

CORROSION PROTECTION OF THIN PRECAST
CONCRETE SECTIONS

by

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I. INTRODUCTION

The rate of corrosion of reinforcing steel in concrete has long been discussed by engineers throughout the world. A majority of the engineers have been content with citing examples of structural failure as a result of this corrosion, while some have carried out partial investigations of its causes. An examination of the building codes revealed that a complete understanding of all contributing factors to corrosion of the reinforcing steel was lacking. This revelation was not a new one, however, for the need of such an investigation has long been expressed by both individuals and organizations employed in concrete design and construction. Realizing the need for such quantitative data, Mr. A. Amirikian, Chairman of the American Concrete Institute Committee on precast concrete units, interested the Applied Mechanics Department at the Virginia Polytechnic Institute in the problem. Professor D. H. Pletta suggested measuring the data by noting the change in electrical resistance of the reinforcing as it corroded, and interested Mr. R. H. Conklin in starting the preliminary work.

The funds for the investigation were made available by the U. S. Navy Bureau of Yards and Docks. A contract was drawn up and entered into by the Bureau and the Virginia Polytechnic Institute Research Foundation. The project was to be carried out on the fellowship plan under the general direction of Dean L. B. Norris and the guidance of Professor Pletta. The author was employed to complete the preliminary investigation and carry on the experimental work. To date an experimental technique has been developed and the investigation is partially completed. It has not progressed to the point, however, where final conclusions may be drawn.

The discussion and conclusions of this thesis are restricted to the preliminary investigations, and trends indicated by experimental work.

II. HISTORY OF PROJECT

Many reports and discussions have been published on the rate of corrosion of steel reinforcing in most of the leading construction and engineering periodicals. After reviewing over fifty of such articles, the author found that a large majority of the reports were discussions on concrete structural failure resulting from the corrosion of the steel reinforcing.⁽¹⁾ A few were discussions on laboratory tests on the rate of corrosion of the steel. All of these discussions were based on qualitative results, however, while no evidence could be found of quantitative measurements being made. The articles reviewed were fairly well dispersed over the years 1911 to 1940, inclusive.

The history of the investigation described in this thesis was covered in the introduction. The contract for the investigation became effective April 23, 1948 and equipment needed for the project was placed on order. Mr. Conklin spent most of the spring of 1948 locating necessary material and running some preliminary tests. The author was employed in June 1948 to assist Mr. Conklin on the investigation. This arrangement did not last long, however, for Mr. Conklin was required to give up his work as a result of ill health.

III. EXPERIMENTAL INVESTIGATION

A. Object of Investigation

The primary purpose of this investigation was to establish a method by which a study of the rate of corrosion of reinforcing steel in concrete could be made. The change in the Modulus of Elasticity of concrete during the test period, measured by a sonic analyzer, and accompanying tests on small cylinders, completed the test program.

B. The Approach

Since the corrosion of steel is an oxidation process, the primary interest of this project is the prevention of the combination of the reinforcing steel and oxygen. The combination could be prevented by coating the steel with one of the many anti-corrosion compounds, but in so doing either the necessary bond strength between the reinforcing steel and the concrete is reduced or the **cost** of the steel is beyond an economical limit. There is one possibility, however, that can satisfy requirements of both bond strength and economy. This possibility, the use of concrete as a protective covering, is being used extensively, although not conservatively in the field of concrete design and construction. In the field of precast thin-shell concrete construction an excess of concrete protective covering is not only uneconomical but also undesirable.

The problem is reduced to one of finding the minimum depth of concrete cover of sufficient density which will insure protection of the reinforcing steel when subjected to various atmospheric conditions. In the investigation,

therefore, three variables should be considered. They are depth of cover, density of concrete, and atmospheric conditions. If these three variables are held constant at several points throughout their ranges their influences on corrosion of the steel may be compared.

At this point another problem is encountered. A method of determining the degree of corrosion of the steel is needed. Several methods are available for this phase of the investigation. They are: (1) breaking specimens of concrete at various time intervals to expose the embedded steel; (2) examining the embedded steel by X-ray; and (3) using the change in electrical resistance of the embedded steel to indicate decrease in the steel's cross sectional area as a result of corrosion. Since the third method has less variation than the first, and is more economical and accurate than the second, it is the most satisfactory of the three considered. A review of the literature pertaining to the examination of embedded steel reveals no evidence of previous use of the above chosen method. To the authors' knowledge, this method is an original idea of Professor Pletta.

The requirements for a complete investigation have been stated and solutions advanced whereby the requirements may be satisfied. An examination of these solutions was carried out by the author and his results and conclusions are discussed in the following report, as are his recommendations for the continuation of the investigations.

C. Apparatus and Materials

1. The concrete vibrating table, as shown in Fig. 1, was used in this investigation. It was designed in the Virginia Polytechnic Institute

Applied Mechanics Department and was built by the V. P. I. Engineering shops. Its one-half horsepower motor and 0.01 inch eccentric cam are capable of producing a maximum acceleration of 54 feet per sec. per sec. It fulfills the requirement that the test samples be vibrated, as are actual field structures.

2. The concrete forms, as shown in Fig. 1, were designed by the V.P.I. Applied Mechanics Department and were made by the V.P.I. Engineering shops.

3. The constant temperature, 100% relative humidity (R.H.) air conditioner was designed and built by the Engelby Electric Company in Roanoke, Virginia.

4. The constant temperature, constant relative humidity air conditioner, as shown in Fig. 2, was a commercial product of the Westinghouse Corp. It has a relative humidity range from 20% to 70% and a temperature range from 55°F to 100°F.

5. The resistance bridge, as shown in Fig. 3, is a Leed and Northrup Portable Kelvin Bridge. It has a total range of measurement from 0.0001 ohm to 26.6 ohms with a limit of error of 0.2 per cent.

6. The sonic modulus equipment, as shown in Fig. 4, was purchased from Hogentogler and Co. in Chevy Chase, Maryland. Its audio oscillator was capable of covering a frequency range from 600 cycles per second to 6000 c.p.s.

7. The sand used in the investigation was washed Petersburg Sand. Its characteristics, determined in accordance with A.S.T.M. specifications, are listed in Table A.

8. The stone used in the investigation was crushed dolomitic limestone. It was quarried and crushed in Montgomery County, Virginia. Its properties are listed in Table B.



Fig. 1
Vibration Table
and Slab Forms

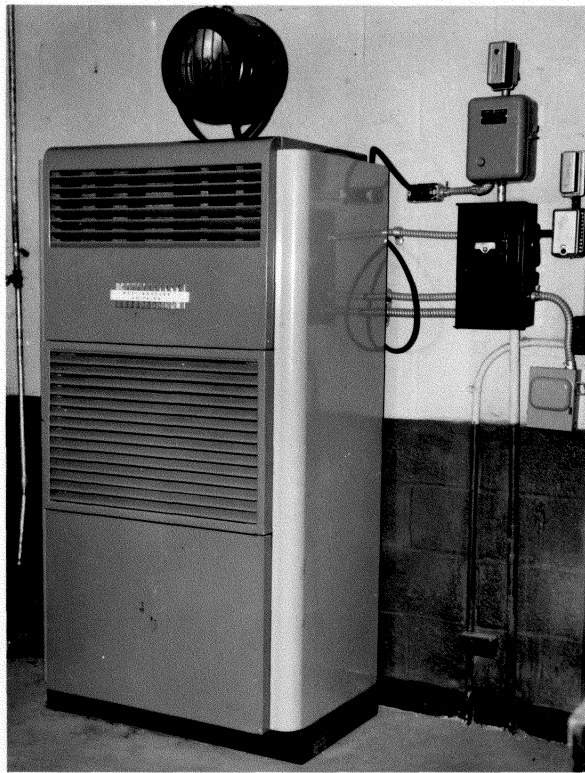


Fig. 2
Heating and
Humidifying Equipment



Fig. 3

Kelvin Resistance Bridge

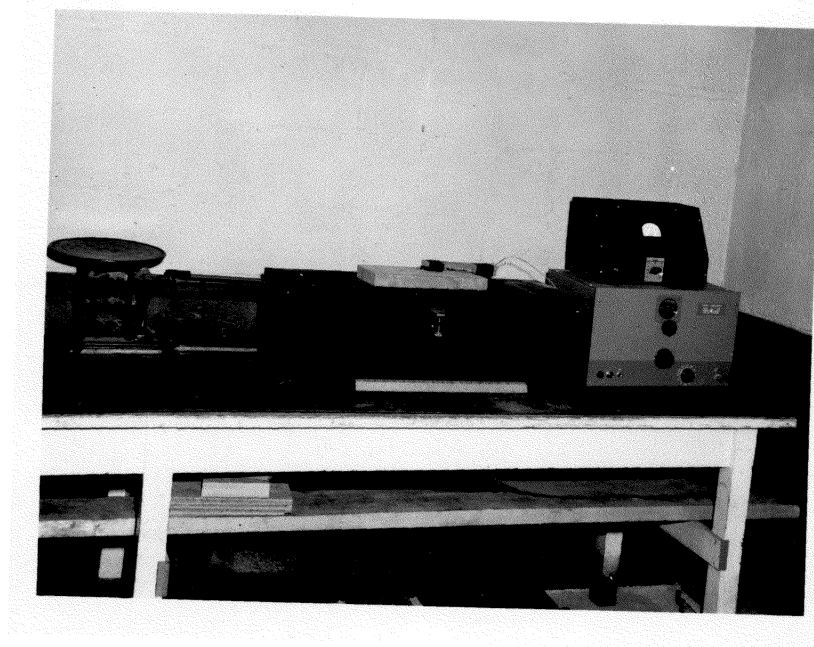


Fig. 4
Sonic Analyzer

TABLE A

PHYSICAL PROPERTIES OF PETERSBURG SAND

Specific Weight (Loose vol.)	97.0 lb./cu. ft.
Specific Gravity	2.63
% Absorption by weight (A.S.T.M. C 70)	3.04 %
Fineness Modulus	2.64

Sieve Analysis

Sieve No.	% Retained *	% Passing
4	0.12	99.88
10	7.05	92.83
16	15.91	76.92
30	30.89	46.03
50	30.66	15.37
100	12.21	3.16
200	1.91	1.25
Pan	1.25	0.00
	100.00	

* Retained on each sieve.

TABLE B

PHYSICAL PROPERTIES OF STONE

	1/4" Size	3/8" Size
Specific Weight (lb./cu. ft.)	89.0	96.0
Specific Gravity	2.70	2.70
% Absorption by weight	0.70 %	0.64 %

TABLE C

PHYSICAL PROPERTIES OF CEMENT

Surface Area	1742
Soundness	O.K.
Initial Set	3:10
Final Set	5:35
7 Day Strength	365 p.s.i.

9. The cement used was ordinary Portland cement manufactured by North American Cement Company. The manufacturer's certifications are listed in Table C.

10. All water used in the concrete mixtures, and in the curing procedure was tap water obtained from the college water-system.

11. All concrete mixes were prepared in a one quarter cubic yard concrete mixer located in the V. P. I. Highway Materials Testing Laboratory.

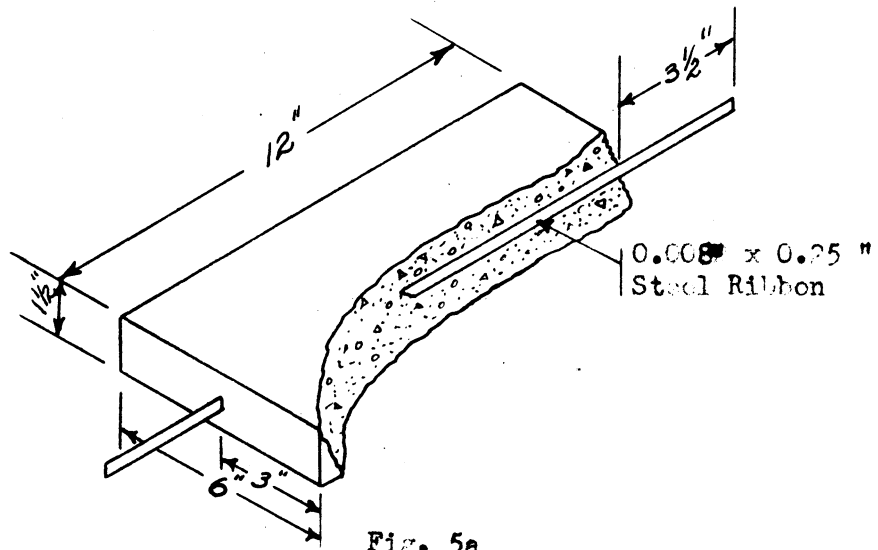
12. The 0.25 in. x 0.008 in. steel ribbon was cold rolled steel purchased in a 2,000 ft. long strip. It was cut and soldered to the copper bars.

