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AN EXAMINATION OF CAVITATION EROSION EFFICIENCY

by

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1. Introduction

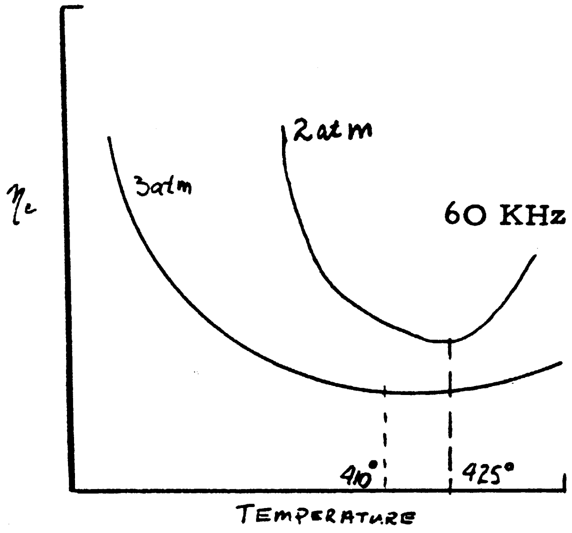
Previous work of Hobbs and others suggests the possibility of relating the ultimate resilience of a material to the damage experienced by material during cavitation. This correlation has proven to be somewhat successful in correlating cavitation damage in laboratory cases.

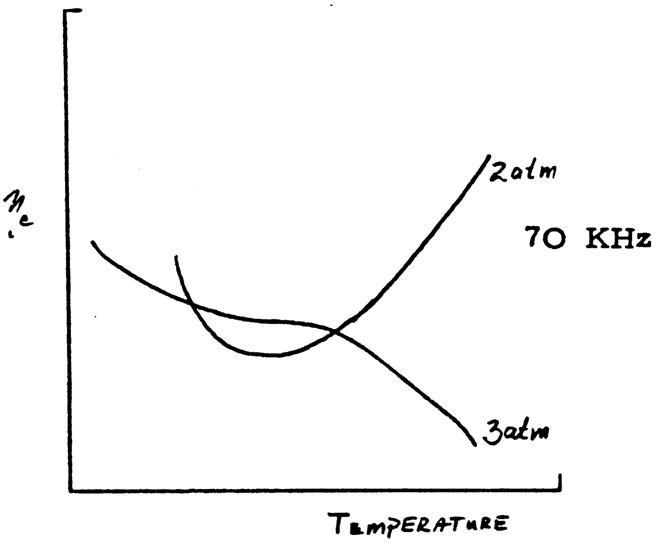
An attempt has been made on our part to develop a correlation between the product of ultimate resilience and the cavitation damage volume loss rate of a material to the acoustic energy present in a cavitation field. This product (UR x VLR) represents the "power" involved in eroding away a given quantity of material. We termed this "erosion power". The second quantity, born out of our efforts to quantify cavitation noise, represents the energy/time imparted to the specimen surface by the cavitation cloud and is termed here "spectral area power". The ratio of "erosion power" to the "spectral area power" might then be thought of as "cavitation erosion efficiency" which represents the extent to which the energy/time inherent in the cavitation cloud is actually transferred to the material. (2).

2. Summary

Our experiments show that this "cavitation efficiency" is a function of suppression pressure and temperature. Various trends were observed as we varied the frequency of the high-pass filter used in collecting cavitation noise data.

1. At 60 kHz filter frequency, the efficiency reached a minimum at an intermediate temperature, and attained maximum values at the relatively higher and lower temperatures. As the system pressure decreased, the overall cavitation efficiency tended to increase.
2. At 70 kHz filter frequency, the low pressure efficiency values followed the trend experienced at 60 kHz, but at the higher pressure the efficiency followed a decreasing downward trend.
3. At 80 kHz filter frequency, the low pressure efficiency values followed the trend experienced at 60 and 70 kHz, but at the higher pressure, the efficiency values followed a general decreasing trend with a slight increase at an intermediate temperature.





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itation Efficiency

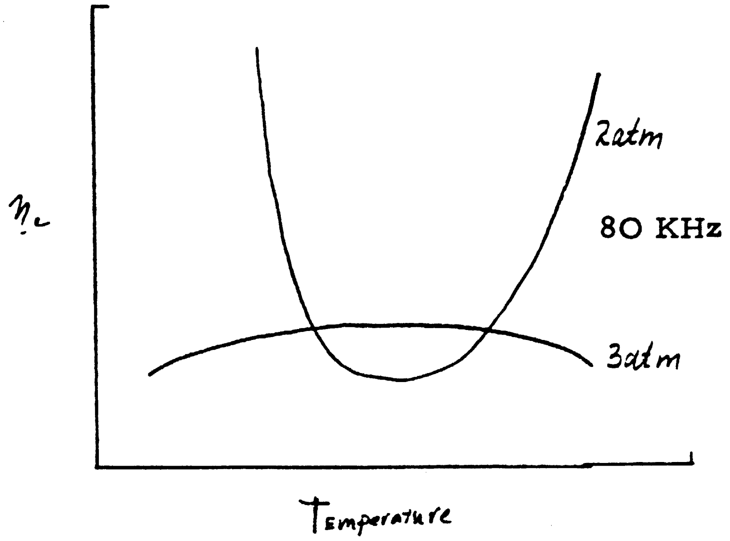

Figure 1 shows in an approximate manner the trends described. Figures 12, 13, and 14 show these trends in more detail.

We are unable at this time to offer any hypotheses concerning these trends. To our knowledge, this was the first attempt to quantify such concepts in this way, so that no comparable data exists.

Future work is planned. Spectral area measurements can hopefully be taken utilizing a multi-channel analyzer and related equipment, and the wave-guide probes will be replaced with a newly-developed direct-submergence high temperature probe (Fig. 7). This instrumentation should provide us with more reliable spectral area data from which hopefully more applicable theories concerning observed trends will result.

3. Explanation of Cavitation Efficiency

The cavitation efficiency for a certain cavitation regime as here defined is the ratio of two quantities: "erosion power" and "spectral area power". The "erosion power" of a material we define to be the amount of energy/time that must be imparted to the material in order to affect a certain amount of damage. The "spectal area power" is the energy/time inherent in the collapsing cavitation cloud as detected by a suitable acoustic probe having the same surface area as the damage specimen. Both these quantities are discussed in detail below.

3.1 Erosion Power

The erosion power refers to the amount of energy/time that must be imparted to the material in order to damage the material. It is here based on the concept of "ultimate resilience", a term used by Hobbs and others in earlier work. The "ultimate resilience" is a material properly related to the true stress-strain curve of a material.

The figure below represents a typical true-stress-strain curve.

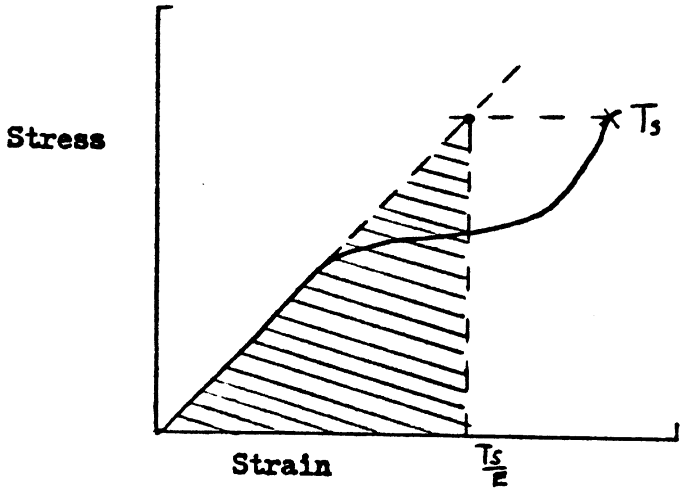

Figure 2

True Stress-Strain Curve

The cross-hatched area is the "ultimate resilience" of the material. Since the process of cavitation represents highly transient loading, it is thus assumed that Hooke's law is valid to final fracture, as little elongation or reduction in cross-sectional area occurs (ie, brittle fracture occurs). Therefore, during the cavitation process, the stress-strain relationship is assumed linear up to the point of failure, as shown in Fig. 4. From geometry, the following then holds:

$$UR = 1/2 \ \frac{(T_s^{\ 2})}{E} \qquad ---- \qquad (1)*$$

Temperature effects on the material tensile strength must be taken into account, when large temperature differences are involved, as in our sodium tests.

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*Typically the ultimate resilience is in units of $lbf/in.^2$

Finally, the erosion power, EP, or energy/time needed to inflict a certain amount of cavitation damage, is then simply the ultimate resilience times the volume loss rate,

$$EP = UR \times VLR \qquad ---- \qquad (2)$$

Both quantities, UR and VLR are easily measurable from standard laboratory cavitation tests. The VLR, usually expressed in terms of a $\frac{WLR}{\rho}$ $\left(\frac{\text{weight loss rate}}{\text{density}}\right)$, should be in comparable units to afford ease of calculation of erosion power.

