Materials Analysis and Research Laboratory

DEVELOPMENT OF A CONDUCTOMETRIC TEST FOR FROST RESISTANCE OF CONCRETE

ANNUAL REPORT PHASE II
NOVEMBER 1, 1986

IOWA DOT PROJECT HR-272
ERI PROJECT 1775

Sponsored by the Highway Division of the Iowa Department of Transportation and the Iowa Highway Research Board.

ENGINEERING RESEARCH INSTITUTE
iowa state university
eri 87-410

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INTRODUCTION

The purpose of this report is to describe the major research activities during the period of February 1, 1985 - October 30, 1986 for the Iowa Highway Research Board under the research contract entitled "Development of a Conductometric Test for Frost Resistance of Concrete." The objective of this research, as stated in the project proposal, is to develop a test method which can be reasonably rapidly performed in the laboratory and in the field to predict the behavior of concrete subjected to the action of alternate freezing and thawing with a high degree of certainty. In the work plan of the proposal it was stated that the early part of the first year would be devoted to construction of testing equipment and preparation of specimens and the remainder of the year would be devoted to the testing of specimens. It was also stated that the second and third years would be devoted to performance and refinements of tests, data analysis, preparation of suggested specifications, and performance of tests covering variables which need to be studied such as types of aggregates, fly ash replacements and other admixtures.

The objective of this report is to describe the progress made during the first 20 months of this project and assess the significance of the results obtained thus far and the expected significance of the results obtainable during the third year of the project.

In this project the conductometric evaluation of concrete durability is being explored with three different test methods. Each method shows good promise for use as a tool in evaluating concrete durability. The merits of each test method are discussed separately in the body of this report. The test methods are:

1) Conductometric evaluation of the resistance of concrete to rapid freezing and thawing.
2) Conductometric evaluation of the resistance of concrete to natural freezing and thawing.
3) Conductometric evaluation of concrete pore size distribution and correlation to concrete durability.

To date tests of types 1 and 3 have been undertaken with varying concrete mixes containing an IDOT class III aggregate from the Alden quarry and results of this testing are contained within this report. Also, specimens for which changes in conductance will be monitored as they are subjected to natural freezing and thawing cycles have been prepared and results will be obtained during the winter of 1986-87.

DESCRIPTION OF CONCRETE MIXES FOR CONDUCTOMETRIC TESTING

In the project proposal it was stated that testing would begin with concrete containing a Class III aggregate and Type I portland cement and that two sets of specimens would be prepared at four different entrained air contents, the first set with constant slumps and the second with constant water-cement ratios. After conversing with Mr. Wendell Dubberke of the Iowa DOT and examining the extensive durability factor data for various concrete mixes provided by him it was decided to deviate somewhat from the original mix plan. Mr. Dubberke pointed out that with some Class III aggregates, durability factors seem to be independent of water-cement ratio and entrained air content. As long as the mix contains some entrained air, when these aggregates are used durable concrete is produced. On the other hand, the durability factors of other Class III aggregates are highly dependent on water-cement ratio and air content.

In light of this information it was decided that mixes with three different aggregates would be tested. This new plan required nine mixes for each aggregate with three different water-cement ratios and three different entrained air contents bringing the total number of different mixes to 27.

Constituent Materials

The portland cement being used for this project is Lehigh Type I. The fine aggregate being used is from the Cordova quarry. It is the same sand the Iowa DOT uses for its durability testing.

For coarse aggregate three different aggregates will be tested eventually. The first aggregate tested was from the Alden quarry. This Class III limestone had a 3/4 inch maximum aggregate size and IDOT durability tests have shown that mixes containing this aggregate are durable regardless of water-cement ratio or entrained air content, except the mixes containing no entrained air at all. The second aggregate selected is an oolitic limestone from the Montour quarry. The aggregate size for this aggregate is also 3/4 inch. IDOT durability studies have shown that mixes containing this aggregate have durability factors that vary quite markedly with changes in water-cement ratio and air content. Also the Montour oolite has a much better service record than measured durability factors would indicate. The final aggregate to be tested is from the Crescent quarry. It is a nondurable Class I aggregate. In accordance with IDOT specifications this aggregate has a 3/8 inch maximum size.

Mixing water is tap water from the Town Engineering Building. Blended with the water is the air-entraining agent Protex Pro-Air. Three different concentrations of Protex are used. They are: 0 ml/100 lbs. cement, 49.8 ml/100 lbs. cement, and 74.7 ml/100 lbs. cement which resulted in total air contents of approximately 2, 6, and 8 percent, respectively.