13. The 0.25 in. x 0.25 in. copper bars were made from 0.25 in. x 0.25 in. x 20 ft. rods.

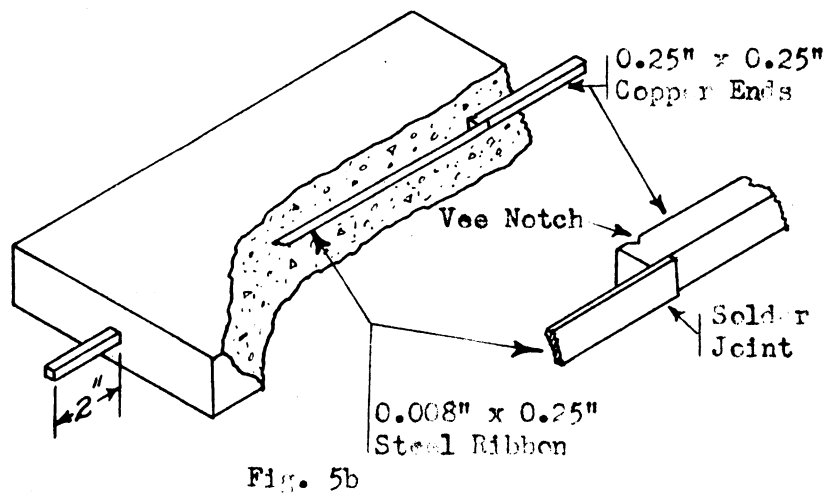
14. The 0.25 in. diameter mild steel bars were made from 20 ft. long rods.

D. The Investigation

At the beginning of the investigation the variables most easily controlled were examined first. The sample sizes were chosen to be 6 in. x 12 in. slabs of three thicknesses, $\frac{3}{4}$ in., $1\frac{1}{8}$ in., and $1\frac{1}{2}$ in. Preliminary tests were made on several slabs of $1\frac{1}{2}$ in. thickness. The concrete mix used for this preliminary test was 5 bags of cement per cubic yard with 5 gallons of water per bag of cement. A steel ribbon 0.25 inches wide and 0.008 inches thick was embedded on edge along the longitudinal center of each slab, (Fig. 5a). The ribbon was of such a length that $3\frac{1}{2}$ inches of it protruded from each end of the slab. The exposed ends were so constructed that the resistance bridge could be connected to each end. After several days of exposure in a 100% R. H. room rapid corrosion of the unprotected steel was noted.



Preliminary Test Slab



Final Test Slab

Another group of slabs were made and the exposed ends of the steel were covered with solder before embedment. Although this modification practically eliminated the corrosion it was not too satisfactory since the exposed steel was easily bent and twisted while handling the slabs.

A third group of slabs were prepared. The steel ribbon was reduced in length to 10.5 in. and each end was connected to a 0.25 in. x 0.25 in. x 2.5 in. brass bar by a $\frac{1}{4}$ in. soldered lap joint, (Fig. 5b). This arrangement proved very satisfactory. The brass bars, however, were replaced by copper ones of like dimensions when the final pilot slabs were poured, since they had less resistance than the brass.

It was noticed that resistance readings taken on the preliminary test gradually increased while the bridge keys were closed. This increase was a result of a temperature change in the steel due to the passage of electrical current. An instantaneous contact key was added to the bridge and the variation was eliminated. Resistance readings could be repeated with less than $\pm 0.5\%$ error. A comparison of the resistivities of the steel and concrete showed that the concrete slab in parallel with the steel had a negligible influence on the resistance readings. This was only true, however, if all slabs were allowed to remain in a 50% R. H., constant temperature room for at least two days, thus allowing most of the moisture in the concrete to evaporate.

The concrete mixes chosen for the investigation were 5, 6, 7, 8, and 10 bags of cement per cubic yard with 5, 6, and 7 gallons of water per bag of cement. However, only the results of the 5, 6, and 10 bags of cement per cubic yard with 5 gallons of water per bag of cement are discussed in this thesis. Ordinary Portland cement was used in all mixes. These mixes

were chosen as extreme end points of a complete practical range of mixes. The proportions of sand and stone were determined on the theory that the most dense concrete mix is obtained when the dry unit weight of the sand and stone mixture is a maximum. The unit weights for various ratios of sand and stone are listed in Table D. The sand content was increased 2% above the point of maximum unit weight of the mixture because of the coarse nature of the Petersburg Sand.

Two stone sizes were used. Stone passing a $3/8$ in. sieve and retained on a $1/4$ in. sieve was used in slabs of $1\ 1/8$ in. and $1\ 1/2$ in. thicknesses. Stone passing a $1/4$ in. sieve and retained on a No. 4 sieve was used in the $3/4$ in. thick slabs. The smaller stone was used in the thin slabs in order that some stone be able to go between the steel ribbon and the face of the slab.

The atmospheric conditions of exposure of the slabs were as follows:

Exposure 1 - 70°F , 100% R. H.,

Exposure 2 - 70°F , 50% R. H.,

Exposure 3 - 70°F , one day wet, one day dry, and

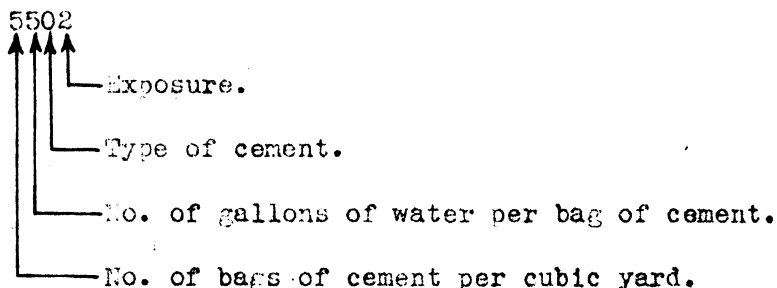
Exposure 4 - Out-of-doors.

Exposures 1, 2, and 3 were controlled mechanically, while exposure 4 was used for comparative purposes.

A numbering system was set up whereby any one particular slab could be identified completely. The thickness of the slab, of course, was itself indicative. The information to be conveyed by numbers, therefore, was the number of bags of cement per cubic yard, the number of gallons of water per bag of cement, the type of cement, and the exposure condition. An example of the system is the best explanation. The first slabs poured, for instance, were 5 bags of cement per cubic yard with 5 gallons of water per bag of cement.

TABLE D SAND & STONE PROPORTIONS FOR MAXIMUM DRY UNIT WEIGHT 1/4 " Stone				
Trial No.	Weight of Stone in lb.	Weight of Sand in lb.	% Sand	Unit Weight of Mixture
1	20.00	5.00	20.0	100.7
2	20.00	8.55	30.0	102.0
3	20.00	10.75	35.0	108.1
4	20.00	13.35	40.0	110.8
5	20.00	13.45	42.0	109.6
3/8 " Stone				
Trial No.	Weight of stone in lb.	Weight of Sand in lb.	% Sand	Unit Weight of Mixture
1	20.00	5.00	20.00	110.2
2	20.00	8.55	30.0	114.9
3	20.00	10.75	35.0	116.1
4	20.00	13.35	40.0	117.7
5	20.00	16.40	45.0	115.8
6	20.00	20.00	50.0	115.3

Ordinary Portland cement (0) was used, and the exposures were classified as in the previous paragraph. Therefore, the code number of the mix was, (Fig. 6):



Twenty-four slabs were poured for each batch of concrete, of which 8 were of each of the following 3 thicknesses, 3/4 in., 1 1/8 in., and 1 1/2 in. Of the 8 slabs 4 contained the steel ribbon while the 4 remaining contained 1/4 in. diameter steel bars 10 in. long embedded at the longitudinal center of the slab. The latter were made for comparative purposes and to provide a means of examining reinforcing when the test is complete.

The sonic modulus test was investigated in this experiment to determine the possibility of obtaining information regarding the effect of curing conditions and time on the elastic properties of concrete. The slabs containing the steel ribbon were also subjected to the sonic test when they were checked for corrosion. The instructions that accompanied the sonic apparatus were published by the American Society for Testing Materials.⁽²⁾ The formula for computing the modulus of elasticity was a part of these instructions. That formula was:

$$E = \frac{W L^3 T}{408 d^3 b} \quad f^2 \text{ ----- (1)}$$

where:

- E = modulus of elasticity in pounds per square inch,
- W = weight of tested sample in pounds,
- L = length of tested sample in inches,
- b = width of tested sample in inches,

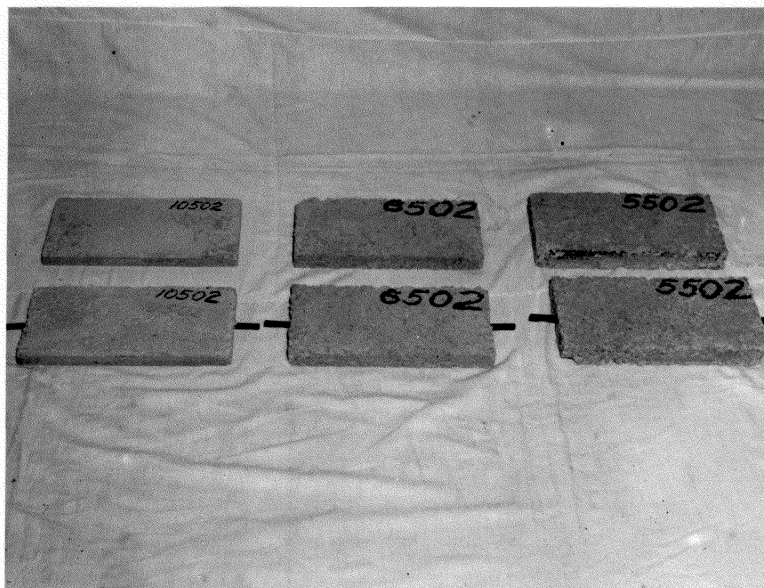


Fig. 6

Pilot Slabs

d = depth of tested sample in inches,

f = frequency in cycles per second, and

T = a correction factor depending upon L/K and Poisson's ratio.

A mathematical solution by W. Ritz was compared to the above formula. (3)

Ritz, working with square plates, derived the following formula:

$$f = \frac{\alpha}{a^2} \sqrt{\frac{g D}{\gamma h}} \text{ ----- (2)}$$

where:

f = frequency in cycles per second,

α = a correlation factor for the mode of vibration,

g = the acceleration due to gravity in feet per second per second,

a = length of side in inches,

γ = unit weight in pounds per cubic inch,

h = depth in inches, and

$$D = \frac{E h^3}{12 (1 - \nu^2)}$$

The terms of the equation (1) substituted in equation (2) and the following expression was obtained:

$$E = \frac{(1 - \nu^2)}{C} \frac{W L^3}{\alpha^2 b d^3} f^2 \text{ ----- (3)}$$

The term L of (1) was substituted for the term a of (2) in obtaining (3). Equation (3) is applicable to beams.

Small concrete beams 12 in. in length and 3/4 in., 1 1/8 in., and 1 1/2 in. in depth were made of the same mixture as one set of standard slabs. The beam widths were of three general sizes, 1 in., 2 in., and 3 in. for each of the three thicknesses. Sonic modulus tests were run on these beams

and slabs to determine their theoretical elastic properties. The elastic properties of the beams were then treated statistically to determine the calculated data. The purpose of the statistical treatment was to determine the least number of beam samples that would be needed in future tests to assure the determination of a mean value of the modulus of elasticity that would have less than $\pm 5\%$ variance 95% of the time.

The calculated modulus data was divided into two groups according to age and the statistical mean was determined for each group. The following expression was used in this phase of treatment⁽⁴⁾:

$$m = \frac{\sum E}{n}$$

where:

- m = mean modulus value,
- E = individual values, and
- n = number of values.

The standard deviation ($\tilde{\sigma}$) was then computed for each group by the following equation⁽⁵⁾:

$$\tilde{\sigma}^2 = \frac{\sum (m-E)^2}{n-1}$$

The number of samples (n_1) required to give a mean modulus value with less than 5% variance was determined by use of the following expression⁽⁶⁾:

$$\sqrt{n_1} = \frac{2 \tilde{\sigma}}{.05 m}$$

After a satisfactory method of measuring the corrosion of the embedded steel had been developed the final set of pilot slabs were poured. Four complete sets of slabs were made. The four sets consisted of one set of the 550- mix, one set of the 650- mix, and two sets of the 1050- mix. Immediately after a pouring was completed the slabs were placed in the 100% R. H. room.

Twenty-four hours later they were moved into the 50% R. H. room where they remained for three days. Four days after pouring, the electrical resistance of the embedded steel was measured and recorded, and the slabs were moved to their several exposure stations. They were returned to the 50% R. H. room every ten to fifteen days for resistance readings and sonic tests.