3.2 Spectral Area Power

The "spectral area power" represents the amount of energy/time inherent in the cavitation field around the material or test specimen. This quantity was here used in an attempt to quantify cavitation acoustic energy through the use of wave-guide sonic probes, a high-pass filter, and a pulse counter (3). Our general hypothesis has been that the "acoustic energy" is directly related to the energy needed to damage a material to a certain degree.

Spectral area power is calculated from the "spectral area", which is the quantified cavitation noise of a cavitation regime. The spectral area is related to the intensity of a bubble collapse pressure pulse detected by the sonic probe, and to the number of such pulses. This yields a pulse-count "spectral area". The sonic probes have been calibrated so that "spectral area power" can be derived from spectral area. This method will become clearer after closer scrutiny of the instrumentation and the method for calibrating the probe.

3.2.1 Instrumentation

In order to process the cavitation noise into spectral area the probe signal must be sorted out according to signal intensity and frequency. This sorting operation was here accomplished with the components shown in Fig. 5. In brief, the two variables, frequency and intensity, are controlled by using a high-pass filter and a discriminant pulse counter. The signal from the probe enters the high-pass filter, which can be set to filter out frequencies less than 40,60,70,80 or 90 kHz.* (See Appendix 3 for detailed instruments

After passing through the filter, the remaining signals are then quantified by means of an electronic counter. Pulse intensity is controlled by setting the dial on the counter so that it will count only pulses above a certain intensity. By keeping the frequency setting on the high-pass filter constant and varying the pulse intensity accepted by the pulse counter, a pulse intensity "spectrum" is found for that particular frequency setting. Plotted on a curve, this pulse spectrum resembles Fig. 3. The results are as expected: as the frequency setting decreases, the counter registers more counts. By controlling intensity and frequency of bubble collapse pulses, pulse spectra curves are achieved.

The area under the pulse spectra curve is referred to as the spectral area. If the intensity of the bubble collapse is assumed to be proportional directly to the acoustic energy present during the collapse, then the spectral area quantity is actually an acoustic energy quantity. By collecting data over a measured time interval, spectral area per unit time is achieved, or spectral area power is derived.

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*The high-pass filter is necessary to suppress lower frequency inputs such as the vibratory horn driving frequency (20 kHz) and other low frequency machinery or flow noise.

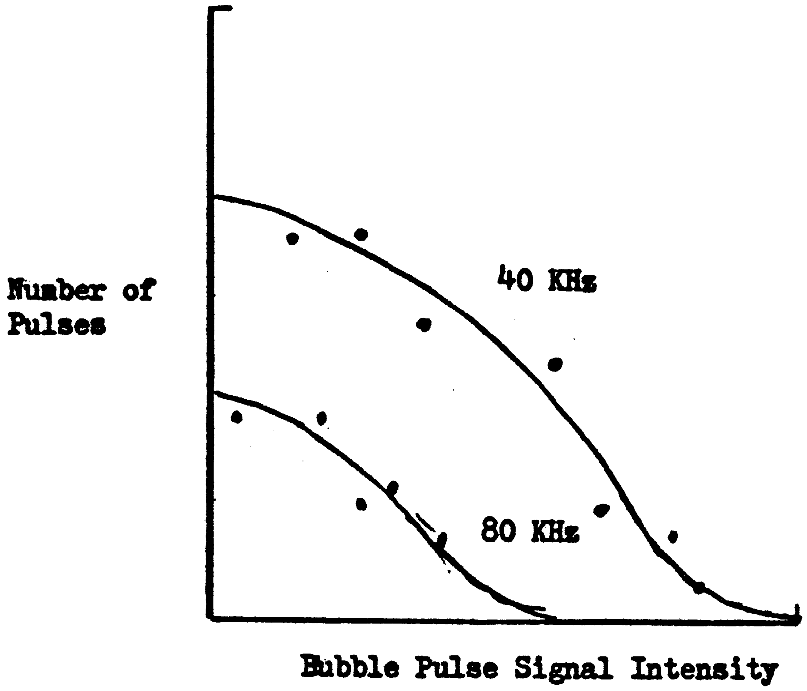

Figure 3

Typical Bubble pulse Count Spectra

3.2.2 Pressure Probe Calibration

The final link between spectral area power in units of spectral area/time, and spectral area power in useable standard units was accomplished through probe calibration. Figure 4 shows the calibration rig used.

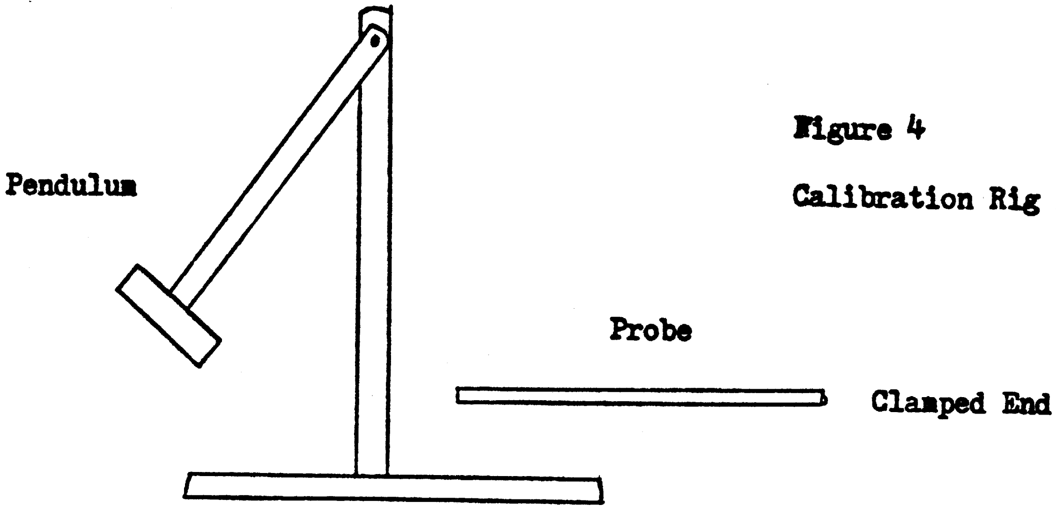

Figure 4

Calibration Rig for Wave-Guide Probe

In short, a pendulum-hammer with a measurable potential energy struck the tip of the pressure probe, thus imparting a pulse signal. Using the instrumentation shown in Fig. 5 the signal was collected and quantified to the appropriate spectral area. In this way, a calibration constant, C, linking the energy imparted to the spectral area outputs was computed. Table 1 lists these values of C for various filter frequencies.

Spectral area power is calculated as the product of the probe constant, C, and the spectral area/time values derived from laboratory data.

$$\text{SAP} = C \bullet \text{SA/time}$$

4. Laboratory Procedure

Cavitation erosion efficiency was calculated from laboratory data in the manner previously described. All data was taken from the vibratory cavitation rig of Fig. 5. The test liquid was liquid sodium, and the test material was SS304.

Due to the high temperature involved suitable conventional pressure probes were unavailable*, and "wave guide" probes were used (Fig. 6). In the wave guide probes, the active crystal element was placed at the non-submerged end of a 12" stainless steel rod. Signal loss along the length of the rod was assumed to be negligible, and this was later verified by calculations.

Figure 8b shows damage versus temperature for SS304 in liquid sodium. The maximum damage occurs at an intermediate temperature.

At the highest temperature however, the damage rate in sodium again increased, presumably due to the increased corrosive effects of sodium on SS304, as well as the reduced mechanical properties of 304 at that temperature (550°C). This damage rate increase was hypothesized to be not due to an increase in the mechanical intensity of the cavitating phenomenon. This hypothesis was supported by the

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*The new U-M direct submergence probe (Fig. 7) could now be used for this purpose.

spectral area vs. temperature curves, which did not show an increase in bubble collapse spectra at high temperatures. Further support comes from Fig. 8c, in which the product of ultimate resilience and volume loss rate was plotted against temperature. This product is proportional to our "erosion power" parameter. At higher temperatures, the rise experienced in the WLR curve was in fact reduced, but not eliminated, indicating that some effect of increased corrosivity at high temperature is in fact present.

Figures 9, 10 and 11 show spectral area versus temperature for a number of filter frequencies, and Figs. 12, 13, and 14 show cavitation efficiences for the same filter frequencies.

5. Conclusion

The concept of "cavitation erosion efficiency" has been postulated, introduced, and all necessary parameters defined. This "cavitation efficiency" is the ratio of the erosion power and the spectral area (acoustic) power. The erosion power is defined to be the energy/time needed to cause a certain volume loss to a material. The spectral area power is defined to be the acoustic power inherent in a cavitating regime, as collected and analyzed by an acoustic probe and related instrumentation.

Various trends were observed as we varied the cut-off frequency of the high pass filter used to quantify the sonic bubble pulses of the cavitating regime. We offer no explanation as yet concerning the observed trends.

We find that the effect of temperature in cavitating sodium upon volume loss rate, excluding corrosion, can be predicted by our spectral area power measurements in terms of "erosion power", ie, product of volume loss rate and ultimate resilience. This is shown in Figs. 8b and 8c.