Mix Proportions

Volumetric mix proportions centered around the IDOT C3 mix. In fact, the conductometric test mix designation LM used in this report has the same volumetric proportions as the IDOT C3 mix. All mixes have the same cement content of 605 lbs. per cubic yard and the same volumetric coarse to fine aggregate ratio. The coarse aggregate occupies 55% of the total aggregate volume and the fine 45%. Three water-cement ratios (0.43, 0.51 and 0.60) and three air contents (1.5%, 6% and 9%) are used. This makes the total of 27 different concrete mixes. The mix volumes are shown in a tabular format in Table 1.

As of the writing of this report, samples have been molded for all mixes with the Alden aggregate. Properties of the mixes are tabulated in Table 2. In addition, samples from mixes containing all three aggregates have been molded for conductometric evaluation of the durability of concrete subjected to natural freezing and thawing. Properties of mixes to be tested in this manner are tabulated in Table 3.

TEST METHODS

We stated in the project proposal "The ultimate goal of the proposed research is to establish specifications for concrete quality control in respect to its freeze-thaw durability. It appears to the authors of this proposal that a plausible solution (probably the only solution) to this problem could be achieved by continuously monitoring the physicochemical state of concrete during freezing and thawing cycles as a function of all the variables such as temperature, rate of cooling and warming, degree of saturation, air content, pore structure and the type of freezing-thawing medium. By physicochemical state of a sample we mean the dimensional stability and integrity of its solid and void spaces, the frozen and unfrozen fractions of its water content, and the sizes of its voids occupied by air, water (liquid) and ice. When the functional relationships between the physicochemical state and the variables are developed extrapolations can be made to various field conditions. Once these studies are completed we anticipate being able to develop a reasonably rapid test for predicting the freeze-thaw durability of concrete on the basis of changes occurring under a fixed set of ambient conditions in its physicochemical states during a limited number of cycles. Extrapolations to a different set of ambient conditions will then be possible to make using the functional relationship established as mentioned above. Our current research has shown that electrical conductivity can effectively be used to determine the physicochemical status of concrete subjected to cyclic freezing and thawing."

The tests undertaken and to be undertaken are designed to advance the "state-of-the-art" towards this ultimate goal. The three types of tests as stated earlier are:

1) Conductometric evaluation of the resistance of concrete to rapid freezing and thawing

2) Conductometric evaluation of the resistance of concrete to natural freezing and thawing

3) Conductometric evaluation of concrete pore size distribution and correlation to concrete durability.

The first of these tests (evaluation of resistance to rapid freezing and thawing) is designed to be the tie-in to an existing "state-of-the-art" evaluation of concrete durability. In this testing durability factors as evaluated by ASTM Method C666-84, standard test method for resistance of concrete to rapid freezing and thawing, are correlated to conductometric changes in a concrete. In the second test (evaluation of resistance to natural freezing and thawing) the same conductometric changes are monitored in concrete exposed to ambient conditions. Finally in the last test (conductometric pore size analysis) the physicochemical state of the concrete is examined. By combining and interpreting results of these three tests it is anticipated that a reasonably rapid test for predicting the freeze-thaw durability of concrete will be developed. To narrow the scope of this task somewhat the saturation states tested were limited to two. For the first two tests the degree of saturation was that a concrete would attain at ambient temperatures if a limitless supply of water was available. It was felt that this would be the worst case. For conductometric pore size analysis concretes were also tested at 100% saturation. Also, all mixes were tested after 28 days of curing.

Progress Made on Conductometric Evaluation of the Resistance of Concrete to Rapid Freezing and Thawing

The first portion of the second year of the project was spent refining sample preparation and testing techniques. Two problems associated with sample preparation arose. The first was how to secure the electrode geometry while placing and finishing the concrete. To do this the 1/4" steel bottoms of the molds for casting of 3" by 3" by 16" beams were replaced with 1" thick Plexiglas bottoms. Holes the same size as the 1/8" stainless steel electrodes were drilled in the Plexiglas bottom plates at the desired spacing. The electrodes were force fitted into the holes to provide a secure geometry. Then, molds were assembled and specimens were cast and allowed to harden for 24 hours in a humid curing room. The molds were then disassembled and the Plexiglas bottoms were tapped off with a rubber hammer and each electrode cut flush with the bottom of the beam. The electrode geometry for the beam samples is shown in Figure 1. The second sample preparation problem encountered was in insuring proper consolidation around the electrodes. For the high slump mixes tested this was easily attained by rodding the sample in two lifts. However for mixes with slumps less than about 6 inches vibration was necessary to insure consolidation.