E. Data and Results

The resistance readings on the embedded steel leads were recorded with the date of reading and after several readings had accumulated they were plotted against their corresponding periods of exposure. Charts 1 to 16, inclusive, contain this data. The three slab thicknesses of one mix in one exposure condition were plotted on the same chart for easier interpretation of the effect of the depth of cover. The slab number was recorded in the upper left-hand corner of the chart and the three thicknesses were designated by "t" in their sectors of the chart. Data on some thicknesses was not recorded as a result of the breakage of those slabs when handled.

The elastic properties of the beams and slabs were recorded for a 6701 mix in Tables E and F. The statistical treatment of this data was recorded in Table G. The moduli of elasticity for all beams and slabs were computed by equation (1) on page 18.

SLAB 5501

$t = 0.75$

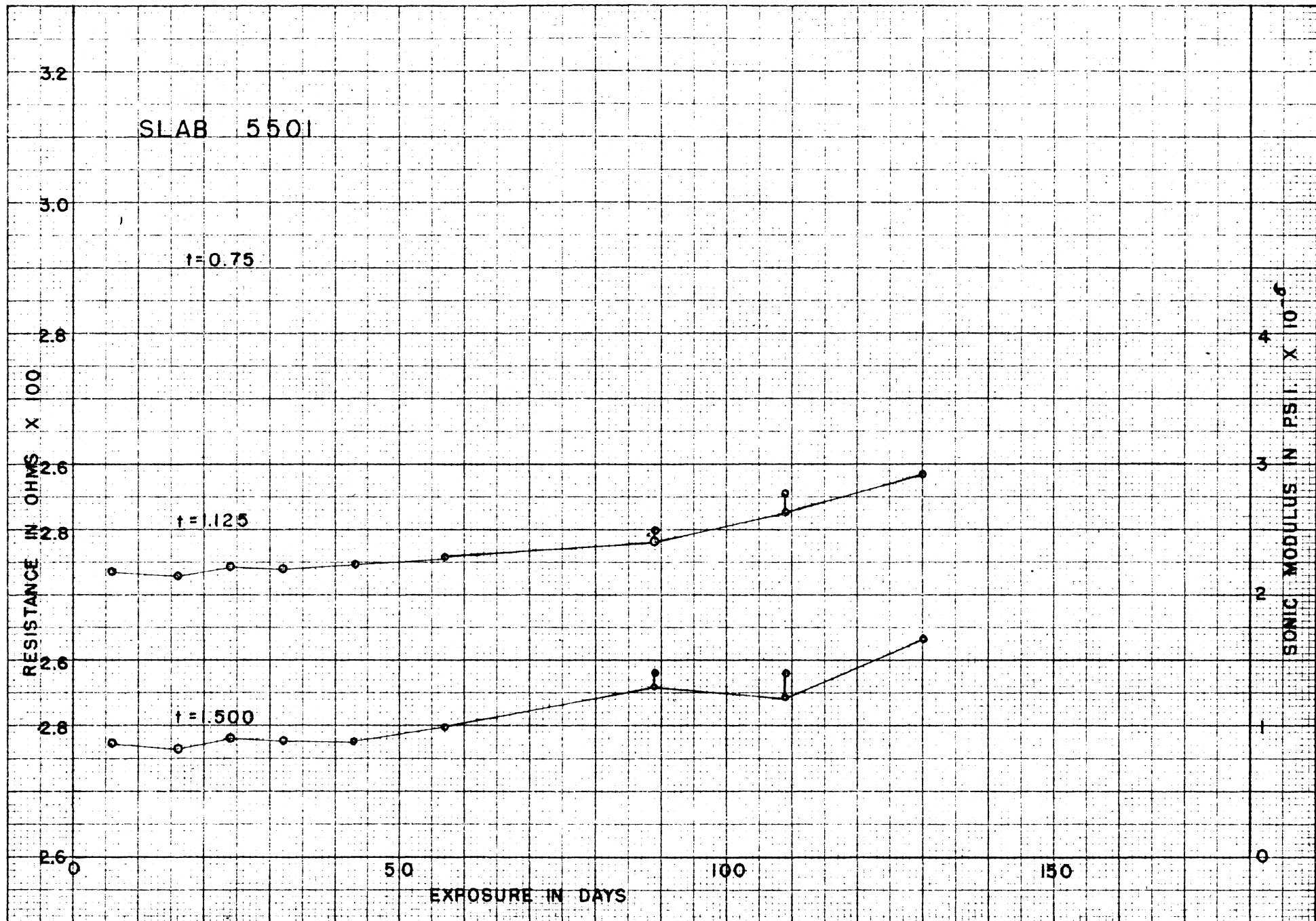
$t = 1.125$

$t = 1.500$

RESISTANCE IN OHMS X 100

SONIC MODULUS IN PSI X 10¹⁰

EXPOSURE IN DAYS



SLAB 5502

$t = 0.750$

$t = 1.125$

$t = 1.500$

RESISTANCE IN OHMS X 100

SONIC MODULUS IN P.S.I. X 10³

EXPOSURE IN DAYS

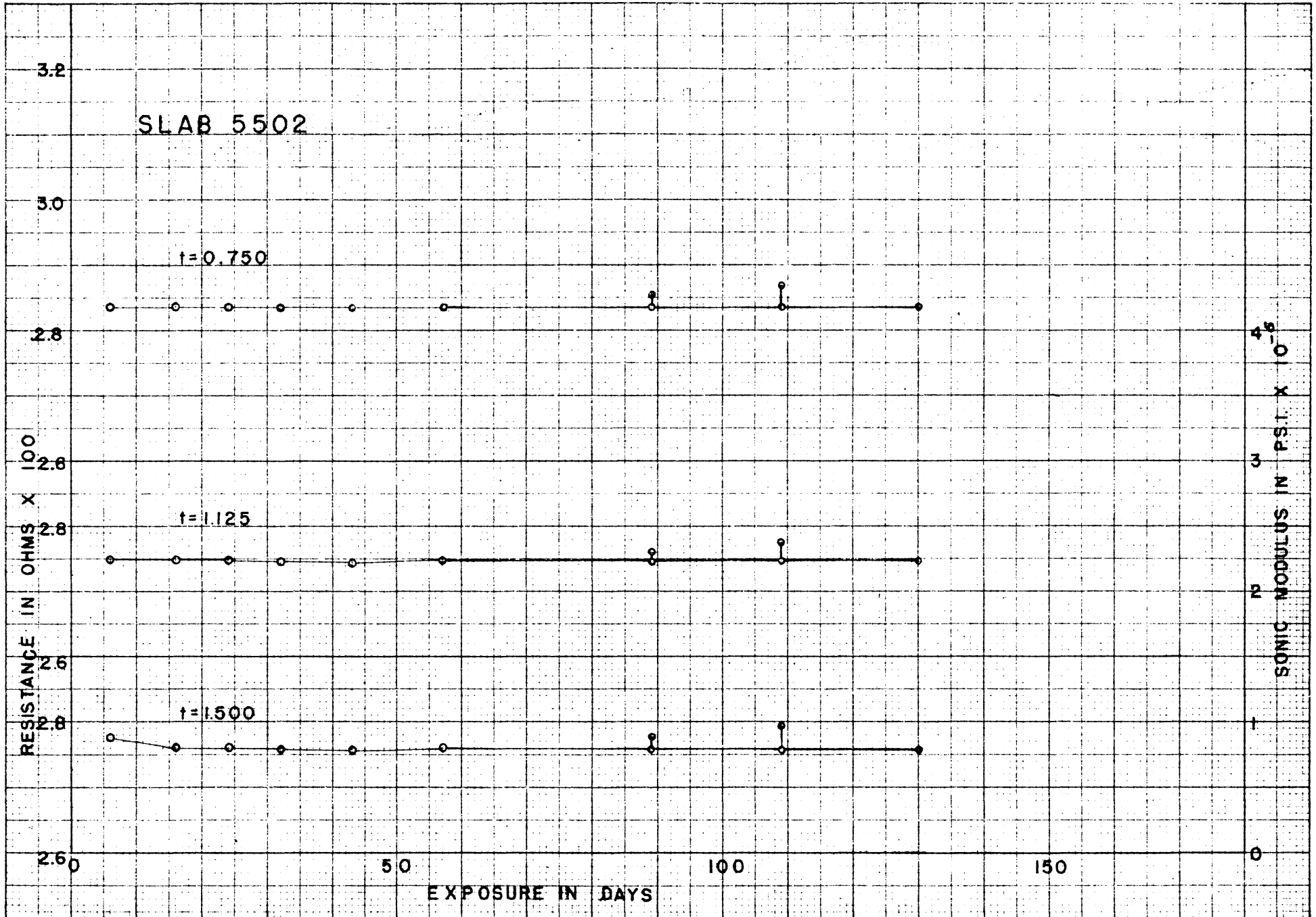


Chart 3

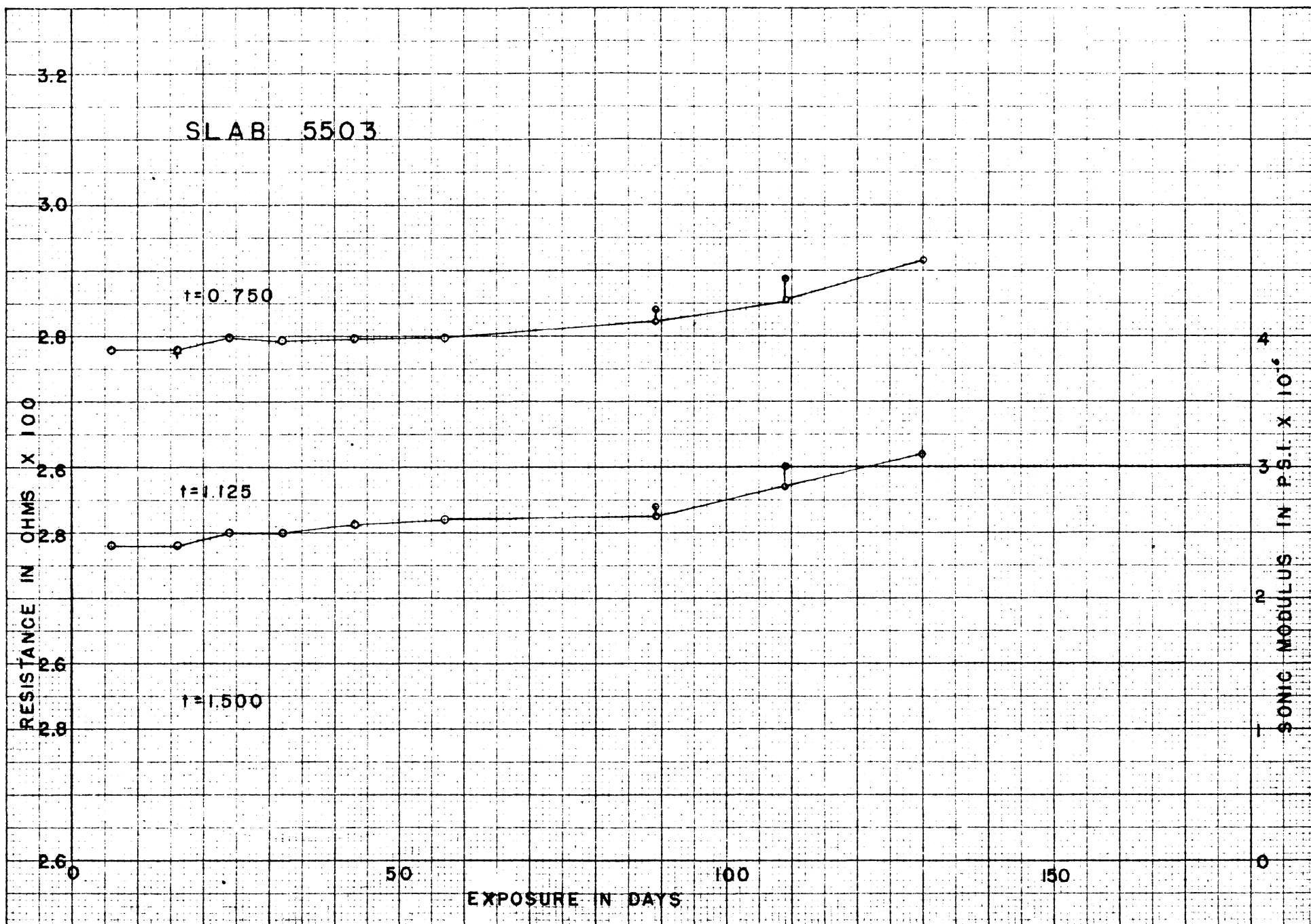
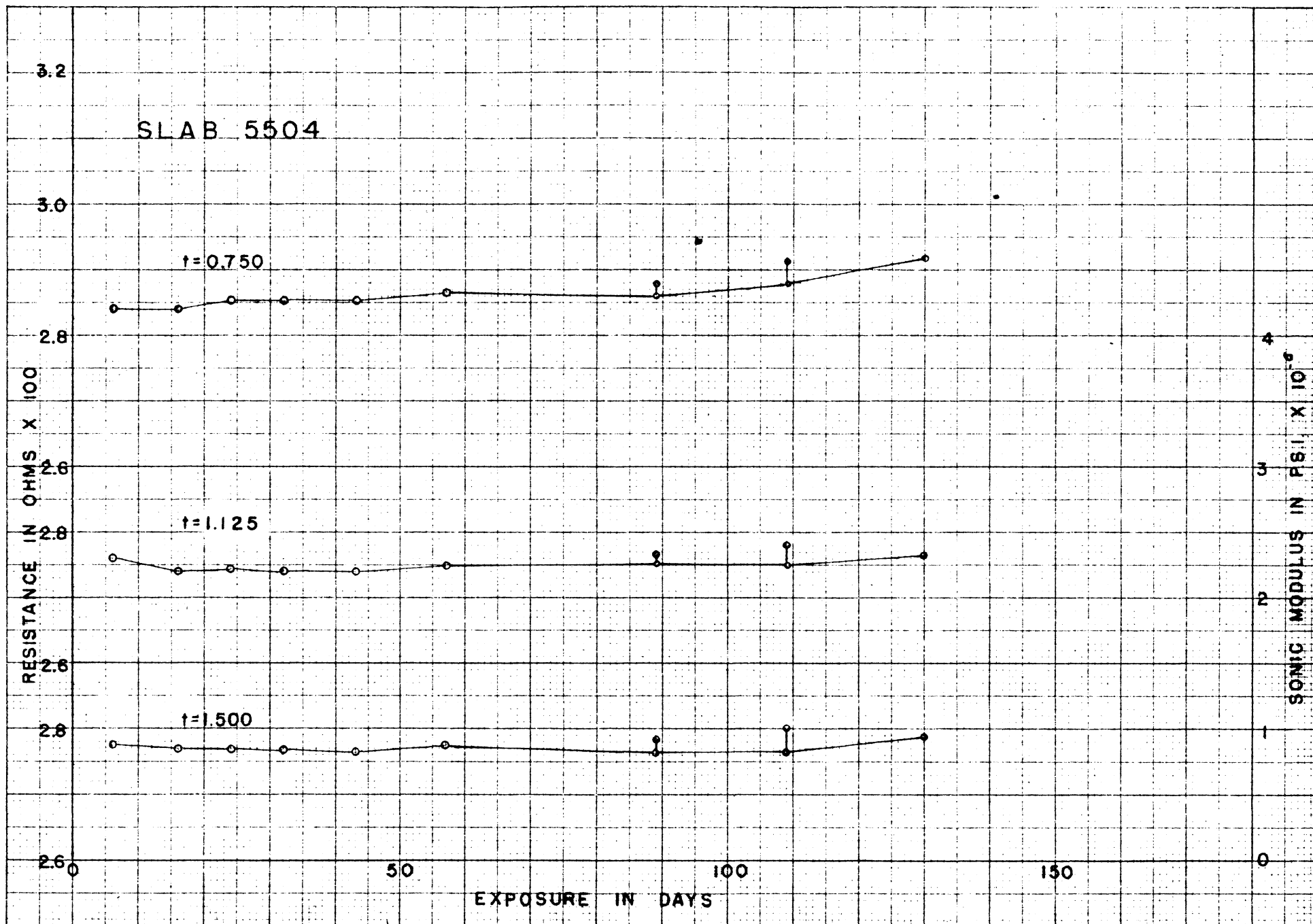