References

1. Ramon Garcia, "Comprehensive Cavitation Damage Data for Water and Various Liquid Metals Including Correlations with Material and Fluid Properties", Ph.D thesis 1966, Dept. of Nuclear Engineering, University of Michigan

2. F.G. Hammitt, S.A. Barber, M.K. De, A. ElHasrouni, "Predictive Capability for Cavitation Damage from Bubble Pulse Count Collapse Spectra", ERDI Rept. UMICH 014456-3-1, Nov. 1976, Dept. of Mechanical Engineering, University of Michigan, submitted I.Mech.E, Univ. of Stirling Conf., Sept. 1977.

3. F.G. Hammitt, et at. "Final Report- Argonne National Laboratory", ORA Rept. UMICH 013503-2-F, June 1976, Dept. of Mechanical Engineering, University of Michigan

4. M.K. De, S.A. Barber, F.G. Hammitt, "Pressure Probe Calibration", Rept. No. UMICH 014456-1-I, Dept. of Mechanical Engineering, University of Michigan

5. Metals Properties, ASME Handbook, edited by Samuel L. Hoyt, 1954.

					60KHz		70KHz		80KHz		EP/SAP		
T °C	WLR g/hr	VLR in³/min	VR lbf/in²	EP lbf-in/min	SA/min	SAP	SA/min	SAP	SA/min	SAP	60kHz	70kHz	80KHz
350	.160	2.09 (10⁻⁵)	92.5	1.93 (10⁻³)	400 (10³)	.48 (10⁴)	225 (10³)	.259 (10⁴)	75 (10³)	.1275 (10⁴)	4.53 (10⁻⁸)	8.40 (10⁻⁸)	
375	.162	2.11	91	1.92	1200	1.44	1250	1.44	250	.425	1.51	1.51	5.12
400	.157	2.05	88.5	1.81	2300	2.76	1750	2.01	1400	2.38	.751	1.03	.872
425	.144	1.88	85	1.59	2200	2.64	1400	1.61	1175	2.0	.690	1.13	.911
450	.132	1.72	82	1.41	1700	2.04	1050	1.21	900	1.53	.795	1.34	1.06
475	.12	1.56	76	1.19	1000	1.20	650	.75	425	.723	1.17	1.86	1.94
500	.112	1.46	71	1.04	400	.48	300	.345	100	.170	1.71	2.37	4.82

Appendix 1

Tabular Data for SS304 in Sodium at 2 atm.

Table 1

Freq.	C
60kHz	1.2×10^{-2}
70 kHz	1.15×10^{-2}
80kHz	1.70×10^{-2}

Wave-guide Probe Calibration Constants $\frac{\text{lbf-in}}{\text{spectral area}}$

					60KHz		70KHz		80KHz		EP/SAP		
T °C	WLR g/hr	VLR in³/min	UR lbf/in²	EP $\frac{\text{lbf-in}}{\text{min}}$	SA/min	SAP	SA/min	SAP	SA/min	SAP	60KHz	70KHz	80KHz
300	.138	1.8 (10^{-5})	92.5	1.67 (10^{-3})	1000 (10^{+3})	1.2 (10^{9})	725 (10^{3})	.834 (10^{9})	850 (10^{3})	1.445 (10^{9})	1.52 (10^{-8})	2.19 (10^{-8})	1.26 (10^{-8})
325	.174	2.27	92.5	2.10	1400	1.68	950	1.093	875	1.49	1.35	2.07	1.52
350	.198	2.58	92.5	2.39	3250	3.90	1300	1.50	890	1.51	.674	1.75	1.74
375	.210	2.74	91	2.49	6600	7.92	1600	1.84	900	1.53	.354	1.52	1.83
400	.208	2.71	88.5	2.40	9200	11.0	1750	2.01	900	1.53	.222	1.21	1.60
425	.196	2.55	85	2.17	4800	5.76	1700	1.96	875	1.49	.418	1.23	1.62
450	.170	2.22	82	1.82	450	.54	1550	1.78	840	1.43	.369	1.12	1.39
475	.128	1.67	76	1.27			1400	1.61	800	1.36		.895	1.06
500	.07	.912	71	.648			1250	1.44	750	1.28		.527	.593

Appendix 1 Tabular Data for SS304 in Sodium at 3 atm.

Appendix 2
Sample Calculations

a) Erosion Power $= UR \times VLR \left(\frac{lbf\text{-}in}{min} \right)$

$$VLR = WLR \left(\frac{g}{min} \right) \left(\frac{2.205\, lbm}{1000\, g} \right) \left(\frac{1}{.282\, \frac{lbm}{in^3}} \right)$$

$$VLR = WLR \left(\frac{g}{min} \right) 7.82 \times 10^{-3}$$

Volume loss rate will be in in^3/min

$$EP = UR \times VLR$$

where $UR = f(TEMP)$

b) SPECTRAL AREA POWER

$$SAP = C \frac{SA}{time}$$

Where C is a constant relating lbf-in to Spectral Area (SA)

Laboratory procedure yields $\frac{SA}{min}$, so SAP will be in units of $\frac{lbf\text{-}in}{min}$

c) Spectral Area, SA

Cavitation noise is collected according to intensity and number of pulses. by various electronic apparati. When this data (intensity vs number of pulses) is plotted, a plot similar to Figure 3 results. We define the spectral area to be the area under this curve.

Pulse count data can be obtained from reference 3.

d) Determination of Probe Constants, C

$$\text{Energy} = mgl(1-\cos\theta) \qquad \theta = 10^\circ,\; m = 144g,\; l = 3.91\ \text{in}$$

$$E = (.144)(2.2046)(3.91)(1-\cos 10^\circ)$$

$$= .23\ \text{in-lbf}$$

$$C_1 = \frac{E}{\text{AREA}} = \frac{.23\ \text{in-lbf}}{\text{spectral Area}}$$

for 60 kHz, Spectral area = 19.1

70 kHz " " = 20.0

80 kHz " " = 13.5

APPENDIX 3

Specific Instrument Settings for Instruments of Figure 5

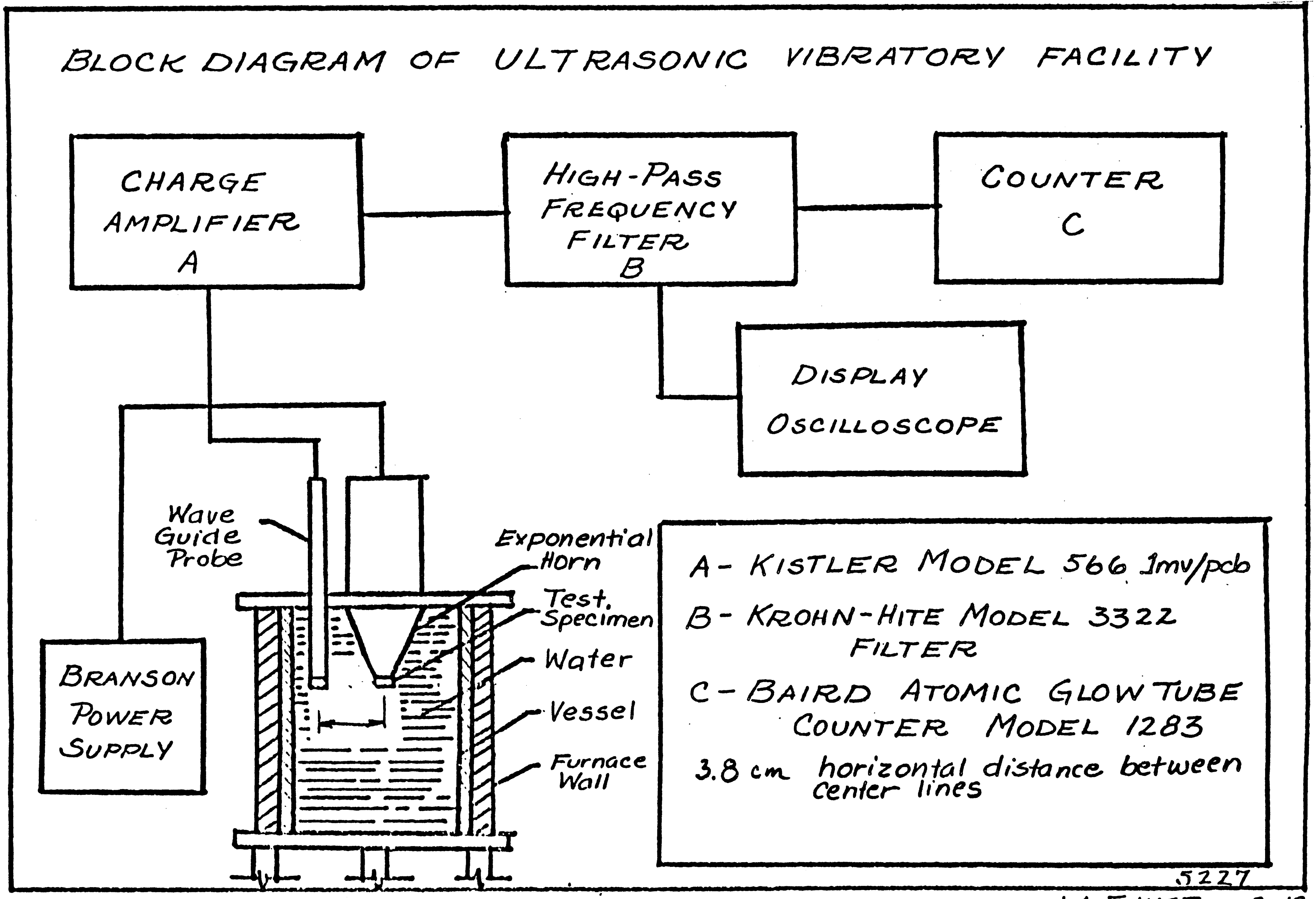
A. Kistler charge amplifier,
Model 566
10 mv/pcb

B. Krohn-Hite high pass filter
Model 3322
20 db gain

C. Baird Atomic glow tube counter
Model 1283

Pulse height selector is variable between 0-5. The intensity of the pulse counted by the counter is proportional to the voltage output of the probe-amplifier combination. At 0, the counter will count all incoming pulses. At 5, the counter will count only pulses greater than a certain intensity.