The samples were subjected to rapid freezing and thawing in accordance with ASTM C666, standard tests and methods for the evaluaton of resistance of concrete to rapid freezing and thawing. Samples were frozen in water and thawed in water. Measurements were taken at five to six cycle intervals. The fundamental transverse frequency for each beam was measured on the side of the beam with no electrodes (see Figure 1). Conductance measurements were taken using each possible pair of electrodes embedded on the other side of the beam using a Solomat model 2009 conductivity meter. This meter measures conductance using a low voltage high frequency AC bridge to minimize effects of polarization. Conductance measurements are particularly sensitive to changes in temperature. Thus, at the end of a cycle for which measurements were to be taken, samples were placed in an ice bath for at least half an hour before measurements were taken to insure all measurements were recorded at a constant temperature.

As discussed earlier in this report, eventually a total of 27 different mixes with three different aggregates, water-cement ratios and air contents will be tested in this manner. As of the writing of this report testing has been completed on mixes containing the Alden aggregate. See Tables 1 and 2 for mix designation, proportions and properties. The following summarizes the results of this testing.

First, the durability behavior of mixes made with the Alden aggregate was similar to that observed by the IDOT. Otherwise stated, mixes with the Alden aggregate had high durability factors regardless of entrained air content or water-cement ratio. The only mixes containing Alden aggregate which produced nondurable concrete were those containing no entrained air at all. Figures 2 and 3 illustrate the extremes of conductance and dynamic behavior of mixes with low and high air contents. In Figure 2 relative dynamic modulus of elasticity and reciprocal relative conductance is plotted against the number of freeze-thaw cycles for the mix with a high water-cement ratio (0.60) and no entrained air. In Figure 3 the same parameters are plotted for the IDOT C3 mix with a low water-cement ratio (0.43) and optimal air content (6%). Similar plots for the other beams and mixes tested are included in Appendix A. Some important observations can be made from the information contained in these plots. First, reciprocal relative conductance seems to be nearly independent of electrode geometry and secondly relative dynamic modulus of elasticity and reciprocal relative conductance are roughly equivalent parameters.

In Figure 4 the same data are presented in a different format for a particular electrode geometry (geometry A, see Figure 1). Similar plots for mixes with common water-cement ratios and air contents are included in Appendix B. Although it is not yet completely conclusive at this stage of the project some important observations can be made. They are:

1) Prior to any cycling the conductance of concrete increases with increasing air content (see Figure 5 and Appendix B).

2) Prior to any cycling the conductance of concrete increases with increasing water-cement ratio (see Figure 6 and Appendix B).

3) The conductance prior to cycling is independent of the concrete's durability.

4) The change in conductance with the number of cycles is directly related to concrete durability.

The first two observations have significant implications which reach far beyond the project's main objective of determination of concrete durability which is verified by the fourth observation listed above. The observations (1) and (2) point to the possibilities for determination of air content of hardened concrete and the water cement ratio used when it was prepared from conductance measurements. After the verification and if necessary modification of these observations for all mixes we will conduct a data analysis to separate the variables affecting the influence of entrained air and water cement ratio on conductance. With the separation of variables we anticipate we will be able to develop methodology for determination of air content and water cement ratio of concrete core samples.

Conductometric Evaluation of the Resistance of Concrete to Natural Freezing and Thawing

Beam specimens have been prepared in the same manner as outlined previously and will be subjected to the natural freezing and thawing cycles imposed upon them by an Iowa winter. Six beams from six different mixes will be tested in this manner. Three of the mixes have the same proportions as the IDOT C3 paving mix. The other three have similar proportions except they contain no entrained air. Within these sets, the mixes are varied by using three different coarse aggregates. The three aggregates are the Alden, Montour and Crescent discussed earlier. See Tables 1 and 3 for mix designations, proportions, and properties. These six beams have been placed in a bed of saturated sand and conductance and temperature measurements will be taken twice daily throughout the winter. From these measurements the deterioration of concrete subjected to natural freezing and thawing will be followed and functional relationships between the ambient conditions and the test conditions imposed in the laboratory will be developed.