Chart 4



SLAB 6501

3.2

3.0

2.8

$t = 0.750$

100

2.6

2.8

$t = 1.125$

2.6

2.8

$t = 1.500$

2.6

50

100

150

EXPOSURE IN DAYS

SONIC MODULUS IN PSI

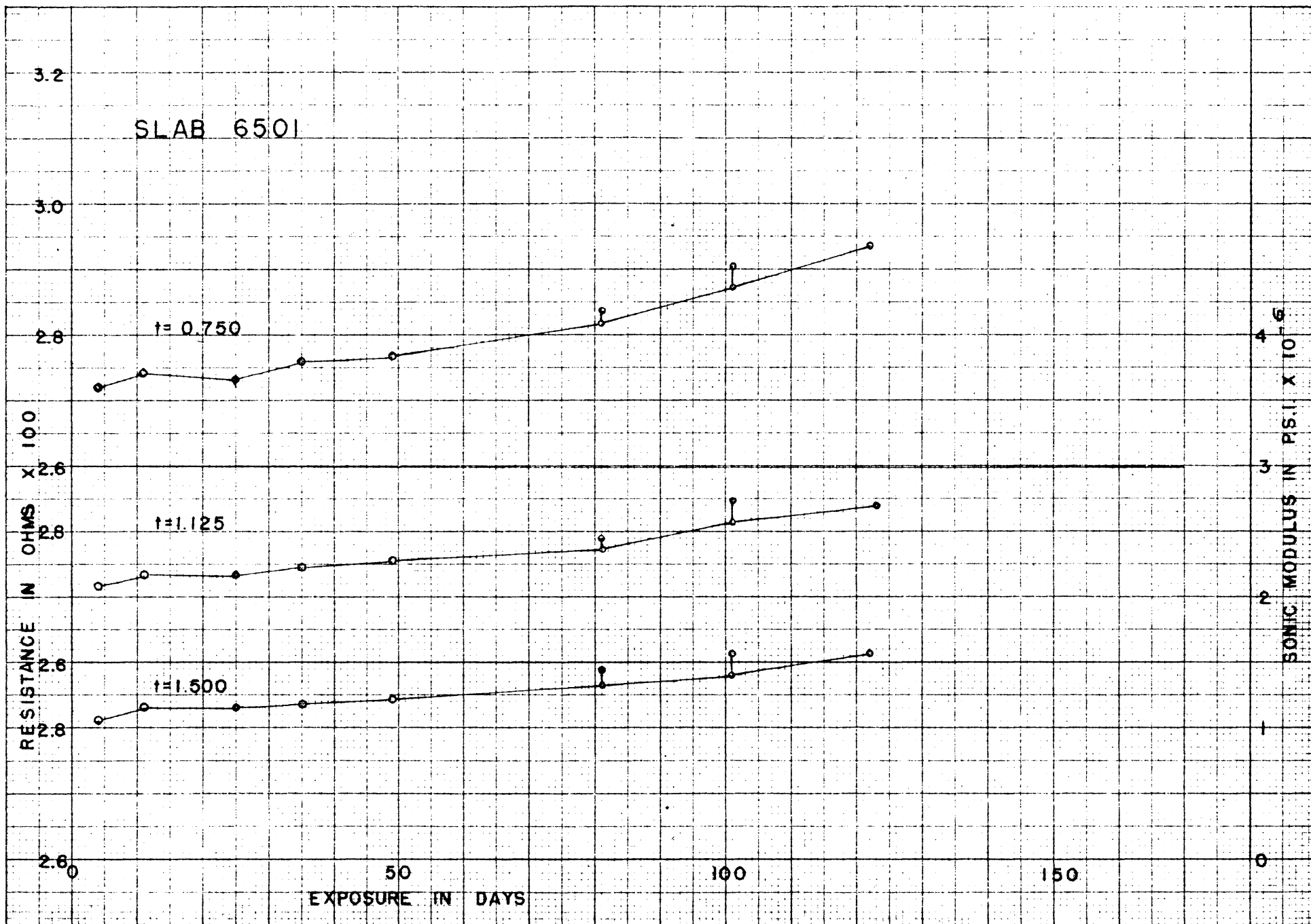


Chart 6

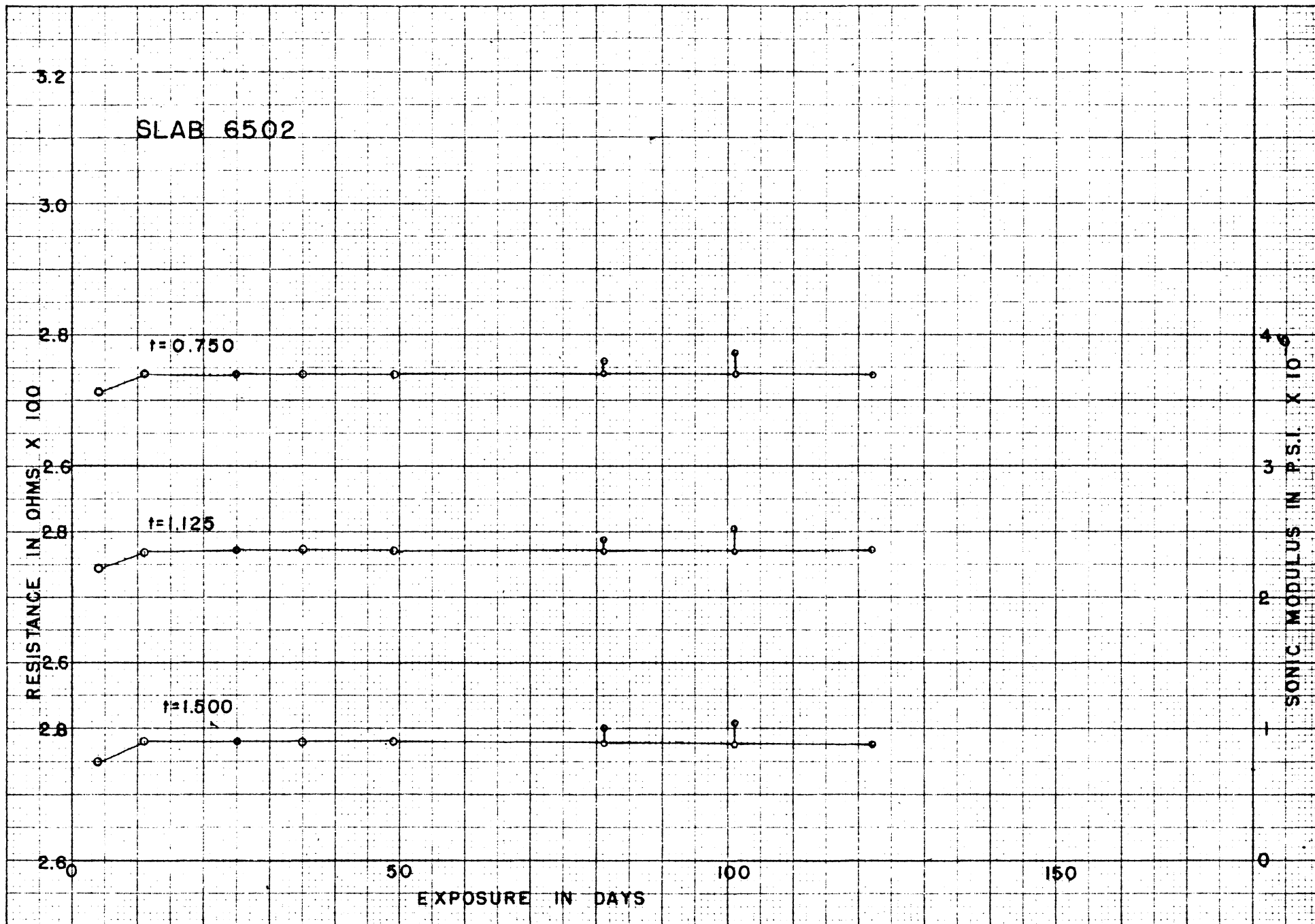


