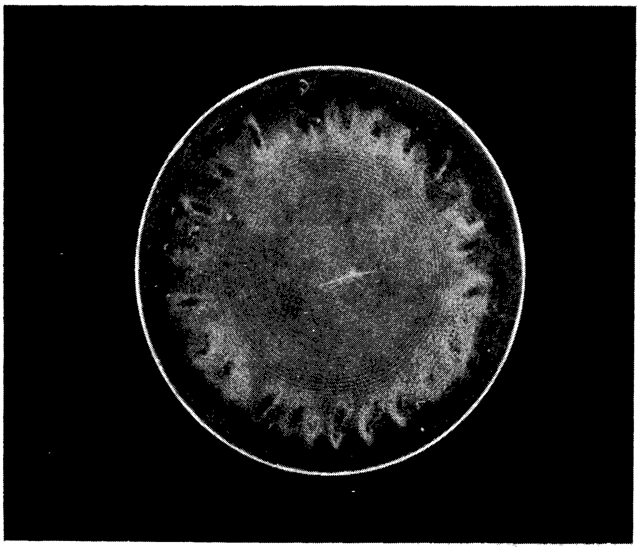
Wgt. Loss = 26.5 mg.



Specimen N-3

Duration = 90 min.

Wgt. Loss = 42.5 mg.



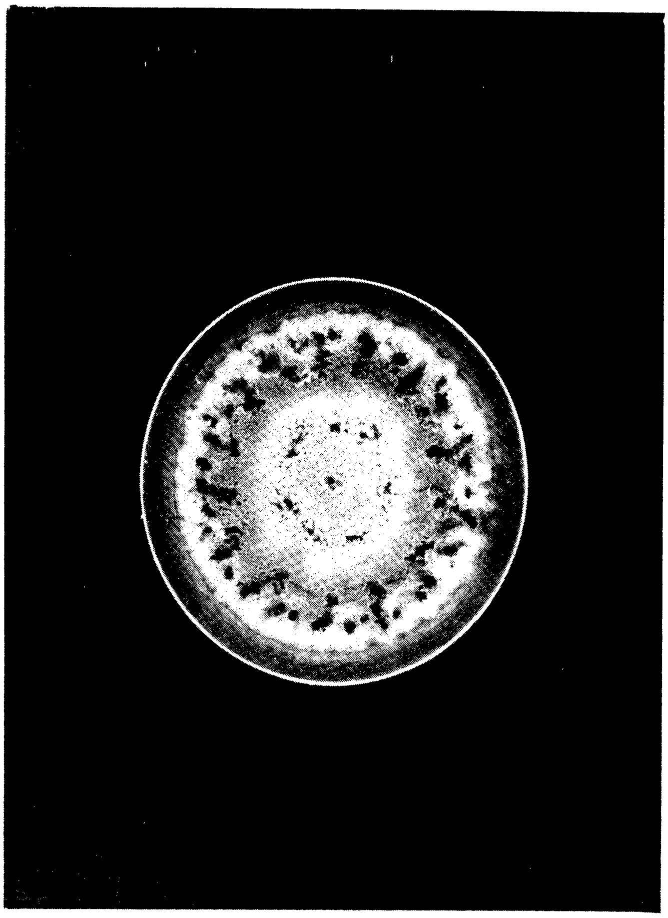
Specimen N-4

Duration = 75 min.

Wgt. Loss = 32.5 mg.

2679

Fig. 15. Specimen Tested at 250°F and 1 atm. NPSH



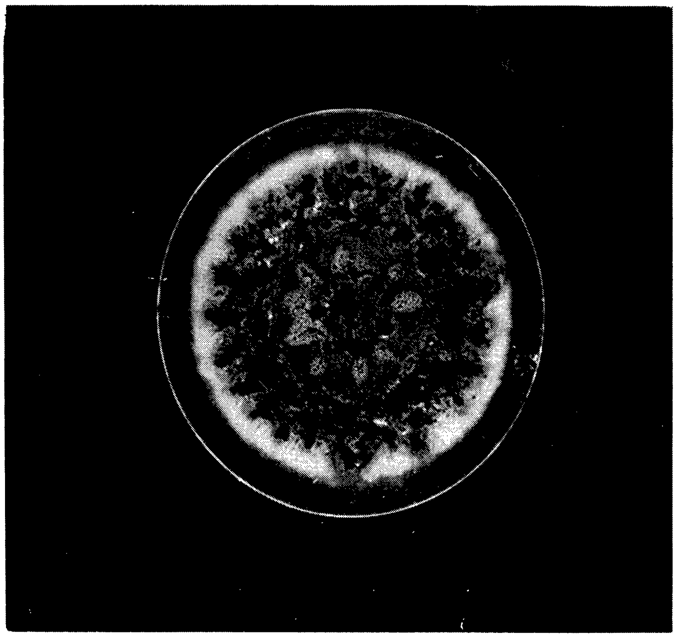
2680

Specimen 2511

Duration = 90 min.

Wgt. Loss = 96.5 mg.