FIG. 5



BLOCK DIAGRAM OF ULTRASONIC VIBRATORY FACILITY

J.A.FAUST 2-19-7

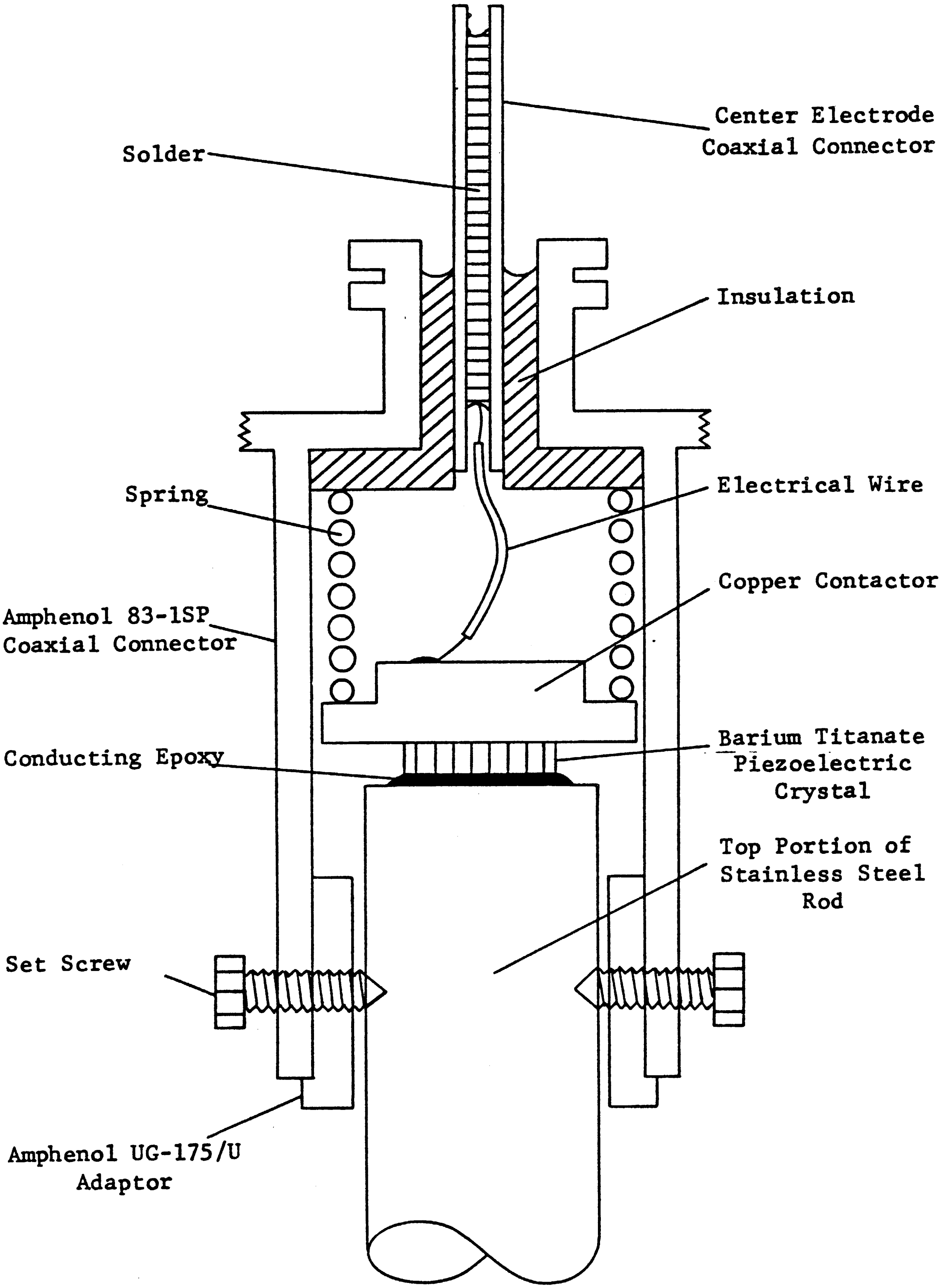


FIGURE 6 SCHEMATIC CROSS SECTIONAL VIEW OF THE CRYSTAL ASSEMBLY FOR THE ACOUSTIC WAVE-GUIDE PROBE

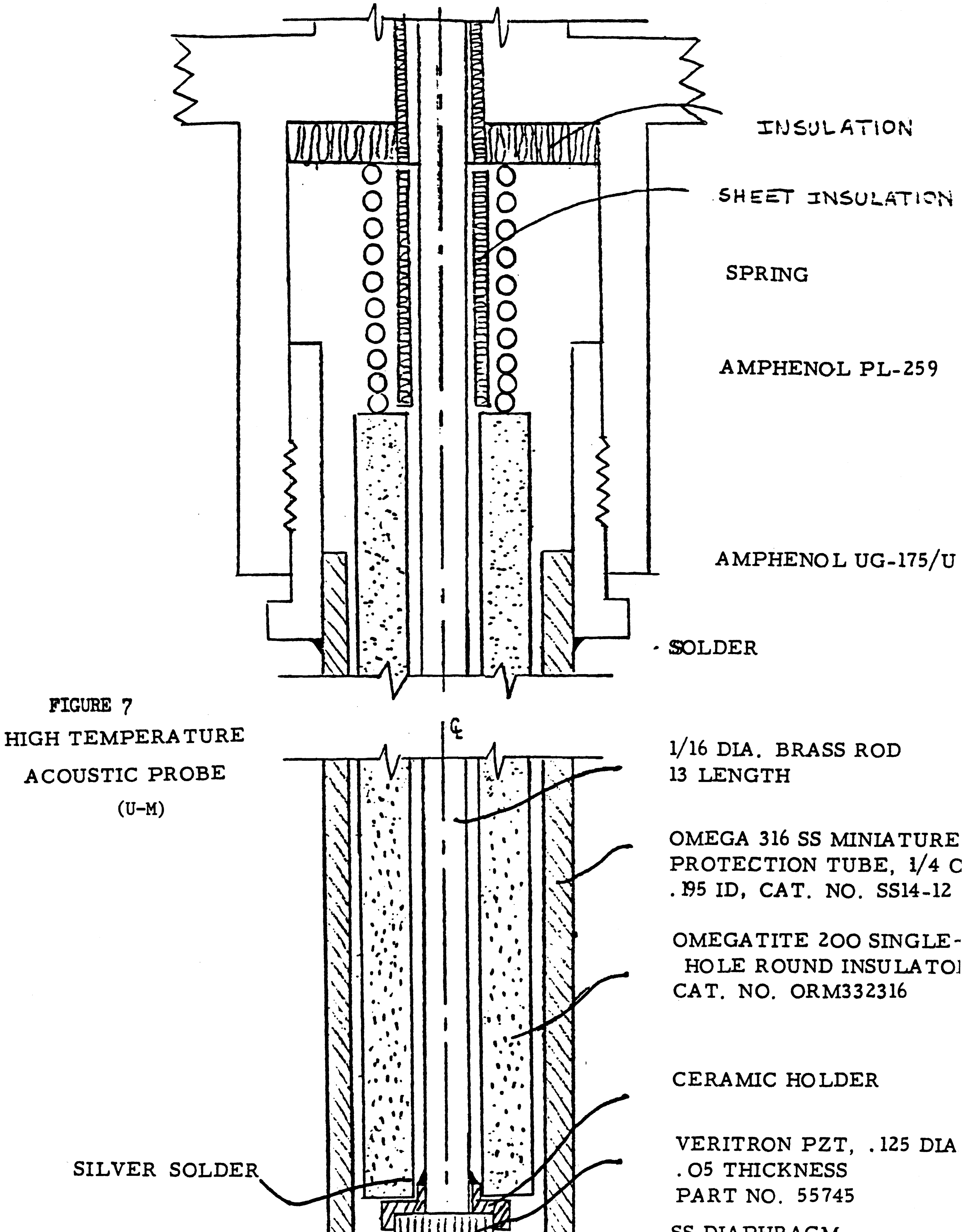


FIGURE 7
HIGH TEMPERATURE
ACOUSTIC PROBE
(U-M)