Chart 7

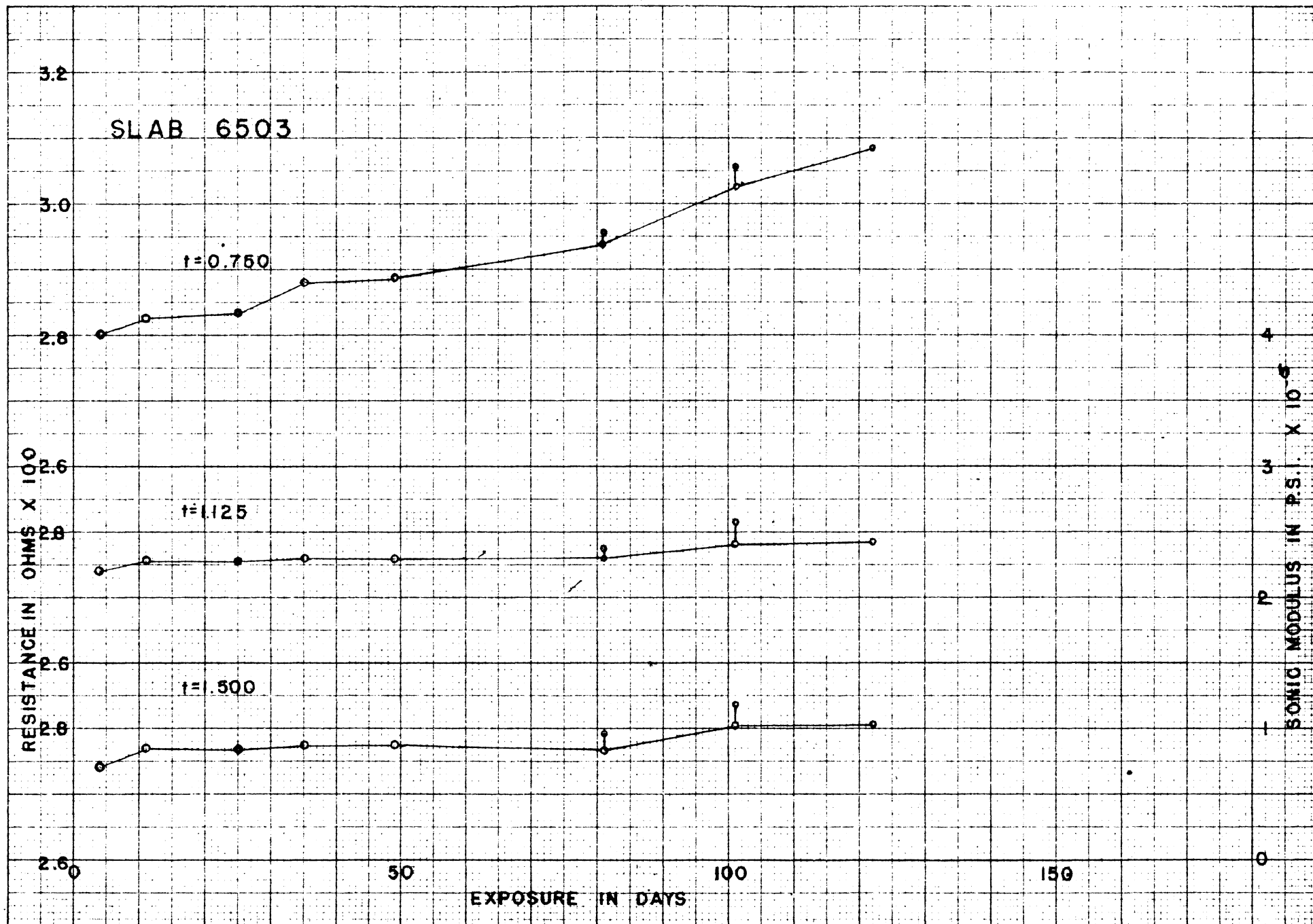


Chart 8

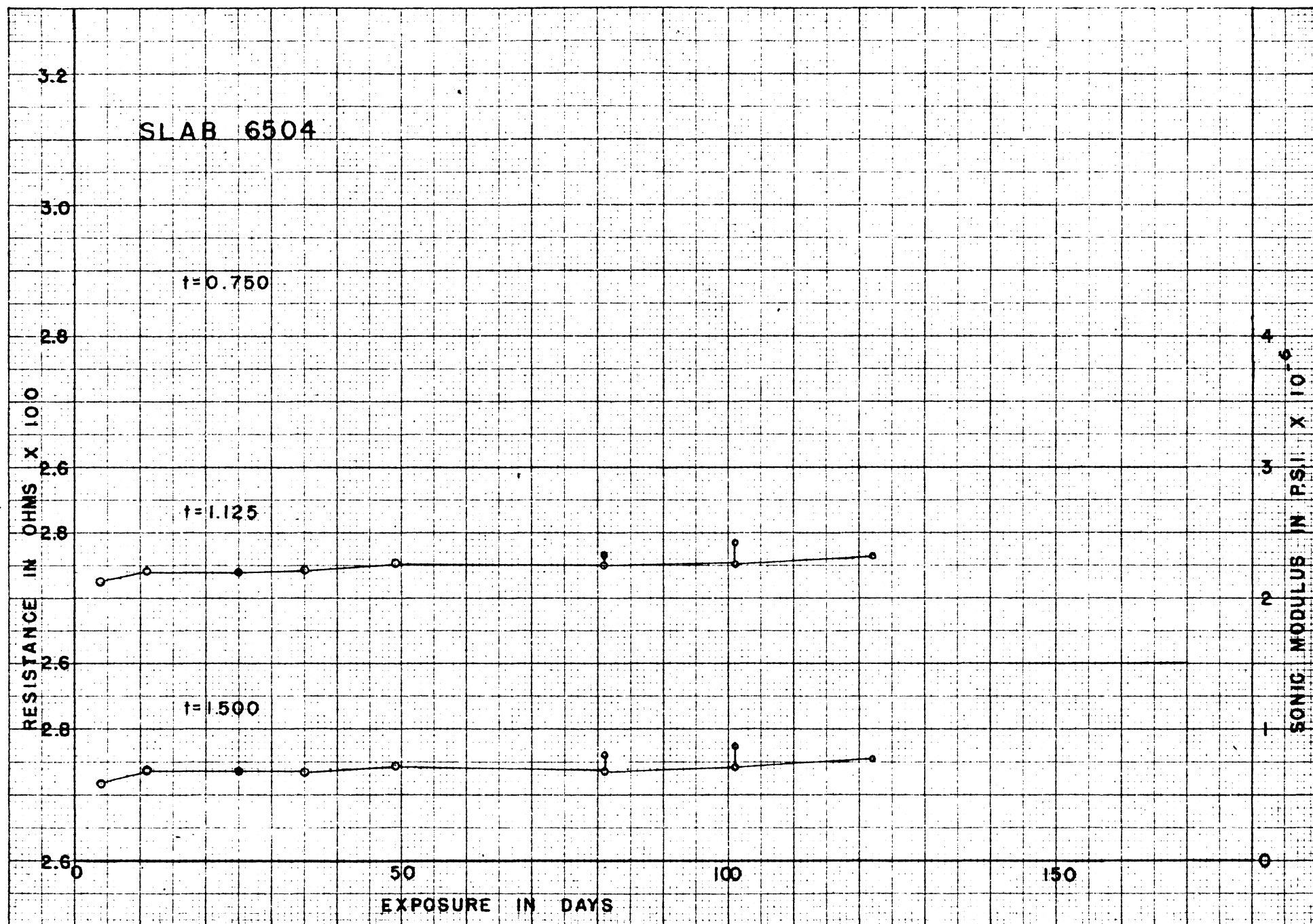


Chart 9

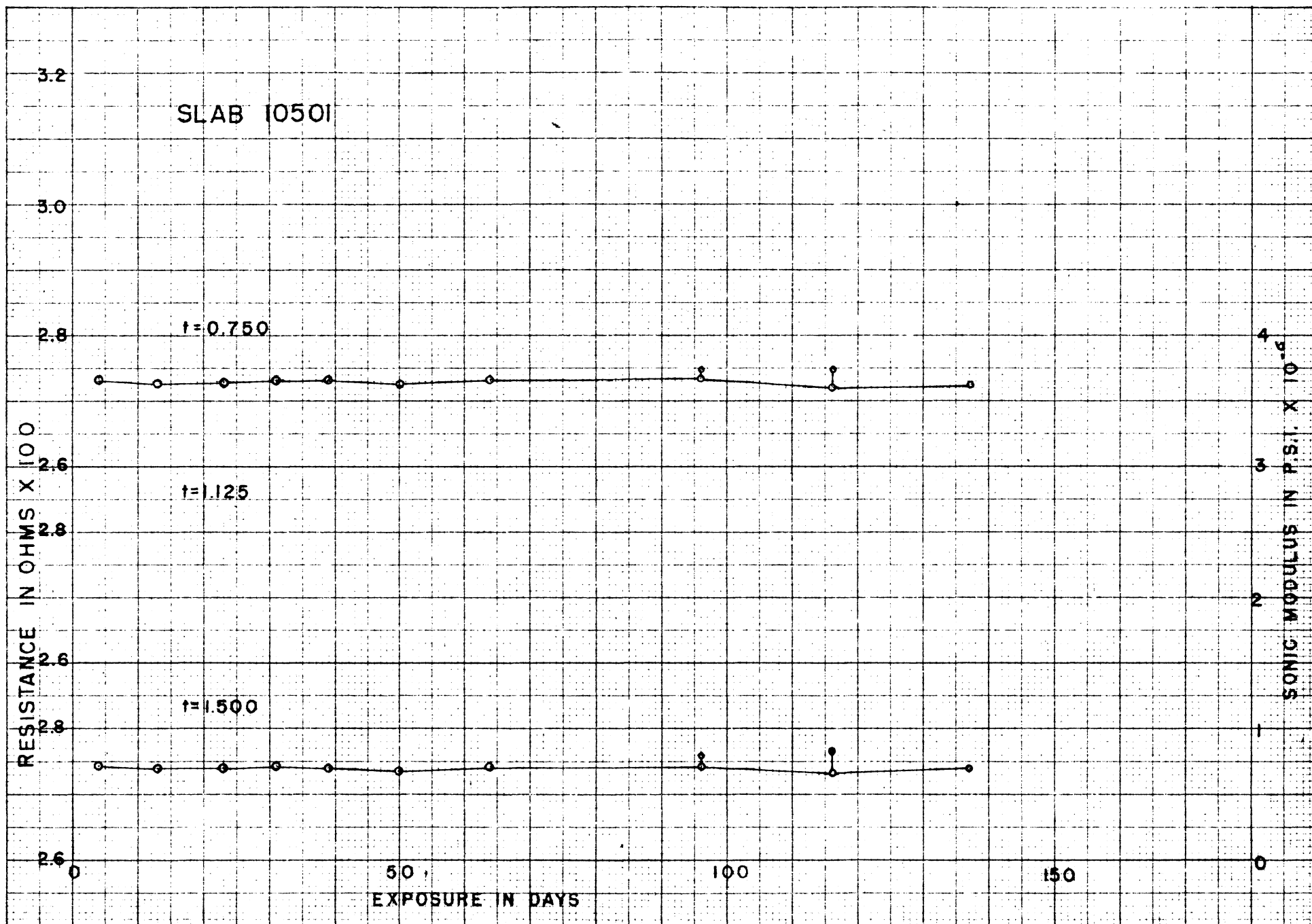


Chart 10

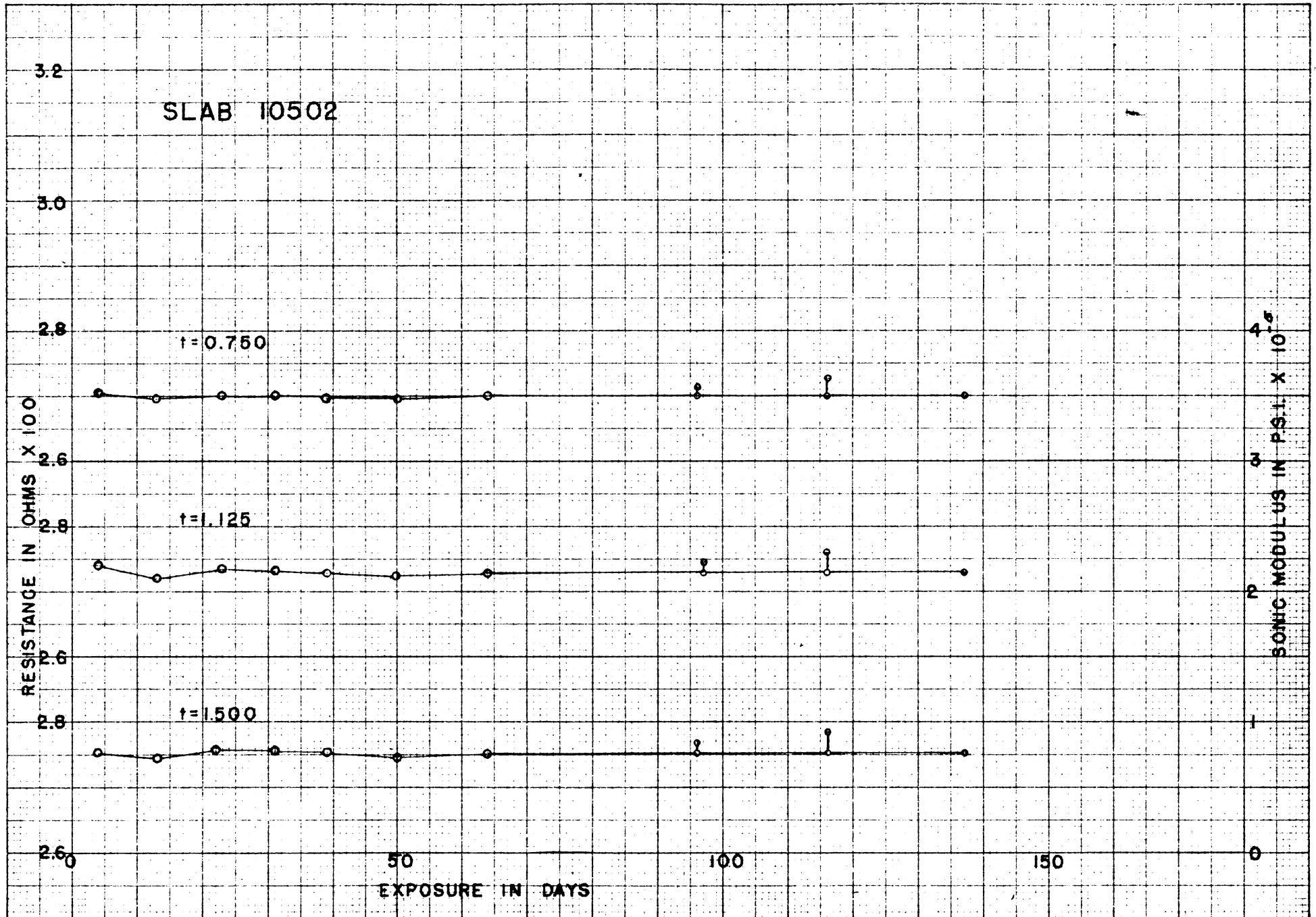
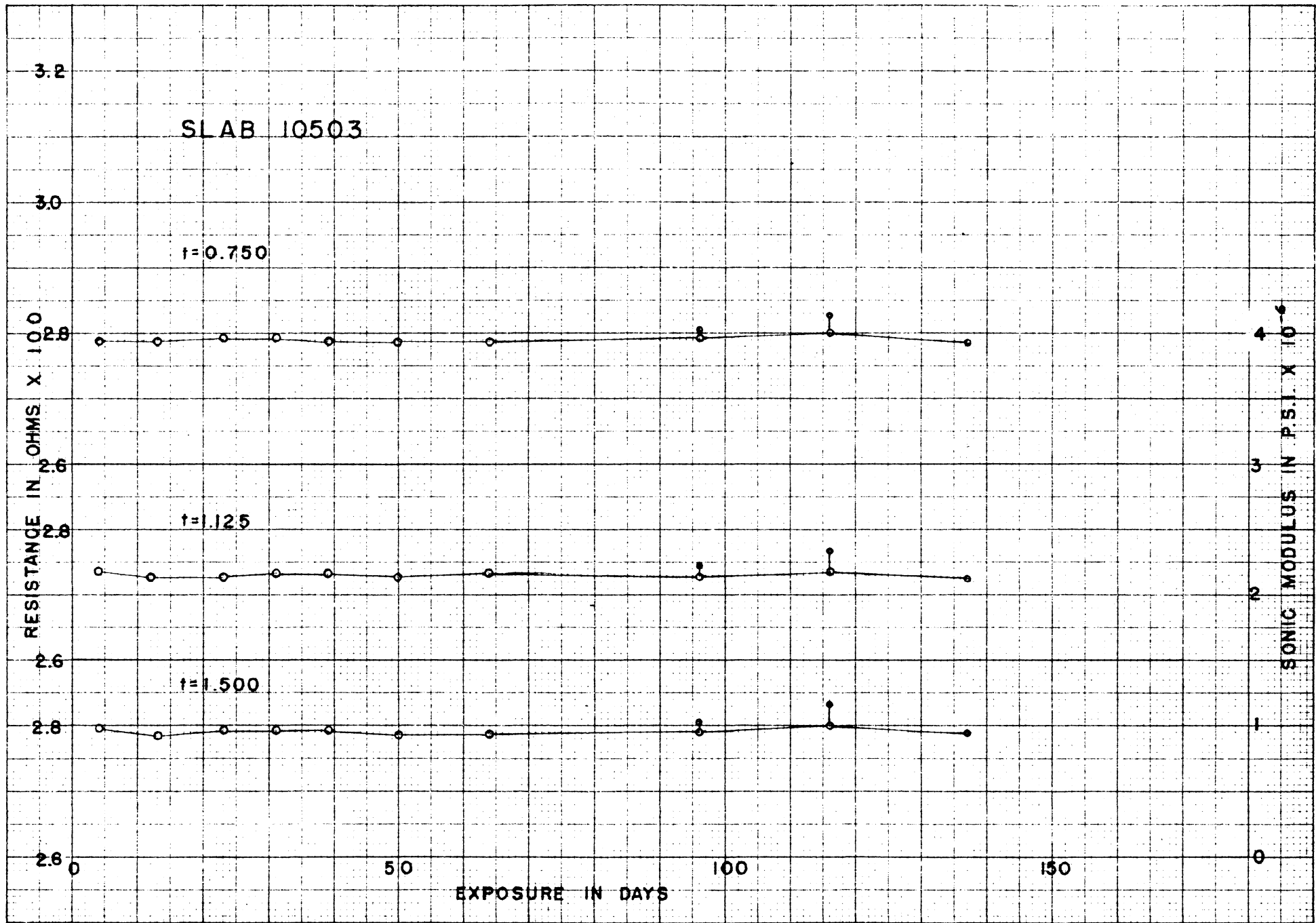