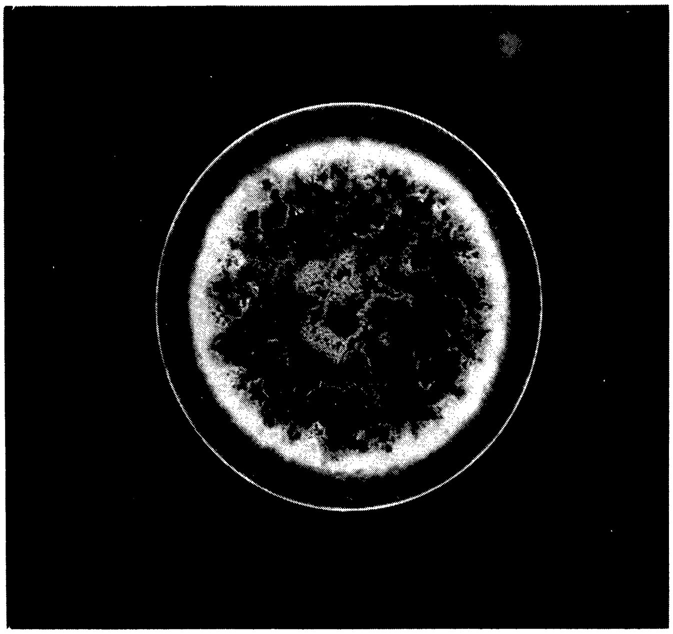
Fig. 16. Specimen Tested at 250°F and 2 atm. NPSH



Specimen 2522

Duration = 90 min.

Wgt. Loss = 130 mg.



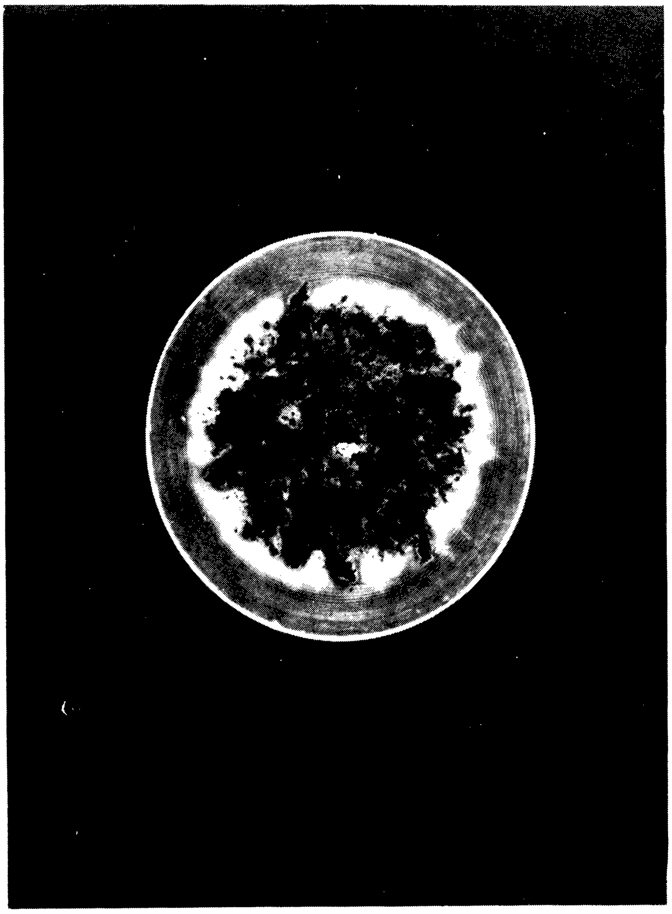
Specimen 2523

Duration = 90 min.

Wgt. Loss = 125.5 mg.

2681

Fig. 17. Specimen Tested at 250°F and 3 atm. NPSH



2682

Specimen N-10

Duration = 90 min.

Wgt. Loss = 173 mg.