J.A. Faust

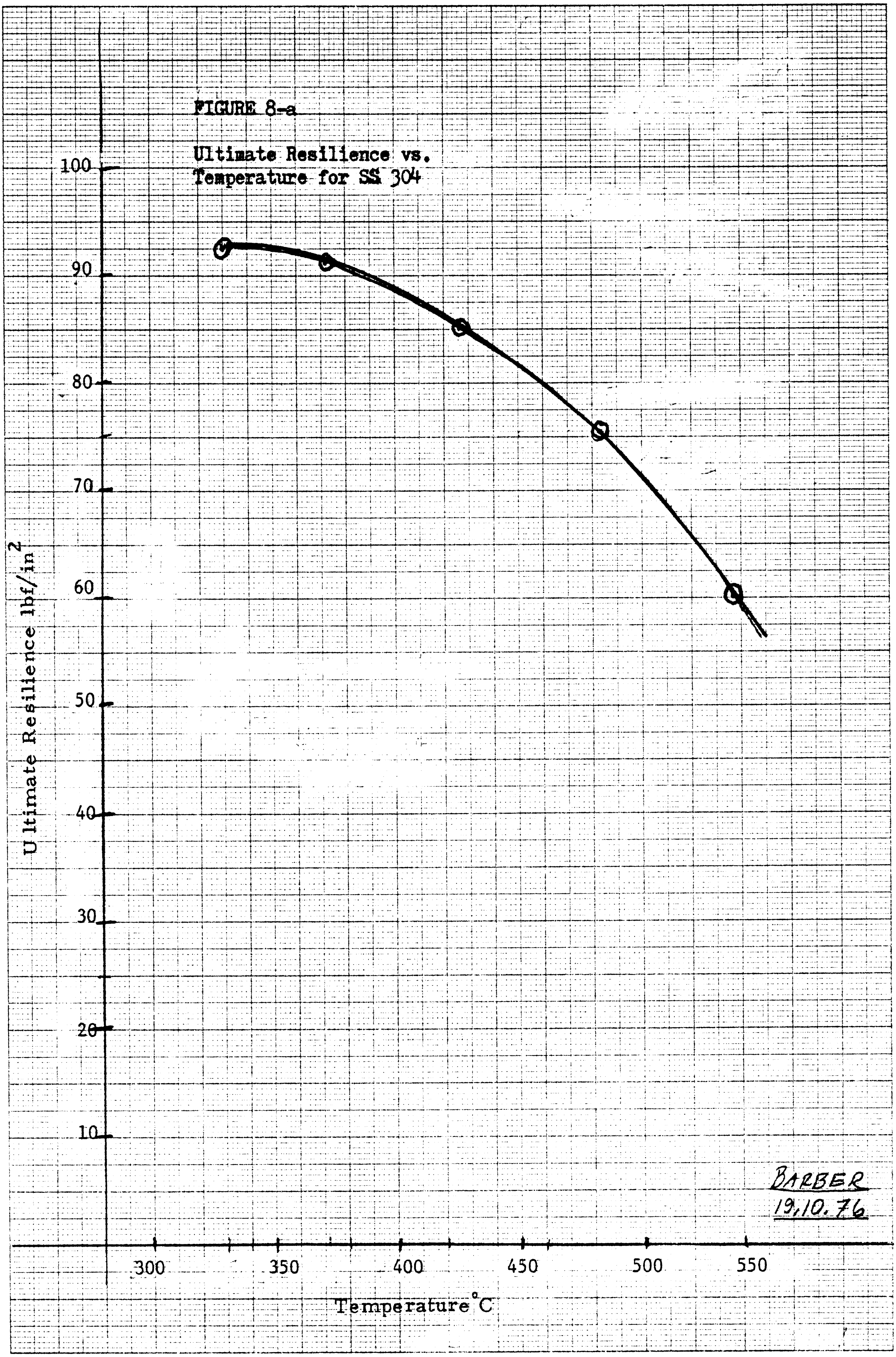


FIGURE 8-a

Ultimate Resilience vs. Temperature for SS 304

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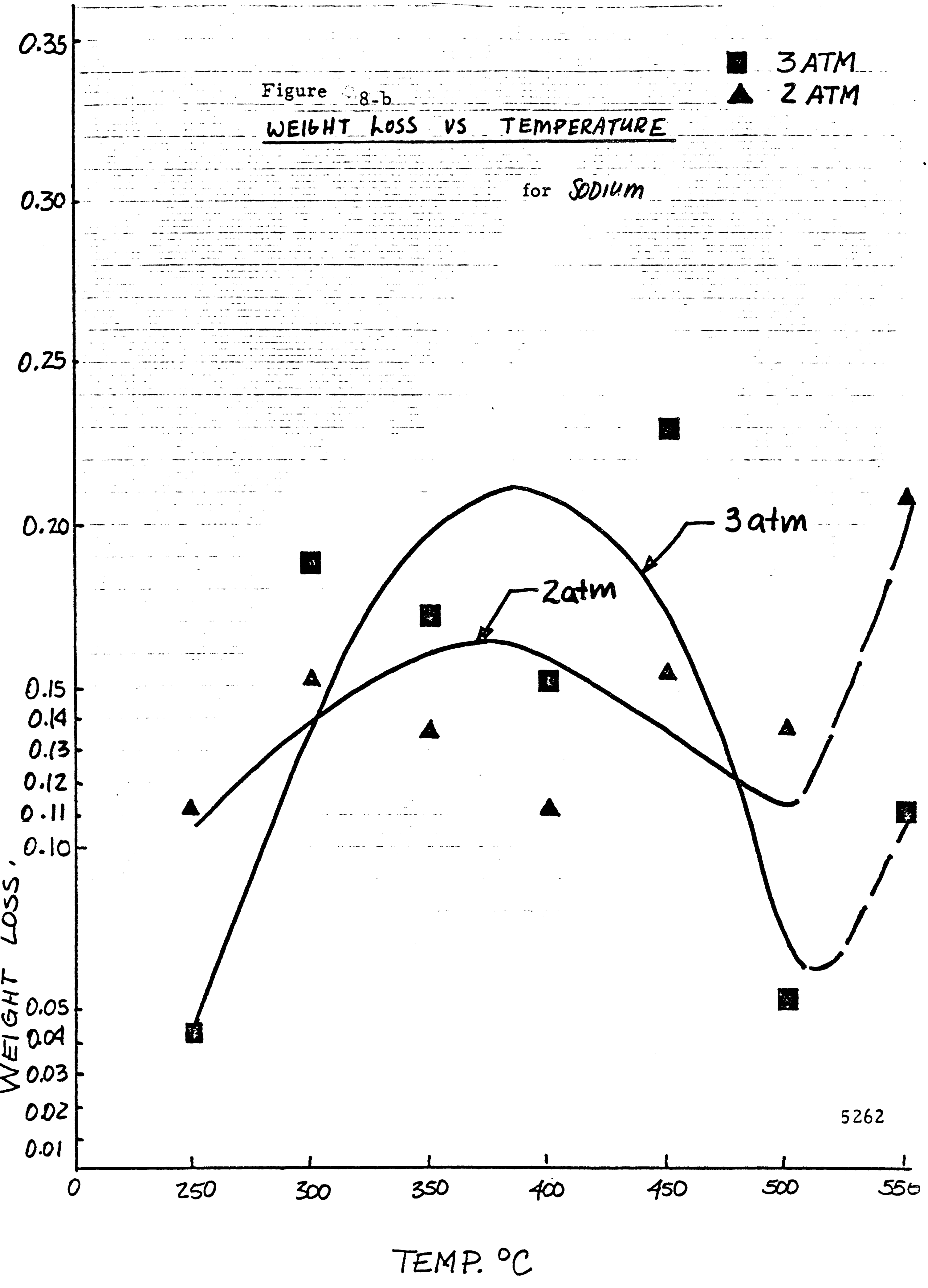