Conductometric Evaluation of Concrete Pore Size Distribution and Correlation to Concrete Durability

An introduction to the theory supporting conductometric phase transition porosimetry was included in the first annual report for this project. A discussion of this theory is not repeated in this report. Currently a paper is being prepared which will discuss conductometric phase transition porosimetry in detail. Upon completion and when proper authorization is obtained from the Iowa Highway Research Board this paper will be submitted for publication. Included in this report is a brief description of sample preparation and experimental methods; as well as a synopsis of testing to be undertaken and a report of results obtained from testing currently completed.

For this testing 4 inch diameter by 4 inch high cylinders were molded with an electrode geometry as shown in Figure 7. As with beam samples the electrodes are fixed in a Plexiglas bottom plate during molding. However, to prevent surface conductance at the bottom of submersed specimens electrodes were embedded in small stubs inserted in holes cut in the bottom plate. After samples are removed from the molds these stubs are cut flush with the bottom. Also, the upper portion of the electrodes are covered with nonconductive plastic tubing to eliminate conductance between the exposed electrodes. Finally, after curing, holes are drilled in each sample to accommodate a thermistor housing which is used to measure the temperature of the concrete sample.

During testing, the cylinders are placed in a thin-walled plastic container and a layer of Ottawa sand is poured between the cylinder and container. The sand is then saturated. Experimentation has shown that the silica crystals in the sand prevent supercooling of the bulk water surrounding the sample, thus allowing both cooling and warming data to be gathered by placing the container in the cryostat (variable temperature alcohol bath). The cryostat, a Solomat conductance meter and a thermistor are interfaced with an Apple IIe computer. The computer controls the cryostat, monitors and records temperature and conductance data, and is used to process the data when a test is completed. Cycle starting and ending temperatures, cooling rates, and data collection intervals are all input by the user. In addition, the user can input the total number of cycles for a test and designate different cycle parameters for each cycle. With this system a wide range of ambient conditions can be simulated.

Cylindrical samples are molded for each mix batched during this project. Cylinders reaching maturity prior to testing are stored at below freezing temperatures (10°F) to prevent further hydration. The number of cycles, and cycle parameters each cylinder is to be tested under are largely dictated by the results of other conductometric testing. To a lesser extent this will also dictate the number of cylinders which will be tested.

Considerable time and effort was expended during the second year of this project developing and refining the software and hardware components of the testing apparatus. As of the writing of this report some testing of this type has been done on samples with mixes containing the Alden aggregate. The results of those tests are reported here.

Testing was conducted on samples from two mixes. Both mixes had the same water-cement ratio, amount of cement, and proportioning of aggregates. They differed in air content. To the mix designated Ald-2LL, no air entraining agent was added, while to the other, designated Ald-2LM, enough air entraining agent was added to reach an air content of approximately 6%. See Table 2 for more detailed mix properties.

Some experimentation was done to explore which saturation condition is best for this type of testing as summarized in Tables 4 and 5. To begin with, both samples were saturated by immersion in water. They were then subjected to what will be referred to as a diagnostic cycle. During such a cycle the sample is cooled from above freezing temperatures to -30°C at a rate of 3°C per hour and then warmed in the same manner. During such a cycle conductance and temperature data are collected at 0.1°C temperature intervals. From these data a pore size distribution is determined as described in the first annual report. After this first diagnostic cycle both samples were placed in boiling water in an attempt to increase the degree of saturation of the sample. Another diagnostic cycle was then run. For the Ald-2LM sample a third diagnostic cycle was run due to some equipment problems. After the second cycle for the Ald-2LL sample and the third for the Ald-2LM sample, both specimen were oven dried (@ 110°C for 24 hrs.) and resaturated by immersion. After another diagnostic cycle both samples were subjected to several freezing and thawing cycles in accordance with ASTM C666. The 13th cycle for each sample was again a diagnostic cycle. In addition to conductance data, sample weights were measured at various points during testing. Tables 4 and 5 show the history of the cycling each sample was subjected to as well as weight and above freezing conductance data. In Figure 8 relative conducting pore volume is plotted against pore radius for sample Ald-2LM obtained after the first diagnostic cycle. Examining this data in contrast with the pore size distribution determined after boiling the sample (see Figure 9) shows that boiling appreciably changes the pore structure of the material. In Figure 10, a pore size distribution determined after the same sample has been oven-dried and resaturated by immersion is shown (4th diagnostic cycle). Again, a change in the pore structure of the material is observable. This same behavior was also observed for the Ald-2LL sample (see Figures 11, 12 and 13).