Fig. 18. Specimen Tested at 250^{o}F and 4 atm. NPSH

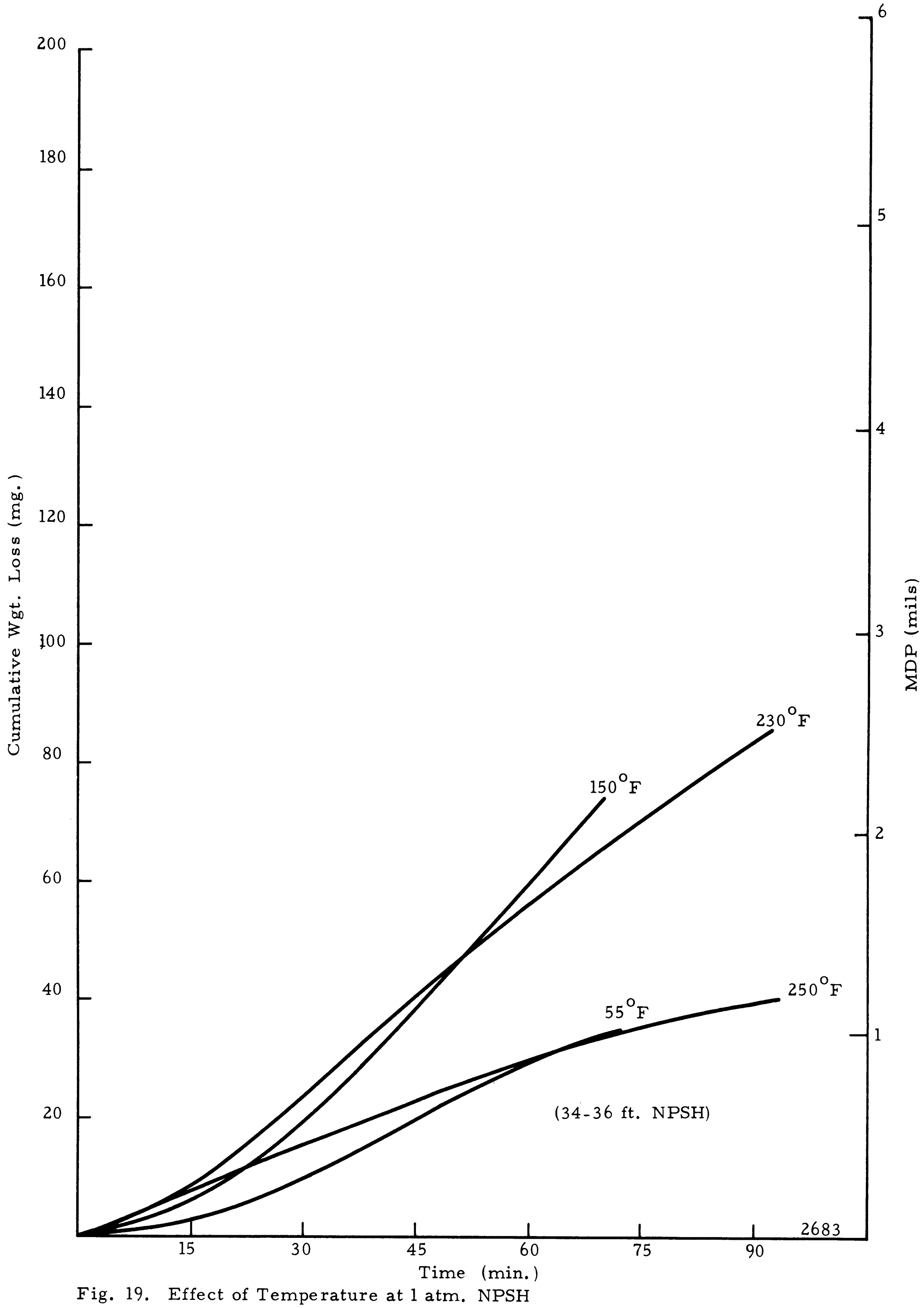


Fig. 19. Effect of Temperature at 1 atm. NPSH