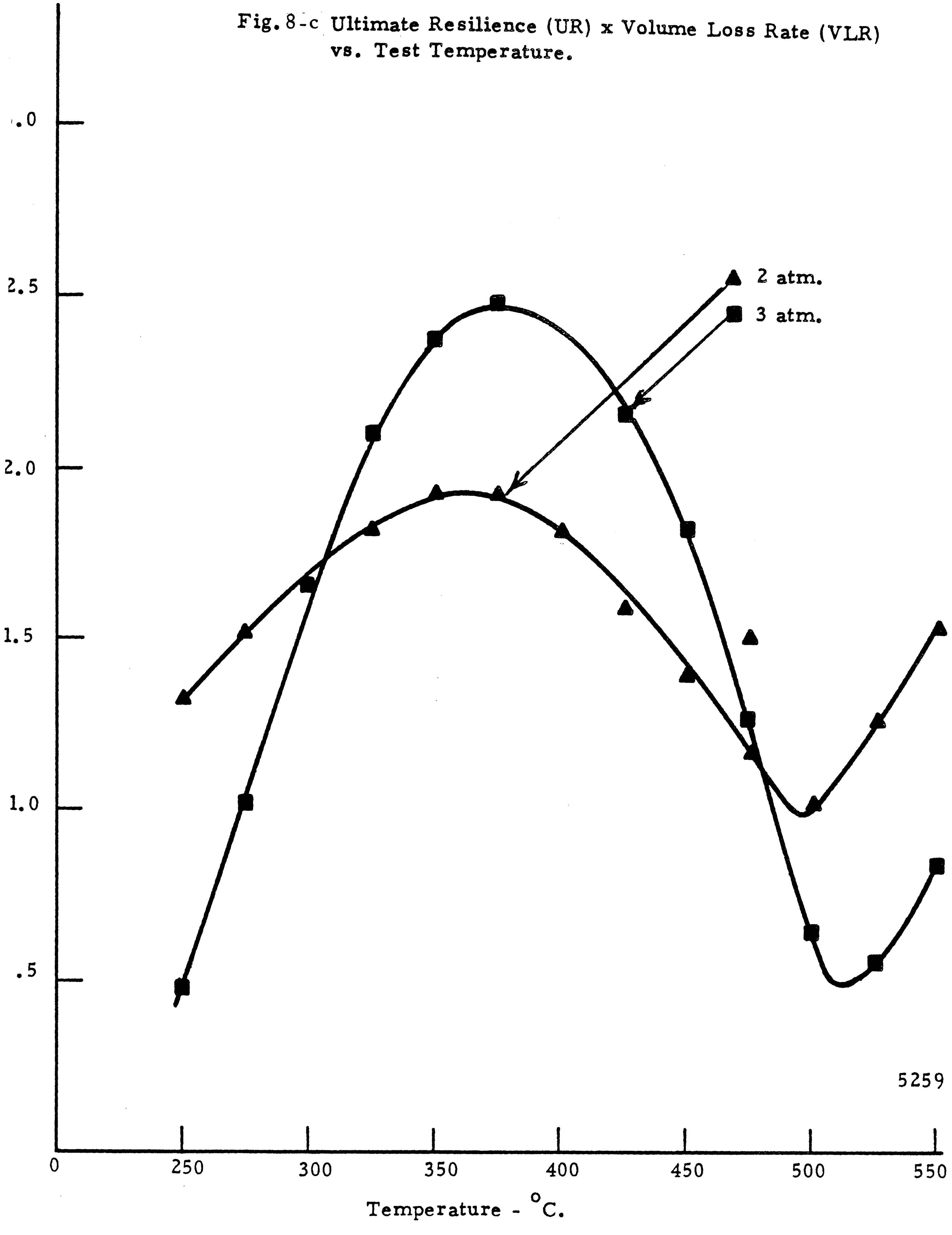
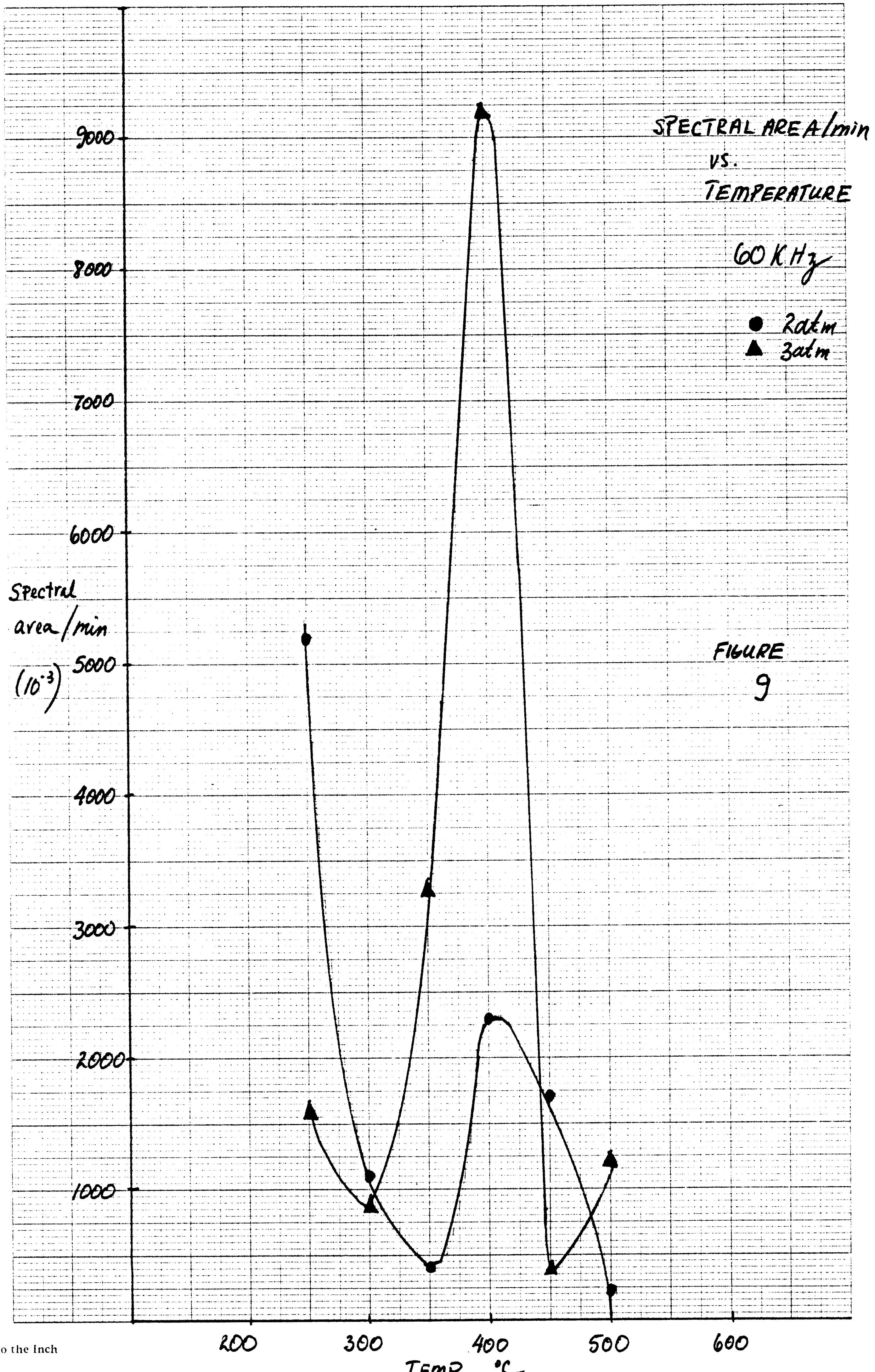


Figure 8-b
WEIGHT LOSS VS TEMPERATURE
for SODIUM

Fig. 8-c Ultimate Resilience (UR) x Volume Loss Rate (VLR) vs. Test Temperature.