It is thought that in both the boiling and oven-drying of the samples, the elevated temperatures are causing phase changes to occur in the calcium silicate hydrates that make up the cement paste. It is apparent that these phase changes alter the pore structure of the material. It is not news that portland cement hydration products go through phase changes at elevated temperature, but observing the effect of these changes on the pore structure of the material is. From a practical standpoint it illustrates that when using pore size analysis to evaluate and predict the behavior of concrete, the concrete should not be saturated at elevated temperatures.

An examination of Figures 8-13 also shows that there is no appreciable difference between the water-filled pore structures of the two categories of samples. The only difference between the two is in their entrained air content; this indicates that even upon boiling, the entrained air voids are not saturated. If they had become saturated, the weight of the sample would have increased significantly and the pore size distribution of the two samples would be different.

The air-entrained mix did prove to be the more durable of the two as expected. Figure 14 shows the pore size distribution for the air entrained concrete after 13 cycles. Figure 15 shows the same information for the non-air entrained concrete after the same number of cycles. Although initially the pore size distributions of the two samples were nearly identical, after only 13 freeze and thaw cycles they are quite different.

Because of normal depression of freezing point of concrete-pore-water in bulk state (of the order of 0.1-0.2°C) due to presence of ions, the pore size distribution results are subject to some uncertainty in the size range larger than about 1000 Å, unless they are corrected for this effect. Therefore, the size distribution results presented at this stage must be considered within this reservation. As we continue to develop this methodology, corrections for this effect will be made.

It seems apparent that this type of testing with continued development will allow us to determine whether a concrete is durable or not after only a few cycles. What remains to be seen is if the same test will reflect the vulnerability of aggregates to freeze and thaw damage.

SUMMARY AND CONCLUSIONS

In conclusion, it appears conductometric techniques can be used to evaluate the resistance of concrete to freezing and thawing. This has been illustrated in this report for concretes with durable aggregate (Alden). It is anticipated that these same techniques will also be effective in evaluating the freezing and thawing resistance of concretes with marginal and poor aggregates as well. Testing will be conducted on concretes containing these types of aggregate during the final year of the project. In addition to this, information obtained from specimens subjected to natural freezing and thawing will be used to bridge the gap between field and laboratory durability performance. Once these studies are completed, we anticipate being able to evaluate the freeze-thaw durability of concrete more accurately and quickly than current techniques.

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Materials	Mix Volumes								
	LL	LM**	LH	ML	MM	MH	HL	HM	HH
Cement	.1142	.1142	.1142	.1142	.1142	.1142	.1142	.1142	.1142
Water	.1538	.1538	.1538	.1834	.1834	.1834	.2158	.2158	.2158
Fine Agg.	.3221	.3019	.2885	.3088	.2886	.2752	.2943	.2741	.2606
Coarse Agg.	.3949	.3701	.3535	.3786	.3538	.3372	.3607	.3359	.3194
Air	.015*	.06	.09	.015*	.06	.09	.015*	.06	.09
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
W/C ratio	0.43	0.43	0.43	0.51	0.51	0.51	0.60	0.60	0.60

*No air entraining admixture added

**Volumes same as for IDOT C3 mix.

Table 1. Volumetric mix proportions for conductometric tests.

Mix Designation	Water-Cement Ratio	Air Content	Slump	Unit Weight
Ald-2LL	0.43	2%	2"	151.4 pcf
Ald-2LM	0.43	5.8%	4½"	142.3 pcf
Ald-2LH	0.43	6.8%	6½"	141.0 pcf
Ald-2ML	0.51	2%	6½"	152.2 pcf
Ald-2MM	0.51	5.8%	78"	141.1 pcf
Ald-2MH	0.51	7.8%	78"	138.9 pcf
Ald-2HL	0.60	2%	78"	148.7 pcf
Ald-2HM	0.60	5.9%	78"	139.9 pcf
Ald-2HH	0.60	7.9%	78"	136.1 pcf
Ald-3LL	0.43	1.8%	3"	150.2 pcf
Ald-3LM	0.43	6.0%	7½"	141.2 pcf

Table 2. Properties of mixes using Alden aggregate.