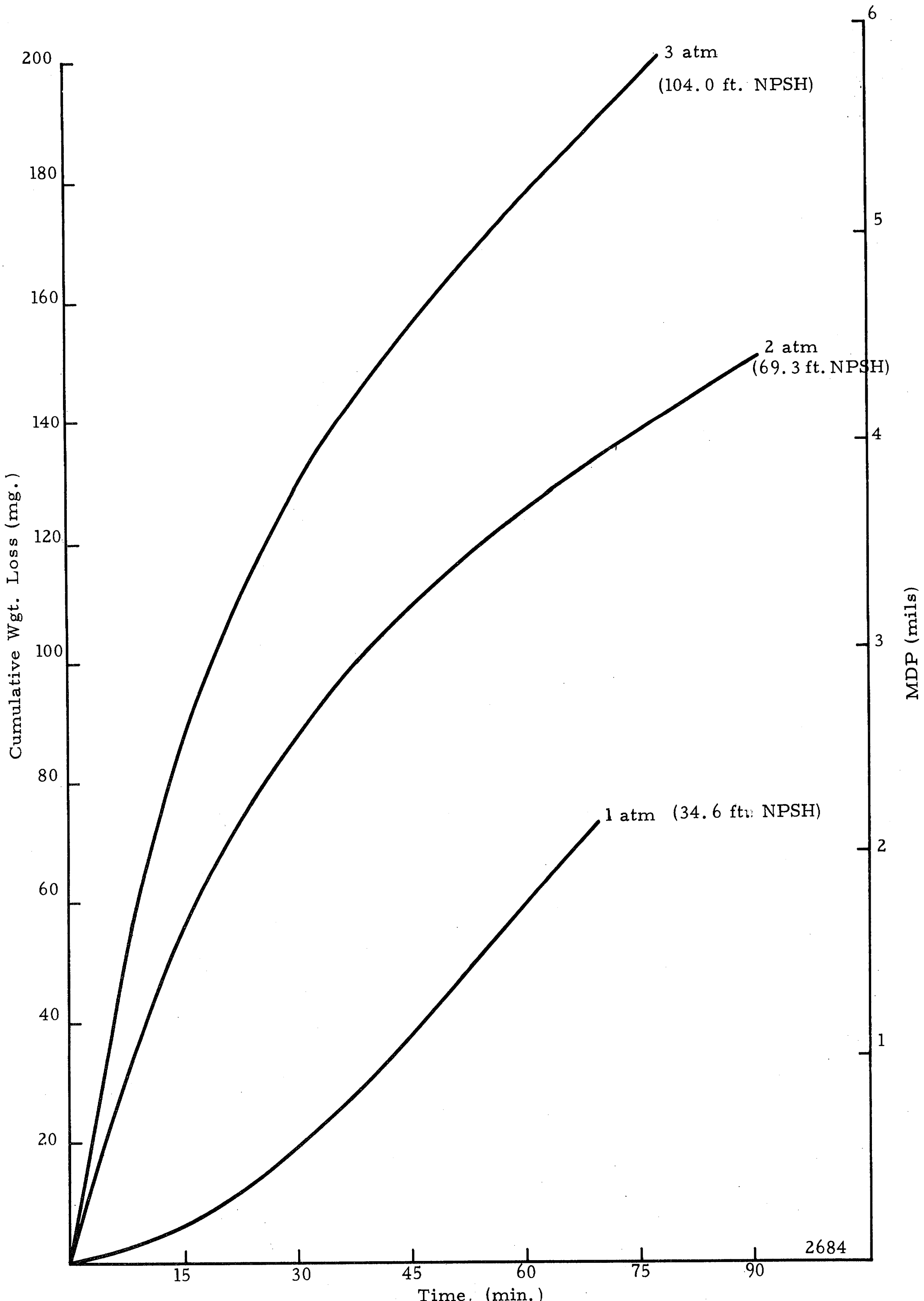


Fig. 20. Effect of NPSH at 150°F

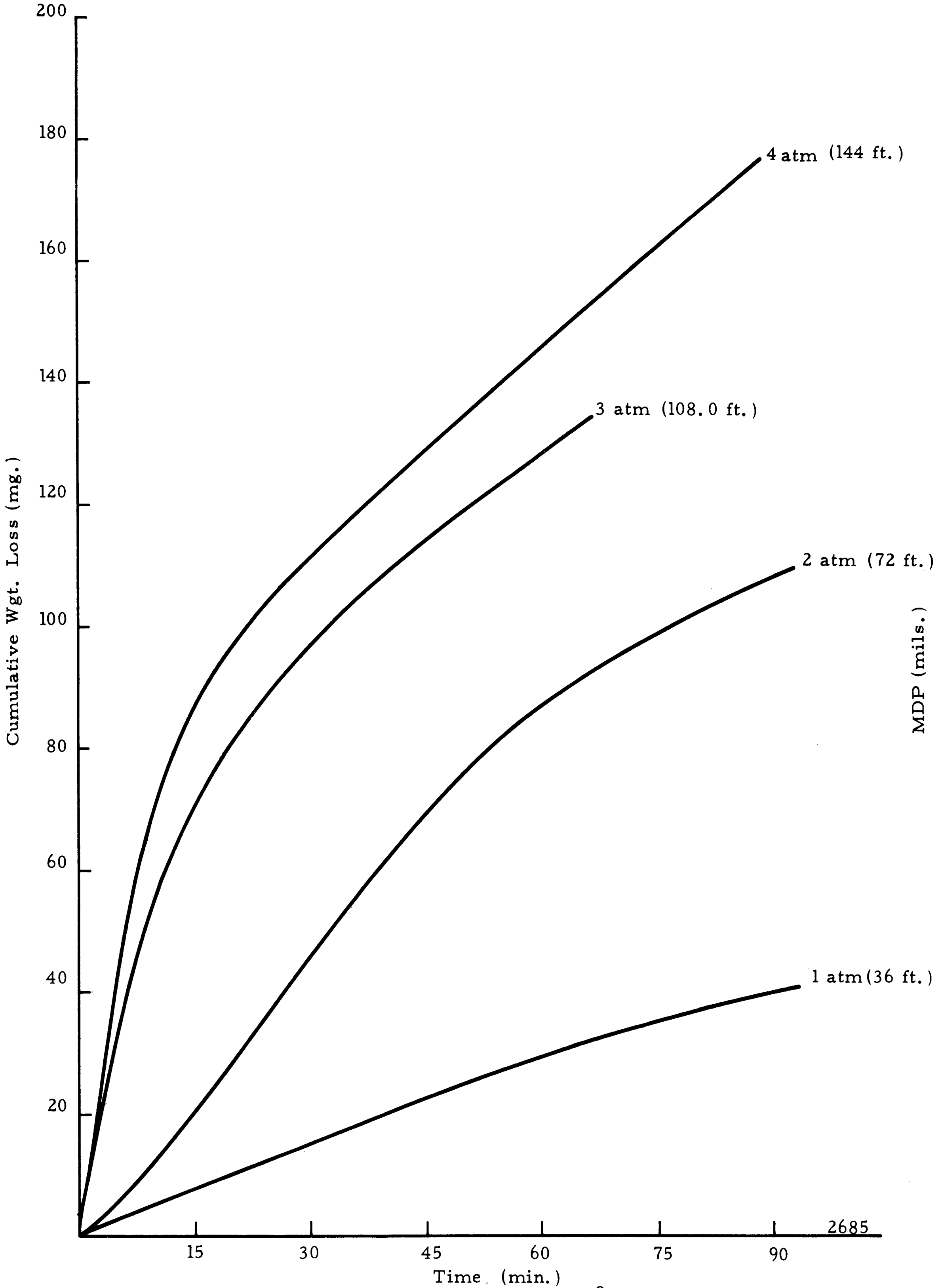


Fig. 21. Effect of NPSH at 250°F