Chart 11



SLAB 10504

$t = 0.750$

$t = 1.125$

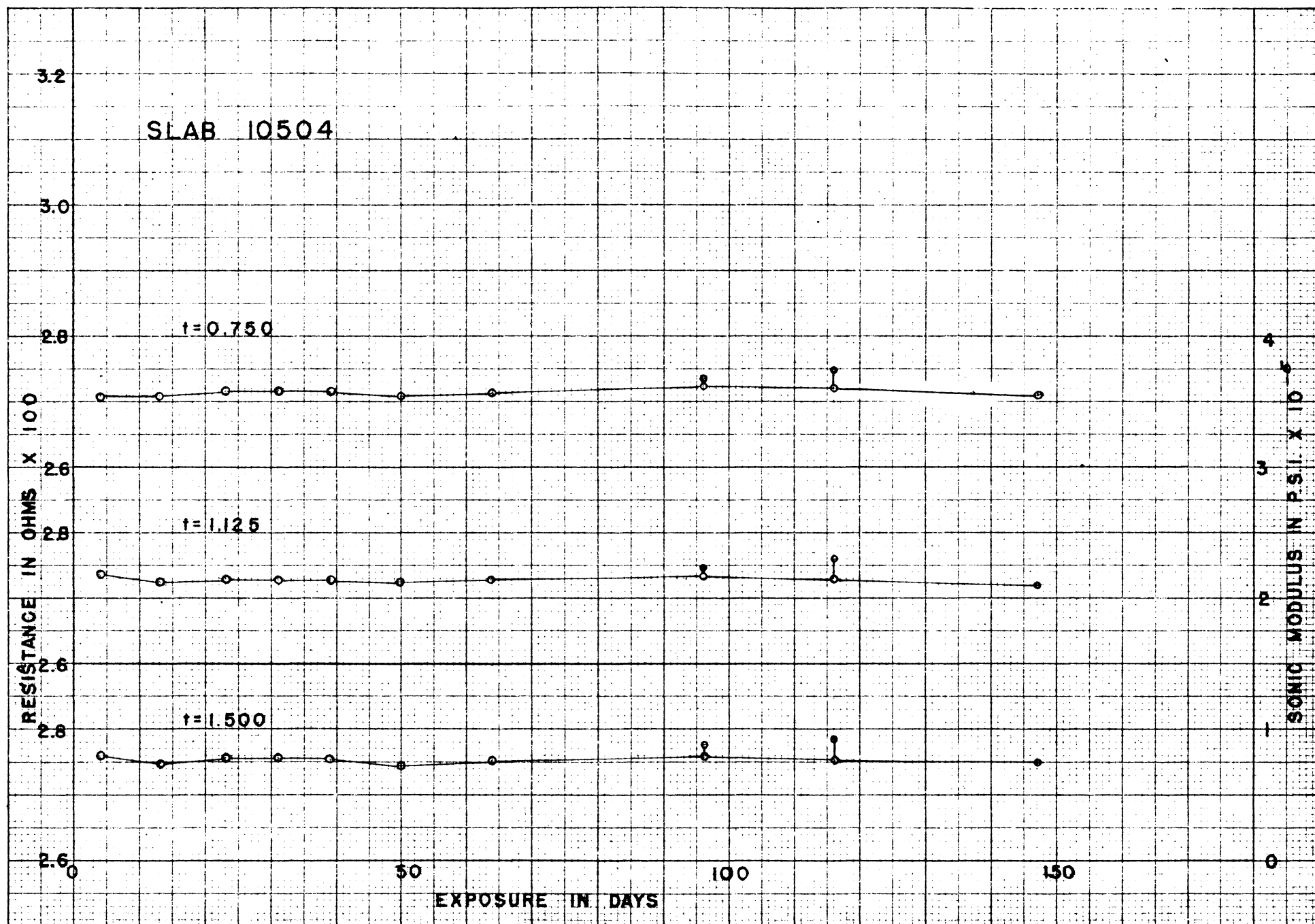
$t = 1.500$

RESISTANCE IN OHMS X 100

SONIC MODULUS IN P.S.I. X 10⁴

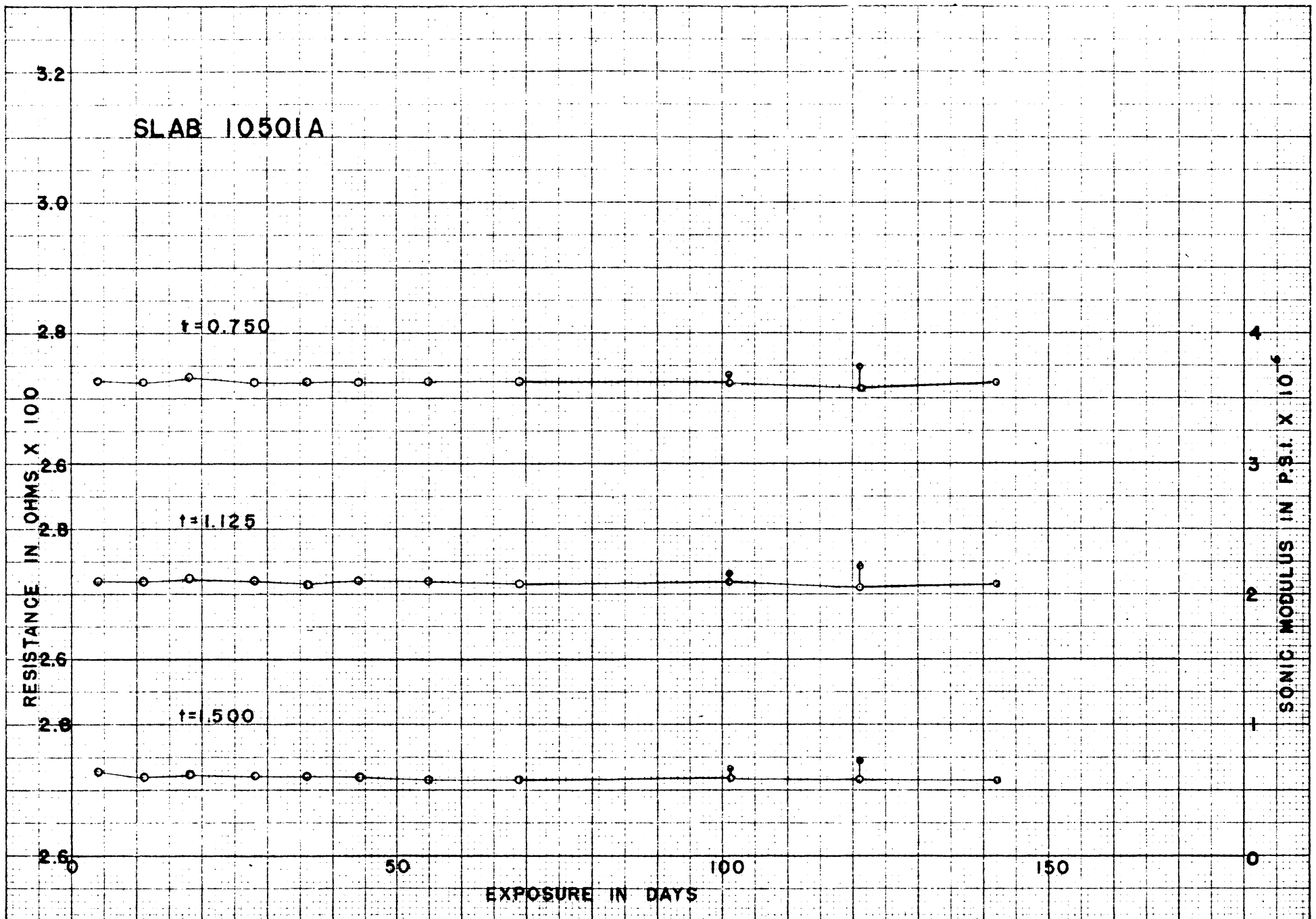
EXPOSURE IN DAYS

Chart 12



SLAB 10501A

Chart 13



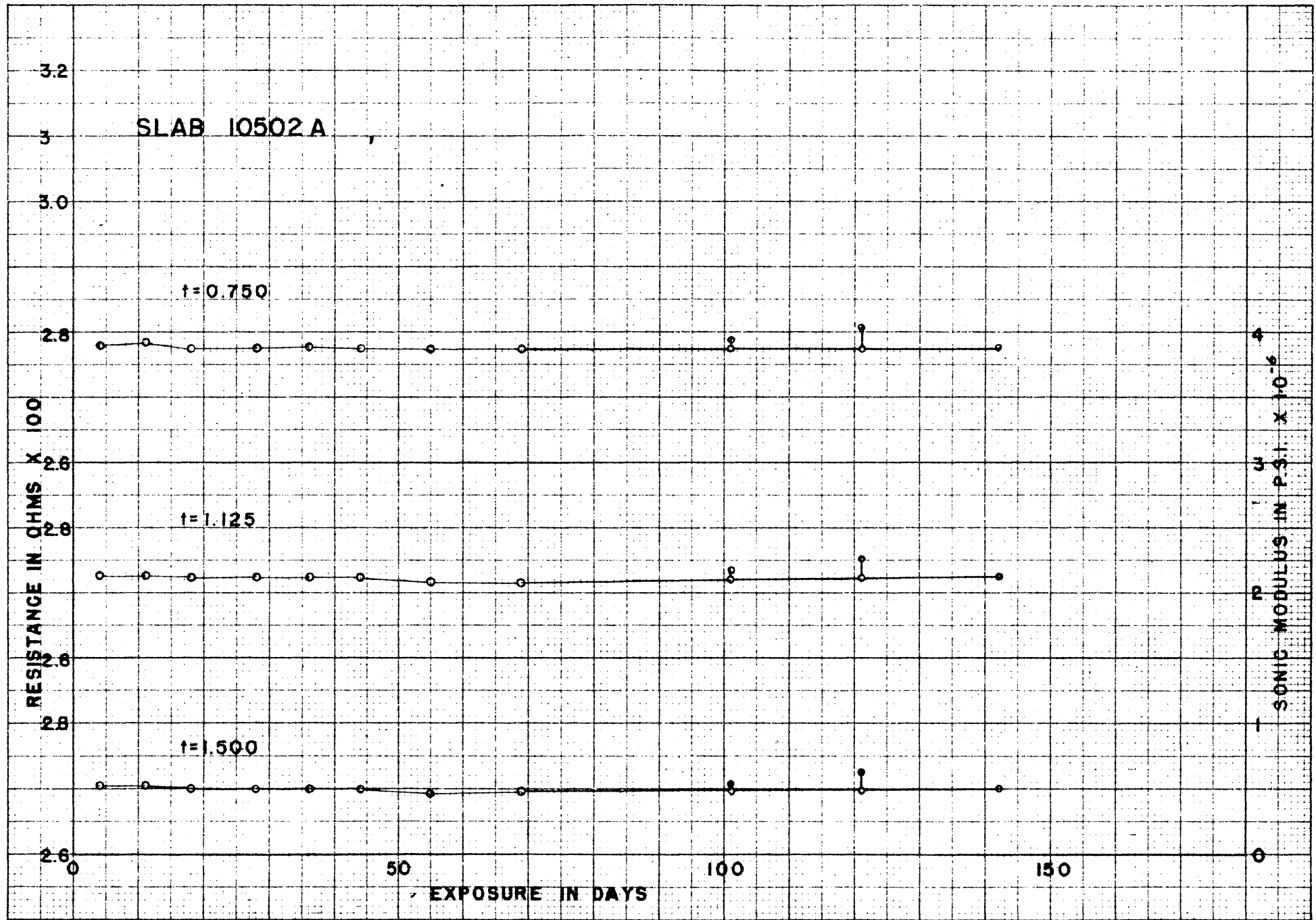
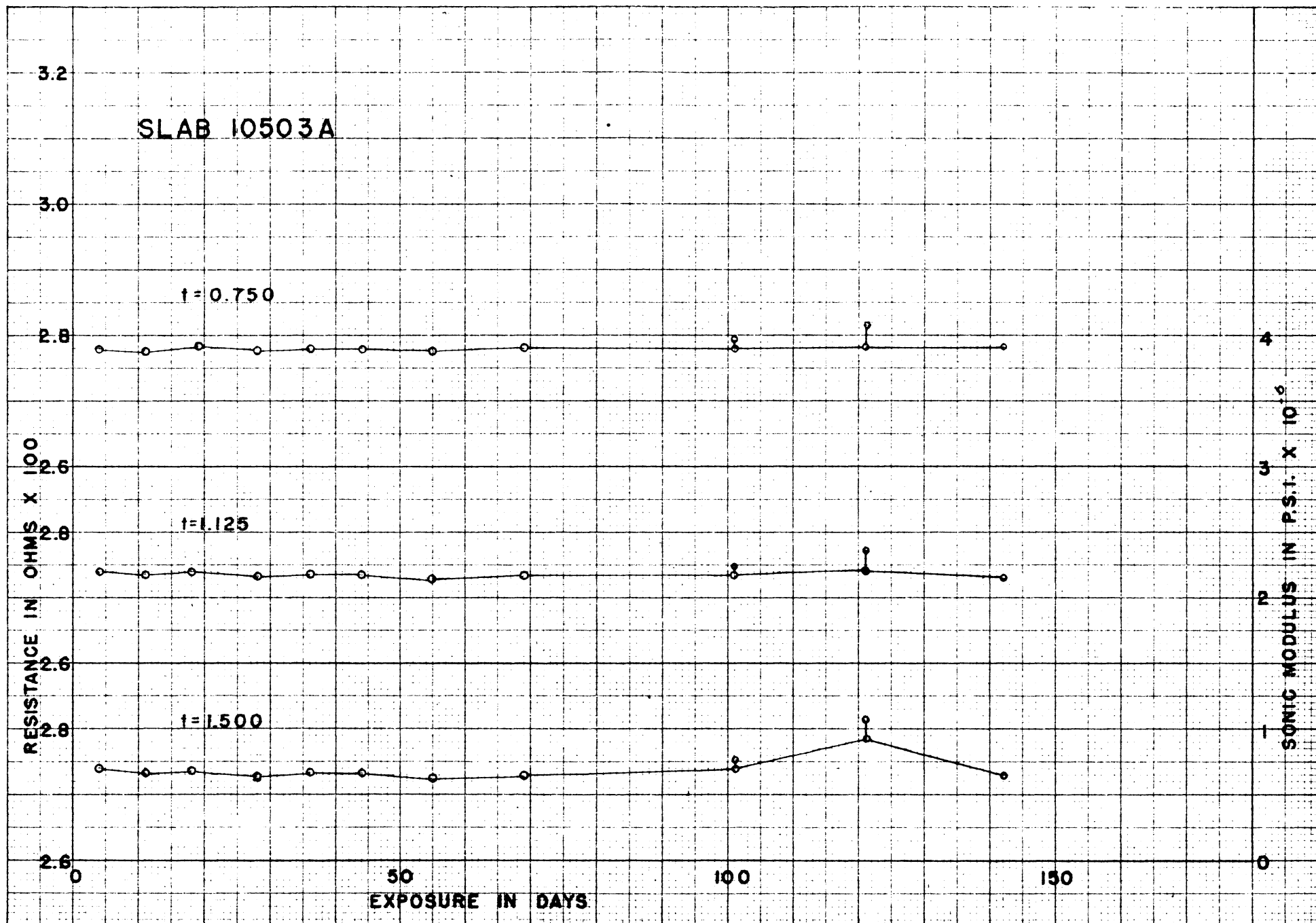


Chart 15



SLAB 10504 A

$t = 0.750$

RESISTANCE IN OHMS X 100

$t = 1.125$

RESISTANCE IN OHMS X 100

$t = 1.500$

50

EXPOSURE IN DAYS

100

150

SONIC MODULUS IN PSI X 10⁴

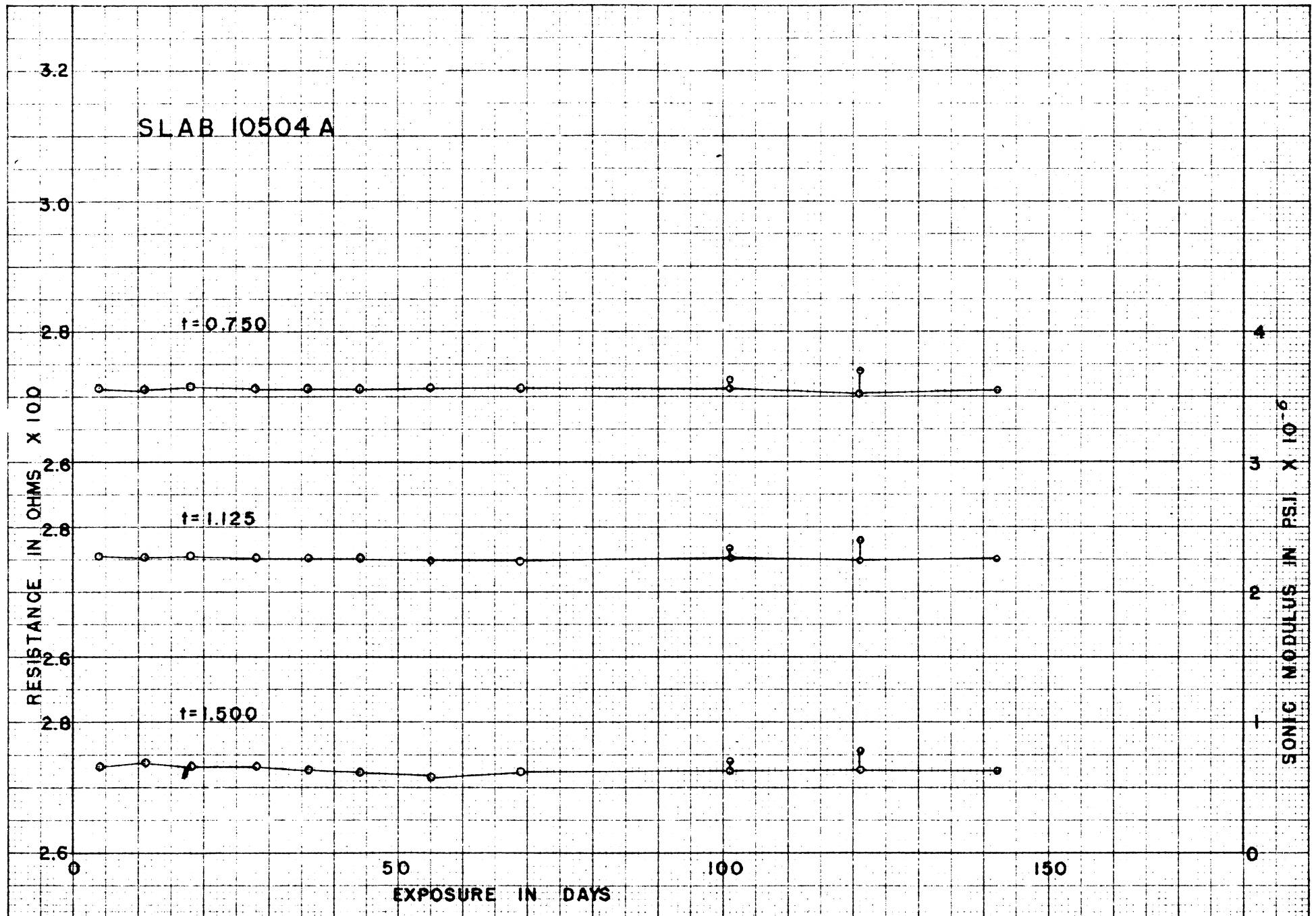


TABLE E
ELASTIC PROPERTIES OF
BEAMS AND SLABS

Beam depth = 0.750 in.

Width in.	Age - 5 days		Age - 35 days	
	Weight	Frequency	Weight	Frequency
2.000	1.581 lb.	610 c.p.s.	1.621 lb.	770 c.p.s.
2.625	1.910 lb.	635 c.p.s.	1.956 lb.	790 c.p.s.

Beam depth = 1.125 in.

Width in.	Age - 5 days		Age - 35 days	
	Weight	Frequency	Weight	Frequency
1.250	1.233 lb..	835 c.p.s.	1.266 lb.	1230 c.p.s.
1.875	2.015 lb.	860 c.p.s.	2.053 lb.	1070 c.p.s.
2.750	3.074 lb.	970 c.p.s.	3.127 lb.	1150 c.p.s.

Beam depth = 1.625 in.

Width in.	Age - 5 days		Age - 35 days	
	Weight	Frequency	Weight	Frequency
1.188	1.720 lb.	1340 c.p.s.	1.749 lb.	1160 c.p.s.
2.000	2.814 lb.	1200 c.p.s.	2.880 lb.	1800 c.p.s.
2.750	3.954 lb.	1200 c.p.s.	4.070 lb.	1580 c.p.s.

TABLE E

(cont.)