SPECTRAL AREA/min
vs.
TEMPERATURE

60 KHz

FIGURE
9

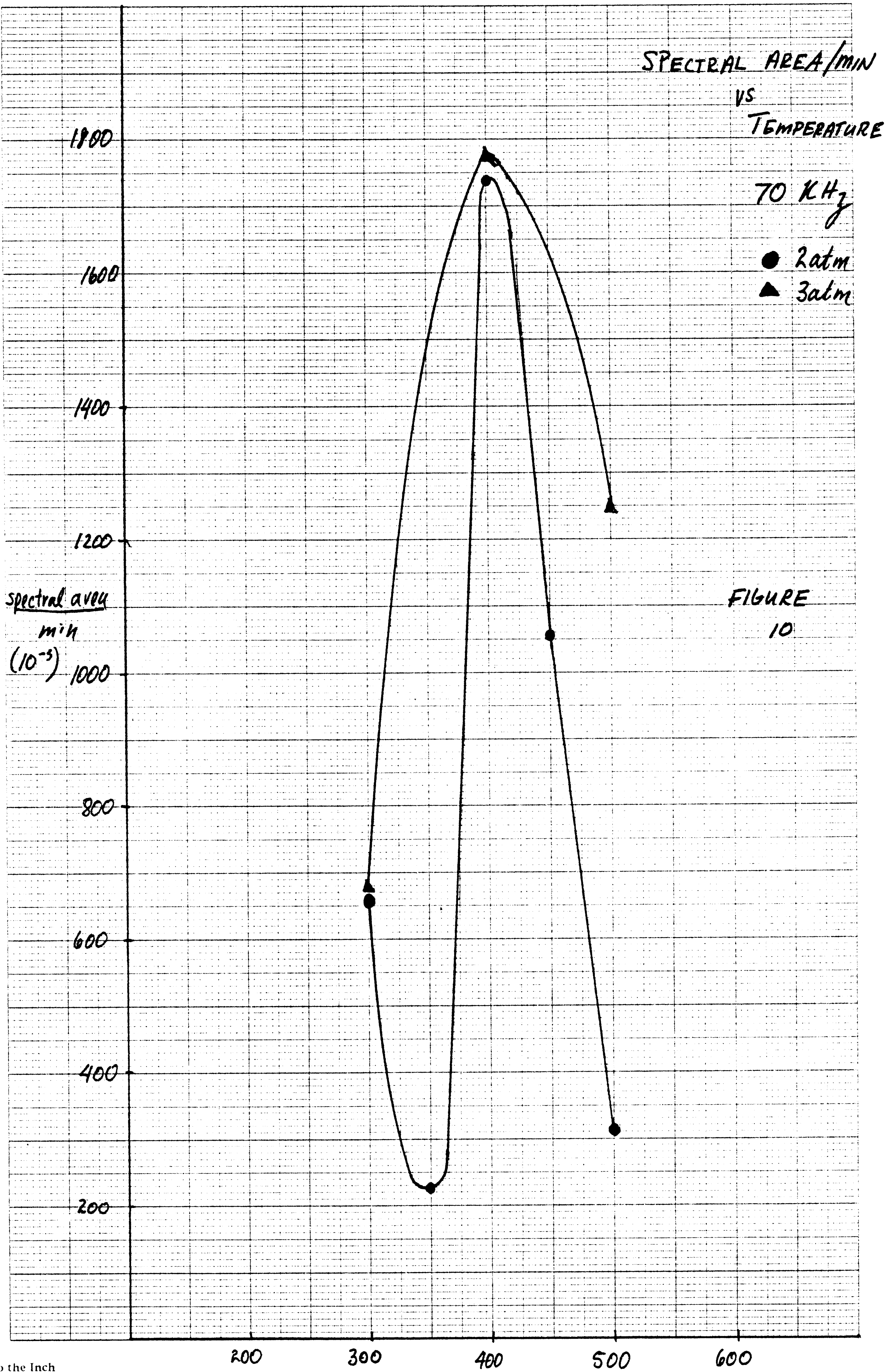

SPECTRAL AREA/MIN
VS
TEMPERATURE
70 KHz
● 2atm
▲ 3atm
spectral area
min
(10^-5)
1800
1600
1400
1200
1000
800
600
400
200
200
300
400
500
600
TEMP °C

FIGURE 10

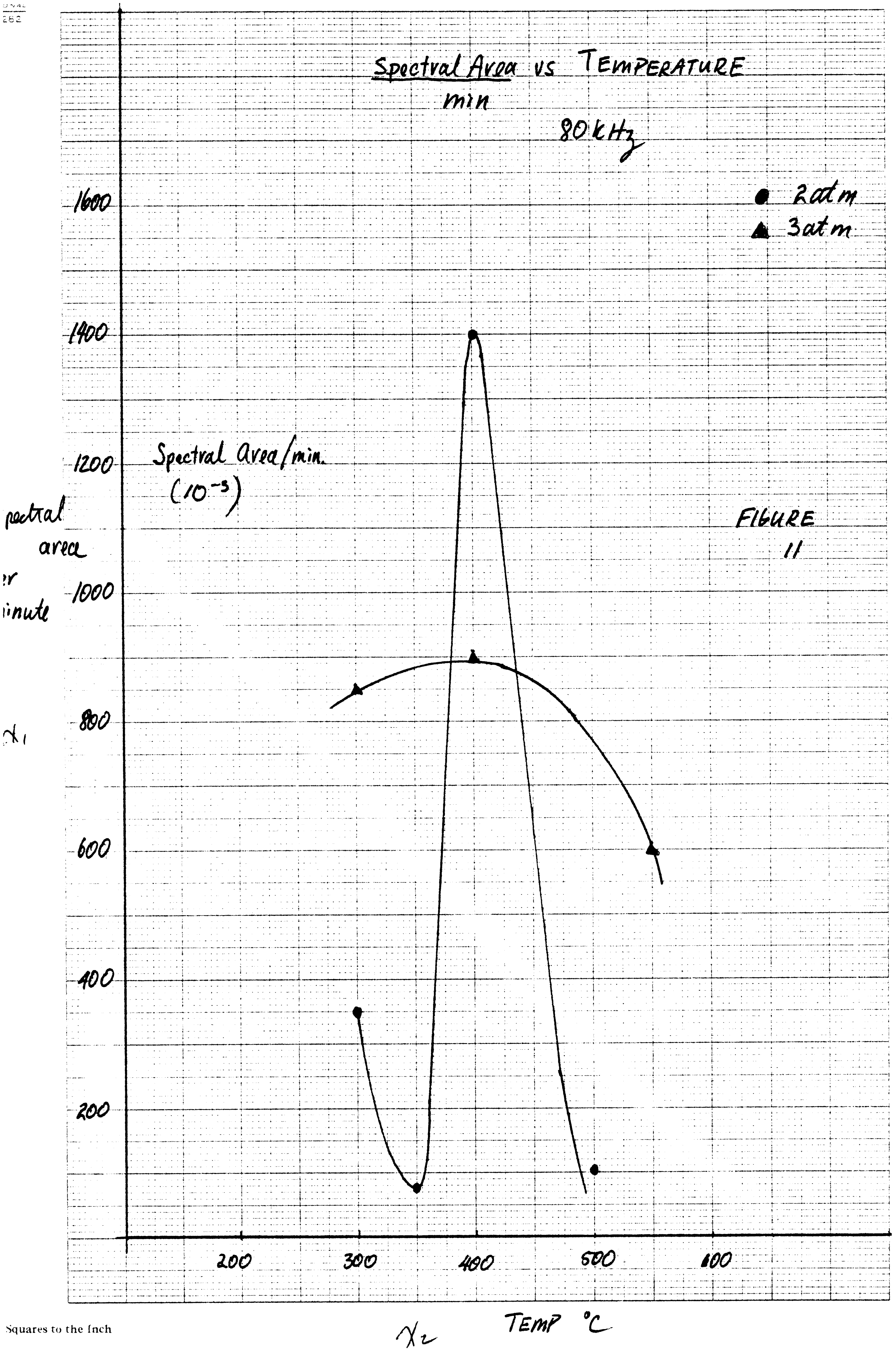

Spectral Area vs TEMPERATURE
min
80 kHz
● 2atm
▲ 3atm
Spectral Area/min.
(10⁻³)
pectral
area
er
inute
x_1
1600
1400
1200
1000
800
600
400
200
200
300
400
500
100
x_2
TEMP °C