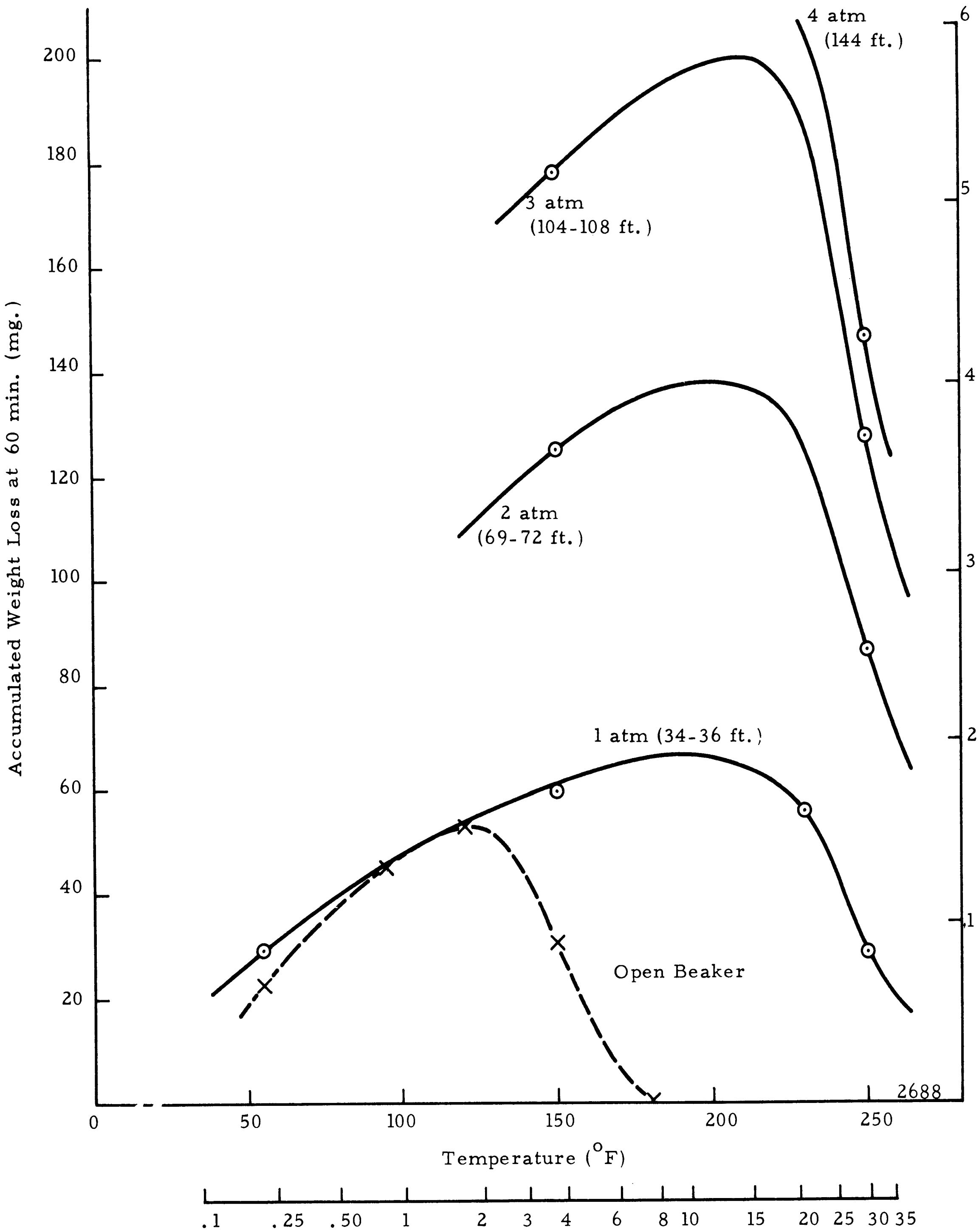


Fig. 22. Damage at 60 minutes vs. Temperature

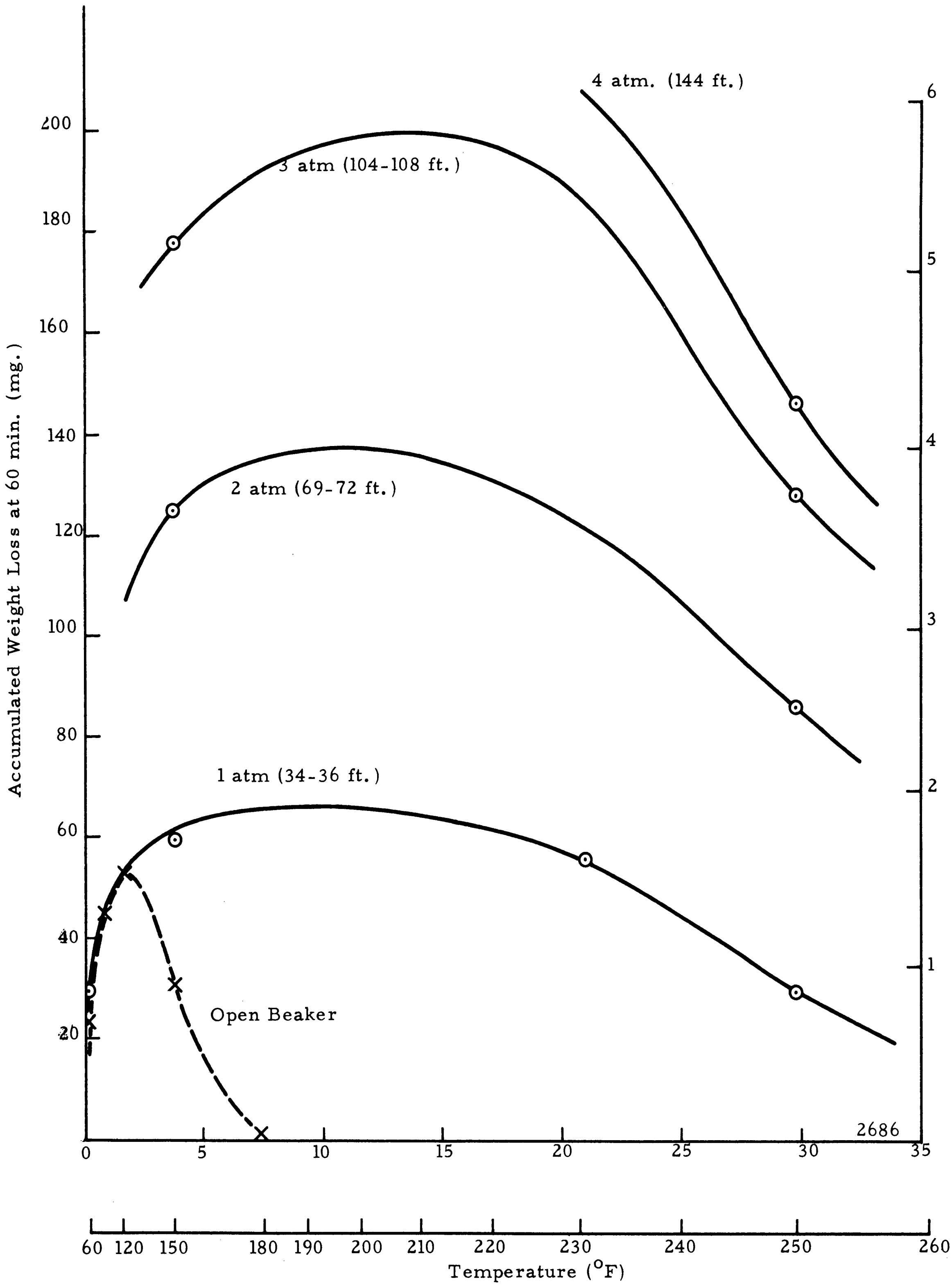