5.875 in. x 12.00 in. Slabs

Depth in.	Age - 5 days		Age - 35 days	
	Weight	Frequency	Weight	Frequency
0.812	4.048 lb.	640 c.p.s.	4.190 lb.	738 c.p.s.
1.125	6.483 lb.	900 c.p.s.	6.637 lb.	1080 c.p.s.
1.625	9.565 lb.	1370 c.p.s.	9.803 lb.	1610 c.p.s.

TABLE F
MODULUS OF ELASTICITY

12 in. Beam

Depth in.	Width	Modulus in p.s.i.	
	in.	Age- 5 days	Age-35 days
0.750	2.000	2,452,000	4,004,000
	2.625	2,945,000	4,668,000
1.125	1.250	2,148,000	4,788,000
	1.875	2,397,000	3,780,000
	2.750	3,285,000	4,701,000
1.625	1.188	2,913,000	2,220,000
	2.000	2,259,000	5,202,000
	2.750	2,309,000	4,115,000

5.875 in. x 12.00 in. Slabs

Depth in.	Modulus in p.s.i.	
	Age- 5 days	Age-35 days
0.812	2,259,000	2,968,000
1.125	2,877,000	4,241,000
1.625	3,446,000	4,873,000

TABLE G
STATISTICAL TREATMENT OF MODULUS DATA

Age - 5 days

E	(m-E)	(m-E) ²
2,452	136	18,496
2,945	-357	127,449
2,148	440	193,600
2,397	191	36,481
3,285	-697	485,800
2,913	-325	105,625
2,259	329	108,241
2,309	279	77,841

$$\Sigma = 20,708 \quad (n-1)\hat{\sigma}^2 = 1,153,533$$

$$m = 2,588$$

$$0.05m = 129.4 \quad \hat{\sigma} = \pm 406$$

$$\% \text{ Variance } 95\% \text{ of time} = \frac{2\hat{\sigma}}{2,588} = \frac{812}{2,588} = 31.4$$

$$\sqrt{n_1} = \frac{2\hat{\sigma}}{0.05 m} = \frac{2 \times 406}{129.4} = 6.3$$

$$n_1 = 40$$

TABLE G

(cont.)

Age - 35 days

E	(m-E)	(m-E) ²
4,004	461	212,521
4,668	-203	41,209
4,788	-323	104,329
3,780	675	455,625
4,701	236	55,696
5,202	-737	543,169
4,115	350	122,500

$$\Sigma = 31,258 \quad \tilde{\sigma}^2_{(n-1)} = 1,535,049$$

$$m = 4465$$

$$0.05m = 223.2 \quad \tilde{\sigma} \pm \pm 505$$

$$\% \text{ Variance } 95\% \text{ of time} = \frac{1010}{4465} = 22.6$$

$$\sqrt{n_1} = \frac{1010}{223.2} = 4.5$$

$$n_1 = 21$$

IV. DISCUSSION OF RESULTS

A. Uncontrollable Influences

The electrical resistivity of any material is dependent on the temperature of the material. A slight change in the temperature of steel will cause a noticeable change in its resistance. There were two probable causes of temperature variation in this experiment. One was the internal heat generated by the chemical reactions taking place in the concrete during the early curing stage. The other was the slight fluctuation of room temperature as a result of the limitations of the mechanical humidifying equipment.

It is interesting to examine the charts for temperature variation over the first twenty days of exposure. This is the period in which the chemical reaction is taking place at a decreasing rate. In general, the charts show a very small decrease in resistance. They also show a larger decrease for the thicker slabs. Charts 9 to 16, inclusive, are the most consistent in their indications. These eight charts are for the 1050- mix, the richest and most dense mix used in the experiment. The 550- and 650- mixes are of such a harsh nature that there are considerable voids in their slabs. It is reasonable to assume that the circulating air has a more rapid cooling or heating effect on the interior points of the slabs having the most voids.

An examination of the chart groups for any one mix over the exposure range from twenty days to the day of the first indication of corrosion reveals that the resistance changes are very nearly uniform. Charts 9 to 12, inclusive, are an excellent example of these variations. The dip in the curve is uniform for all four of the charts between 39 and 64 days of exposure. These constant changes could be caused by a small difference in room temperature

on the three testing dates. All curves show a similar increase in resistance readings for the last two tests. A check of the testing room revealed a slight change in the humidity condition which had in turn caused a change in the dry bulb thermometer reading.

B. Control Charts

The resistance measurements for all slabs exposed to the No. 2 condition are recorded on Charts 2, 6, 10, and 14. The curves on these charts show no significant change in the resistance regardless of the length of their individual exposure periods. Ribbon steel exposed to the same treatment, but not embedded in concrete, has also shown no indication of corrosion. It is reasonable, therefore, to assume that there is no corrosive action taking place within the slabs subjected to the 50% R. H. treatment. These charts shall be designated as control charts and all other charts may be compared to them for relative indications of corrosion.

C. Indications of Corrosion

The first indications of corrosion revealed by the electrical resistances are found in slabs 5503 and 5504. These indications appear on Charts 3 and 4 after 20 days of exposure, while the first pronounced changes in resistance are found on Chart 7, the chart for the 6503 slab. An examination of the 3/4 in. thick 6503 slab revealed that the embedded steel in the slab could be inspected through the concrete voids at several points along its length. Immediately after the change in resistance measurements was noted, the embedded steel was examined and corrosion spots were found on the exposed surfaces. This evidence serves to confirm the theory that the changes in

electrical resistance of steel ribbon can be used to indicate its corrosion.

D. Exposure Conditions

The results obtained in this experiment also supply sufficient data for a general comparison of the effects of exposure conditions. Charts 1, 3, 5, 7, 9, 11, 13, and 15 are for severe exposure conditions while Charts 4, 8, 12, and 16 are for natural conditions. A comparison of the two chart groups reveals that the specimens subjected to the severe conditions of exposure show a higher rate of corrosion than those subjected to ordinary weather conditions. It is evident, therefore, that a correlation can be made between the two conditions and in the future short tests under accelerated conditions of exposure can be used to predict the behavior of the embedded steel over longer periods of natural conditions of exposure.

E. Corrosion Trends

Although the corrosion tests shown on the charts are quite incomplete, their trends have begun to disclose indications of their final results. A comparison of the three curves on Chart 5, for instance, shows that the slopes of the curves at any one exposure date are very nearly the same. Charts 1 and 3 also have this property while the $t = 1 \frac{1}{8}$ in., and $t = 1 \frac{1}{2}$ in. curves of Chart 7 likewise agree. The $t = \frac{3}{4}$ in. curve of the 6503 slab, however, does not have this property. It is of interest to note that all of the curves for the 1050- mix have the same slope throughout their length, and even more interesting is the fact that their slopes are zero. These curve properties may be interpreted, therefore, to indicate that the depth

of concrete cover is secondary to concrete quality in influencing the corrosion of embedded steel.

F. Sonic Modulus

The calculated values of the modulus of elasticity, as recorded in Table F, show considerable variance. This fact is not a surprising one, however, for the equation by which the values were obtained is purely a theoretical one. The assumptions that were made in deriving this expression were not completely true in that concrete is not a perfectly uniform material. Compression tests of concrete cylinders, all made from the same mix, will have a noticeable variance in both ultimate strength and modulus of elasticity.

The statistical treatment of the calculated data, as shown in Table G, is useful in two ways. First, it gives a measure of the variance of the data and second, it can be used to help indicate the most satisfactory experimental technique that should be used in future investigations of the subject.

The thirty-five day modulus value for the 1.88 in. x 1.625 in. beam was not used in the computation in Table G. An examination of its natural frequency, recorded in Table E, reveals that it decreased after the first test while all other values increased. This recorded frequency is, without a doubt, the frequency of an unnatural mode of vibration.

The per cent variance of the mean modulus value in Table G is 31.4% at an age of 5 days, and is reduced after 35 days of curing to 22.6%. It is possible, therefore, that the variance reduces as the concrete ages. This

indication, however, cannot be accepted as a conclusion at this point in the investigation for it was obtained from a small sample of large variance. If this indication is found to be a true one in future studies it would mean that the mean modulus value would become more accurate as the samples aged.

The calculated values of n_1 in Table G show that at least forty sample beams of various sizes should be made in the future if the desired accuracy of the mean modulus is to be obtained.

G. Recommendations

Although the results obtained by the preliminary investigation show definite trends and indications of influences on corrosion of the reinforcing steel, they are not sufficient for final conclusions. Many discontinuities occur in each phase of the investigation. In the future tests should be continued on all of the mixes chosen in the investigation. Tests should also be made on these mixes using High Early Strength cement as well as Ordinary Portland cement. Investigations of temperature, admixtures, and salt water effects on the rate of corrosion should also be made.

The investigation of the sonic modulus method of measuring the modulus of Elasticity should be expanded. In future experiments forty-five beams of one mix should be used. There should be five beams each for the 3/4 in., 1 1/8 in., and 1 1/2 in. depths. Widths of 1 in., 2 in., and 3 in. should be used for each depth. The data obtained from such an experiment could be treated more successfully by a statistical analysis to determine the mean modulus of elasticity.⁽⁷⁾

V. CONCLUSIONS

From the data and results obtained in this experiment, the following conclusions seem justified:

1. The method used to measure the quantitative degree of corrosion of embedded steel in concrete appears to be a practical and accurate one.
2. Severe exposure conditions accelerate the rate of corrosion of reinforcing steel and a correlation between these conditions and natural conditions of exposure is indicated.
3. Good quality concrete of high density and no "honey combing" seems to protect embedded steel sufficiently regardless of the depth of cover.
4. The modulus of elasticity of concrete, measured by the sonic method, indicated an increase with age.
5. Variation of the modulus of elasticity of concrete seemed to decrease as the concrete aged.

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VII. BIBLIOGRAPHY

1. Anon. "Asphalt Coating for Exposed Steel in Waterfront Concrete".
Engineering News 84, 1075, (1920).
- Anon. "Steel from Slag Concrete Shows Little Corrosion". Engineering
News 86, 212, (1921).
- Snow, W. A. "Pronounced Reinforcement Corrosion Due to Sea Water or
Electrolysis". Engineering News-Record 87, 528, (1921).
- Ferguson, R. L. "Small Concrete Roof-Slab Failure in Seashore Hotel".
Engineering News-Record 87, 271, (1921).
- McKibben, F. P. "Some Examples of Corrosion of Reinforcing Steel".
Engineering News-Record 87, 531, (1921).
- Anon. "Fatal Concrete Roof Failure in Atlantic City Hotel". Engineer-
ing News-Record 87, 294, (1921).
- Anon. "Corrosion of Reinforcing Wire in Marlborough-Blenheim Failure".
Engineering News-Record 87, 323, (1921).
- Anon. "Tests on Sea Water Corrosion of Structural Materials". Engineer-
ing and Construction, 530, (May 31, 1922).
- Zschokke, B. "Corrosion of Iron in Concrete". Engineering and
Construction 60, 194, (1923).
- Anon. "Effect of Accelerators on Reinforcing Steel". Engineering
and Construction 60, 202, (1923).

- Clemmer and Burggraf. "Use of Calcium Chloride as Curing Agent and Accelerator of Concrete". Engineering News-Record 91, 143, (1923).
- Anon. "Repairing Steel Floor Framing Damaged by Corrosion". Engineering News-Record 93, 131, (1924).
- Ellis, A. R. "Corrosion in an Old Viaduct at Joints and in Concrete - Encased Steel. Engineering News-Record 96, 779, (1926).
- Shank, J. R. "Tests of Corroded Steel Beams Restored with Gunitite". Engineering News-Record 98, 574, (1927).
- Murray, J. F. "Cable-Sheath Corrosion". Electrical World (Dec. 29, 1928).
- Carothers, S. D. "Notes on Concreting a Reinforced Concrete Beam and Theory of Corrosion in Steel Reinforcing Bars". Engineering 128, 724, (1929).
- McCreery, D. H. "Electrolytic and Corrosion Damage to a Warehouse". Civil Engineering 4, 572 (1934).
- Glanville, W. H. "Reinforced Concrete in Roads and Buildings". Building Science Abstracts 7, 366, (1935).
2. Walker, Stanton. "Computation of 'Dynamic Modulus'". ASTM Bulletin No. 121, 23, (1943).
3. Timoshenko, S. Vibration Problems In Engineering. pp. 423-426. D. Van Nostrand Co., Inc., New York. 1937.
4. Hoel, P. G. Introduction to Mathematical Statistics. pp. 64. John Wiley and Sons, Inc., New York. 1947.

5. Hoel, P. G. Introduction to Mathematical Statistics. pp. 136. John Wiley and Sons, Inc., New York. 1947.
6. Hoel, P. G. Introduction to Mathematical Statistics. pp. 69-70. John Wiley and Sons, Inc., New York. 1947.
7. Freeman, H. A. Industrial Statistics. pp. 52-95. John Wiley and Sons, Inc., New York. 1942.