FIGURE 11

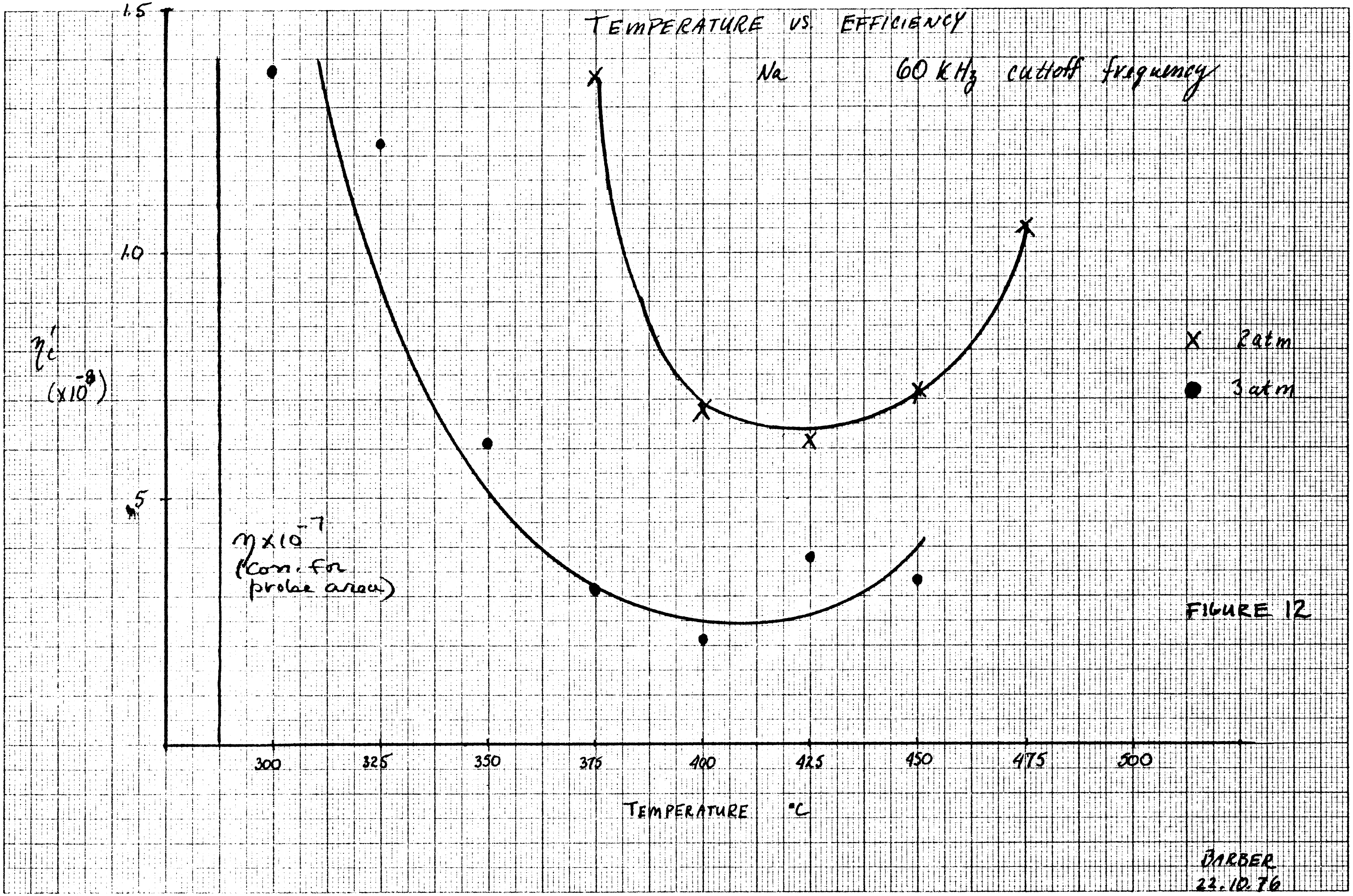


FIGURE 12

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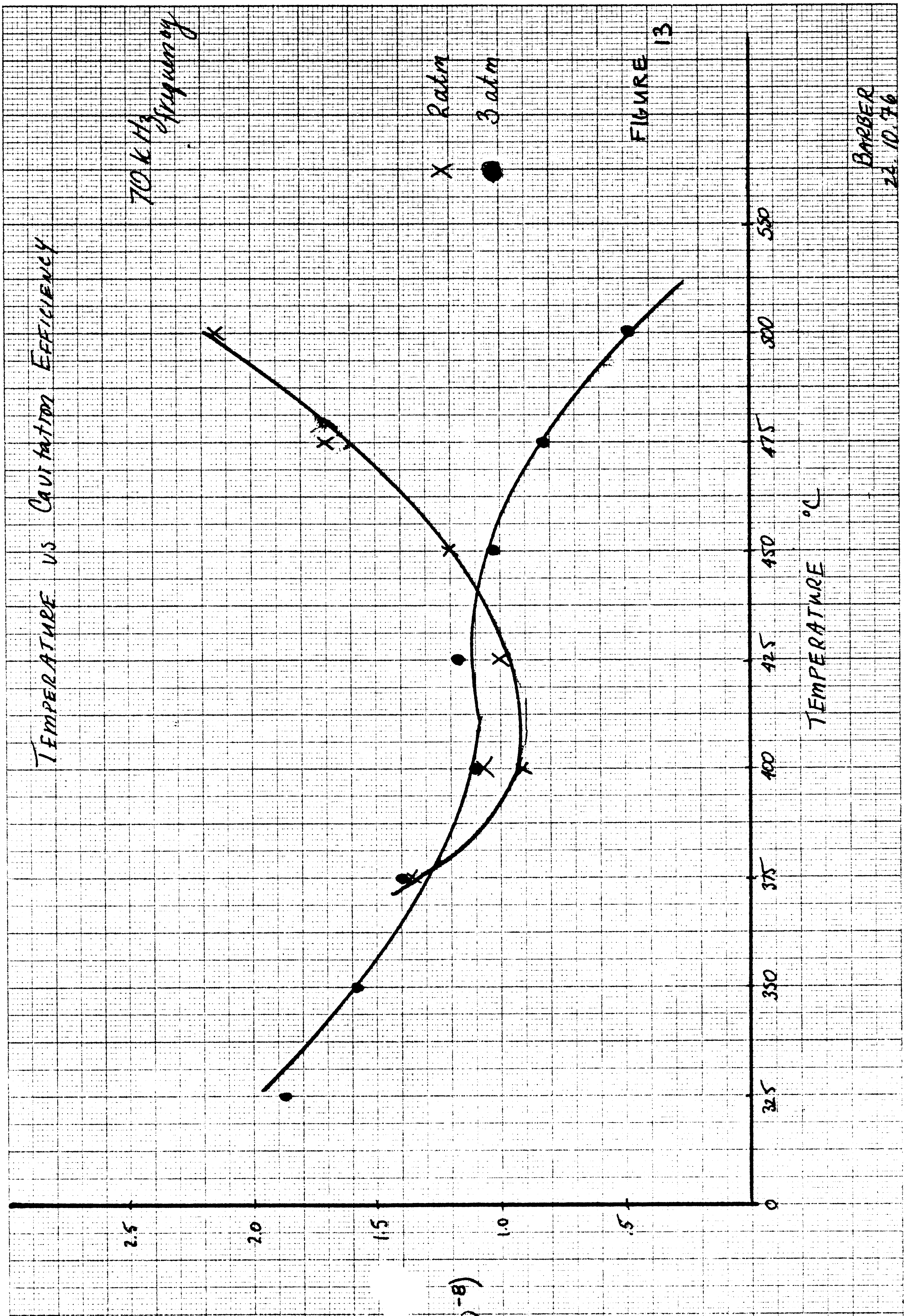

TEMPERATURE VS CAVITATION EFFICIENCY

70 KHz frequency

FIGURE 13

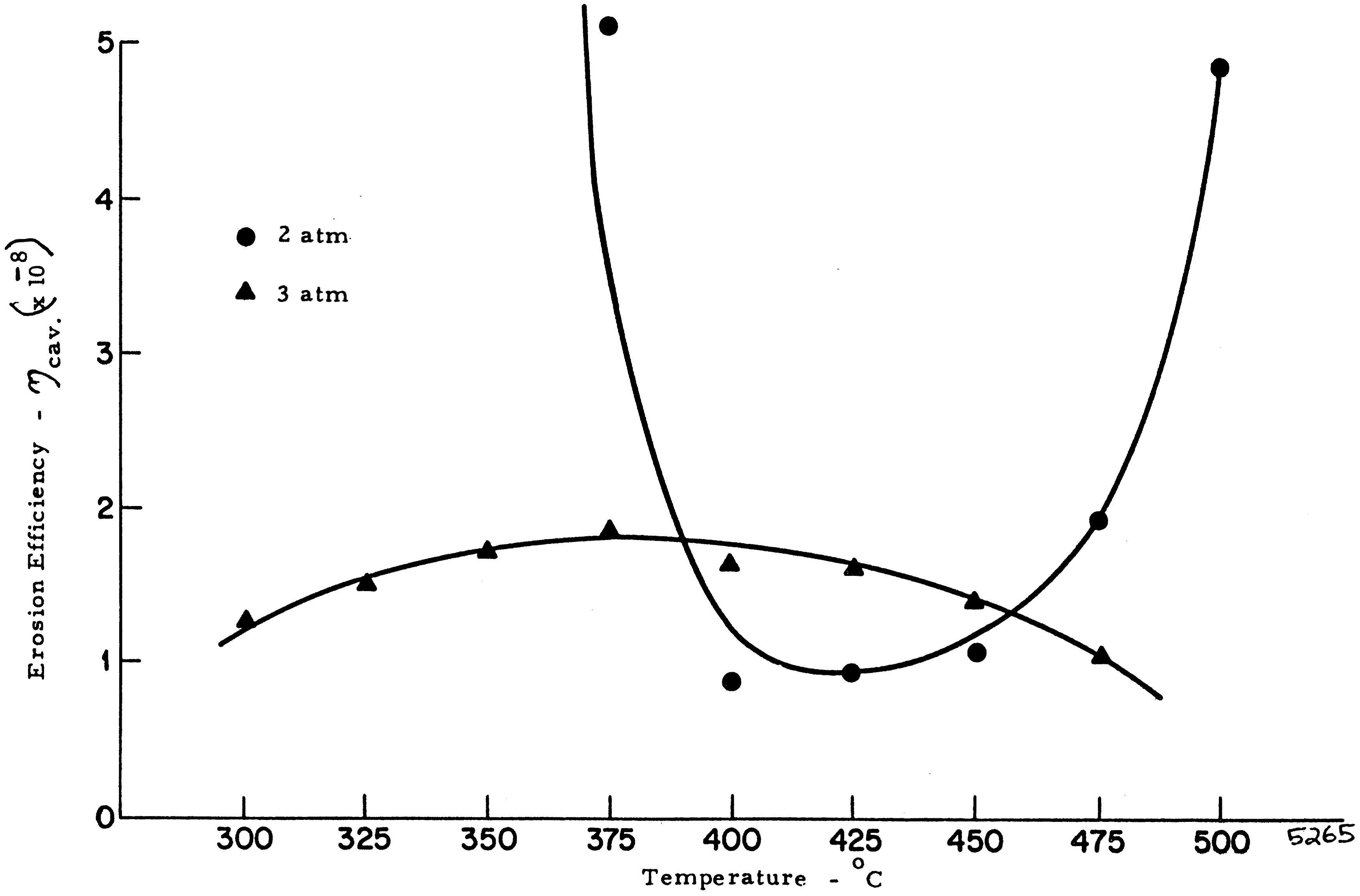

Figure 14 Temperature vs. Cavitation Erosion Efficiency for 80 kHz.