Fig. 23. Damage at 60 min. vs. Vapor Pressure

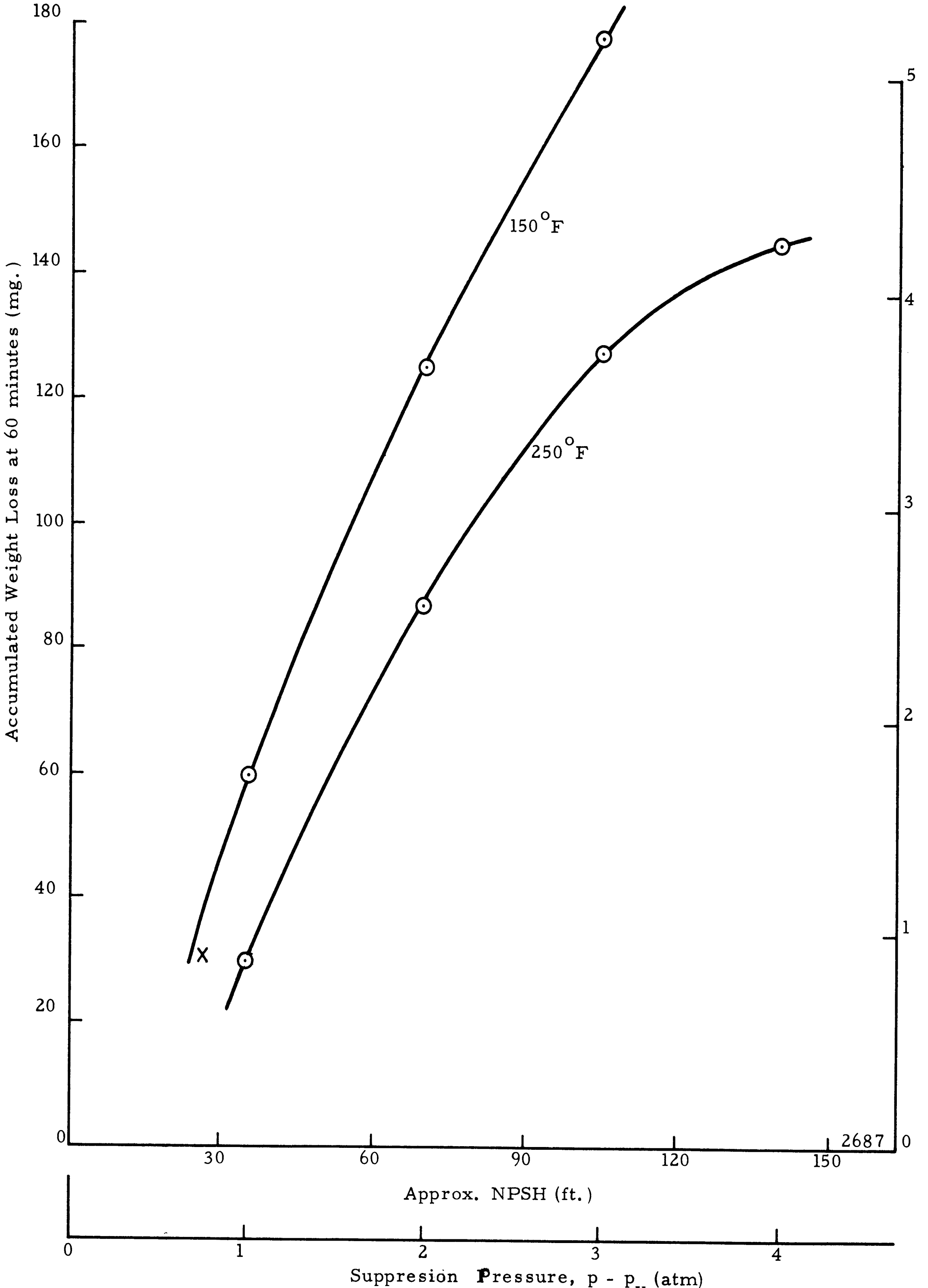


Fig. 24. Damage at 60 minutes vs. NPSH

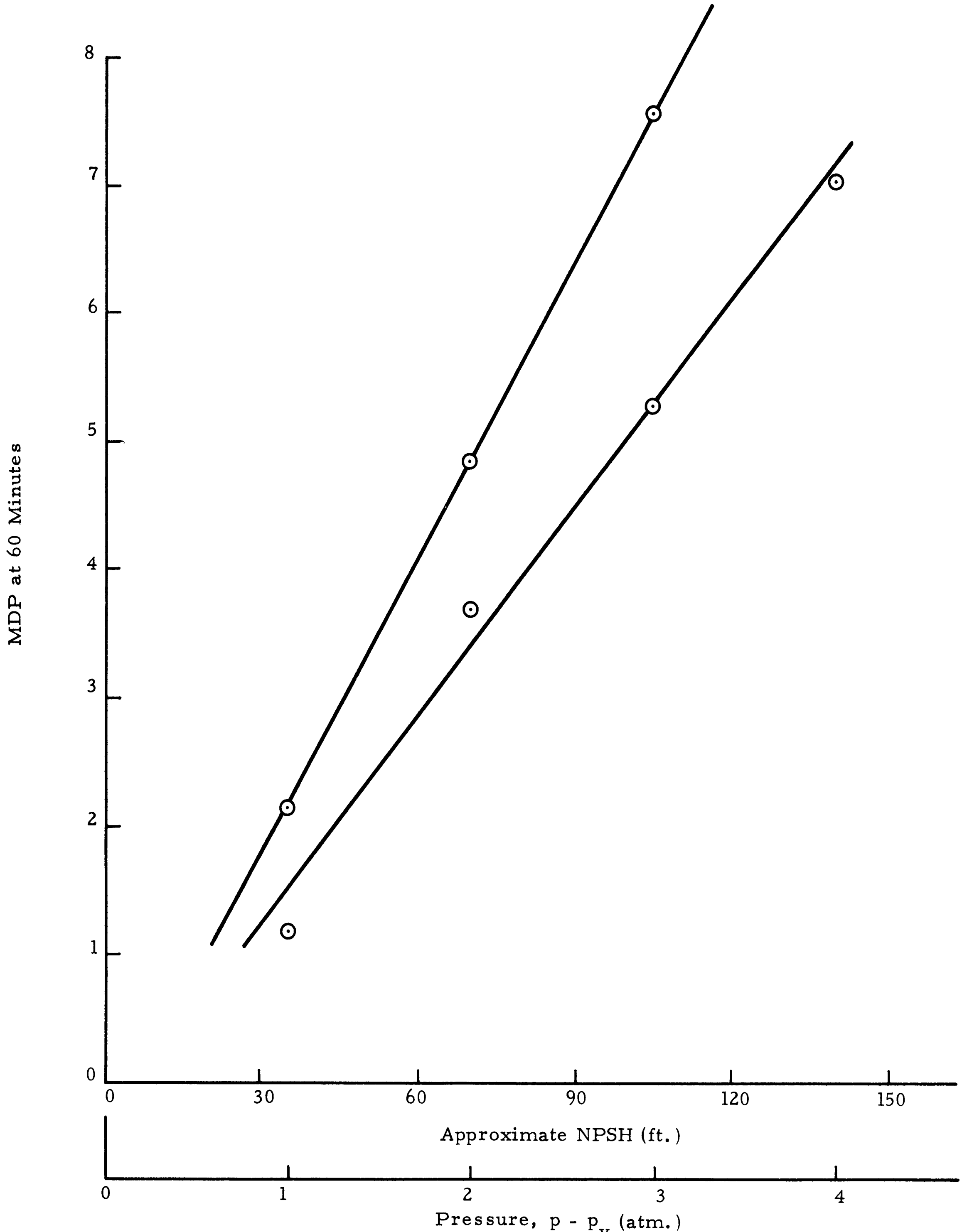


Figure 25. Damage at 60 Minutes versus NPSH Based on Actually Damaged Area

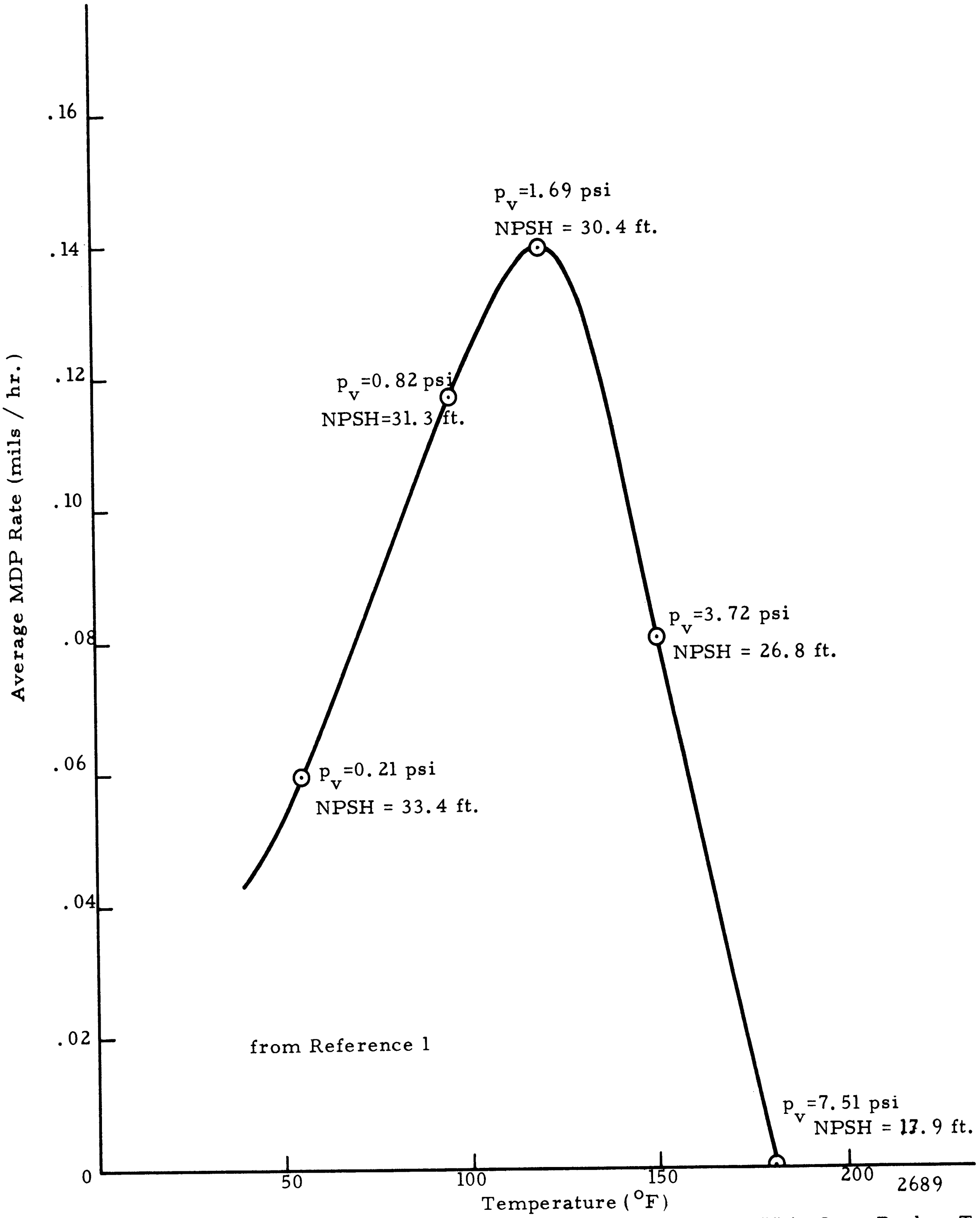


Fig. 26. Damage Rate vs. Temperature for 304 SS in Open Beaker Test

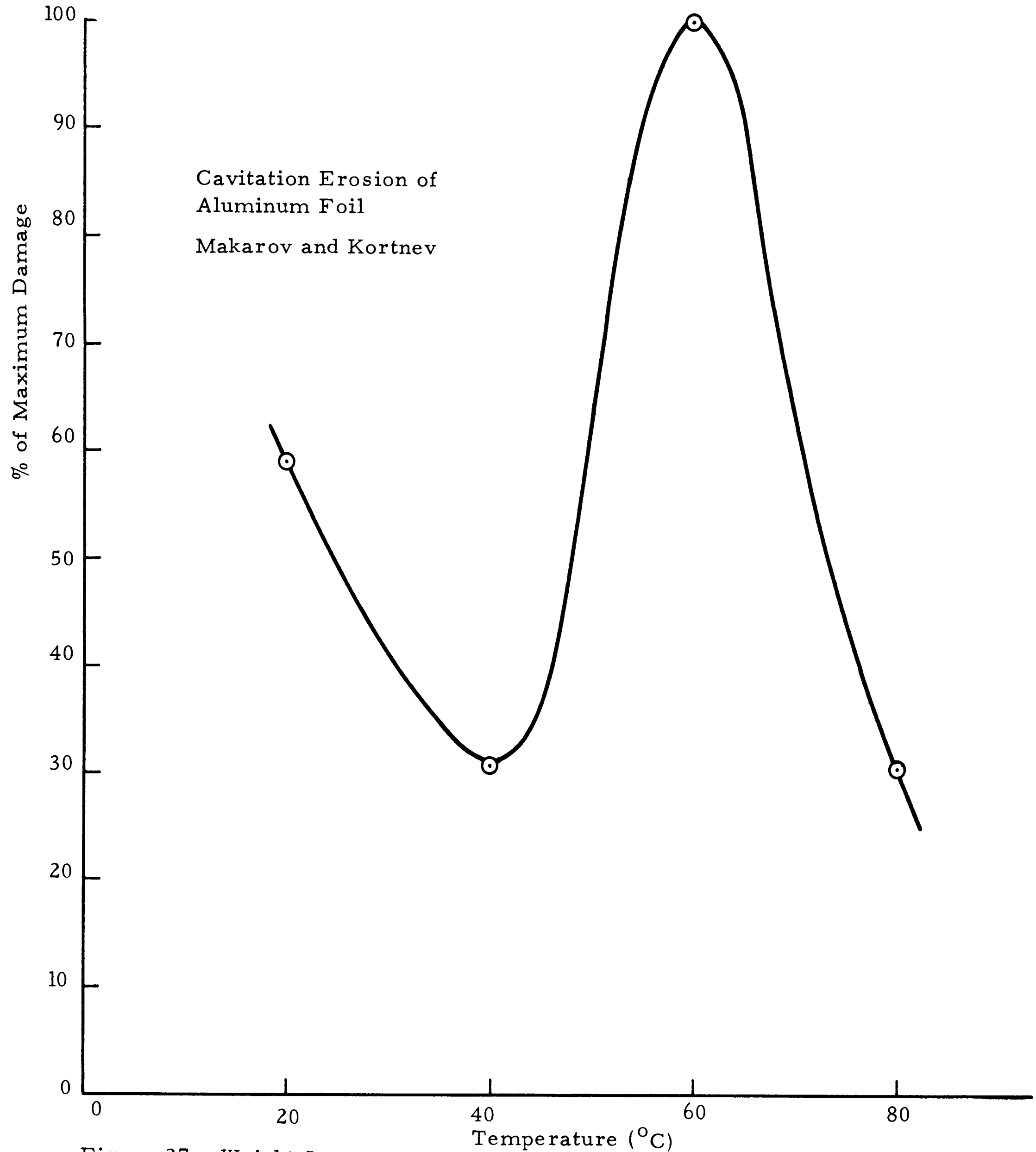


Figure 27. Weight Loss versus Temperature for Cooling