Mix Designation	Water-Cement Ratio	Air Content	Slump	Unit Weight
Ald-3LL	0.43	1.8%	3"	150.2 pcf
Ald-3LM	0.43	6.0%	7½"	141.2 pcf
Mon-LL	0.43	2.0%	2½"	152.2 pcf
Mon-LM	0.43	5.0%	3½"	146.6 pcf
Cre-LL	0.43	2.0%	1½"	152.7 pcf
Cre-LM	0.43	6.5%	6½"	139.0 pcf

Table 3. Properties of mixes from which samples to be subjected to natural freezing and thawing were molded.

Activity	Sample Ald.2LM			
	Conductance @ 3°C		Weight	
	Before	After	Before	After
Cycle #1 diagnostic	1245 μs	1218 μs	1877.0 g (immersed)	—
Sample boiled	1218 μs	1605 μs	—	1878.8 g (boiled)
Cycle #2 diagnostic	1605 μs	1444 μs	1878.8 g (boiled)	—
Cycle #3 diagnostic	1444 μs	1507 μs	—	—
Sample oven-dried	1507 μs	—	—	1794.9 g (OD)
Sample reimmersed	—	1877 μs	1794.9 g (OD)	1873.6 g (immersed)
Cycle #4 diagnostic	1877 μs	1731 μs	1873.6 g (immersed)	—
Cycles #5 through #12 - ASTM C666				
Cycle #13 diagnostic	1698 μs	1620 μs	—	187.9

Table 4. Conductance and weight measurements before and after various sequential stages of exposure for sample Ald.2LM.

Activity	Sample Ald.2LL			
	Conductance @ 3°C		Weight	
	Before	After	Before	After
Cycle #1 diagnostic	969 µs	963 µs	—	1999.9 g (immersed)
Sample boiled	963 µs	1375 µs	1999.9 g	2000.4 g (boiled)
Cycle #2 diagnostic	1375 µs	1386 µs	2000.4 g (boiled)	—
Sample oven-dried	1386 µs	—	—	1897.7 g (OD)
Sample reimmersed	—	1766 µs	1897.7 g (OD)	1994.2 g (immersed)
Cycle #3 diagnostic	1766 µs	1749 µs	1994.2 g (immersed)	—
Cycles #4 through #12 - ASTM C666				
Cycle #13 diagnostic	1917 µs	1838 µs	—	2001.0 g

Table 5. Conductance and weight measurements before and after various sequential stages of exposure for sample Ald.2LL.

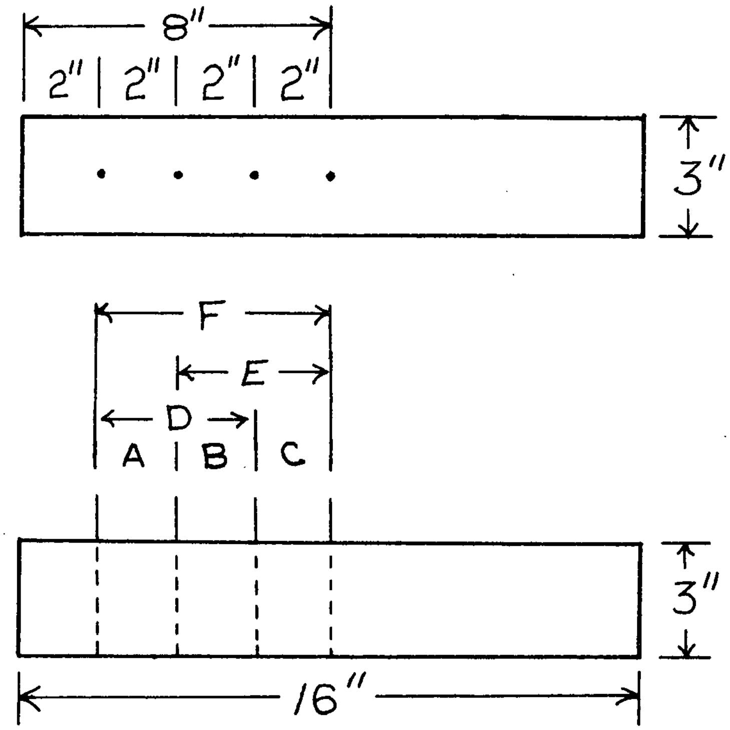


Figure 1. Electrode geometry for beam samples.

RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES ALDEN_2HL1

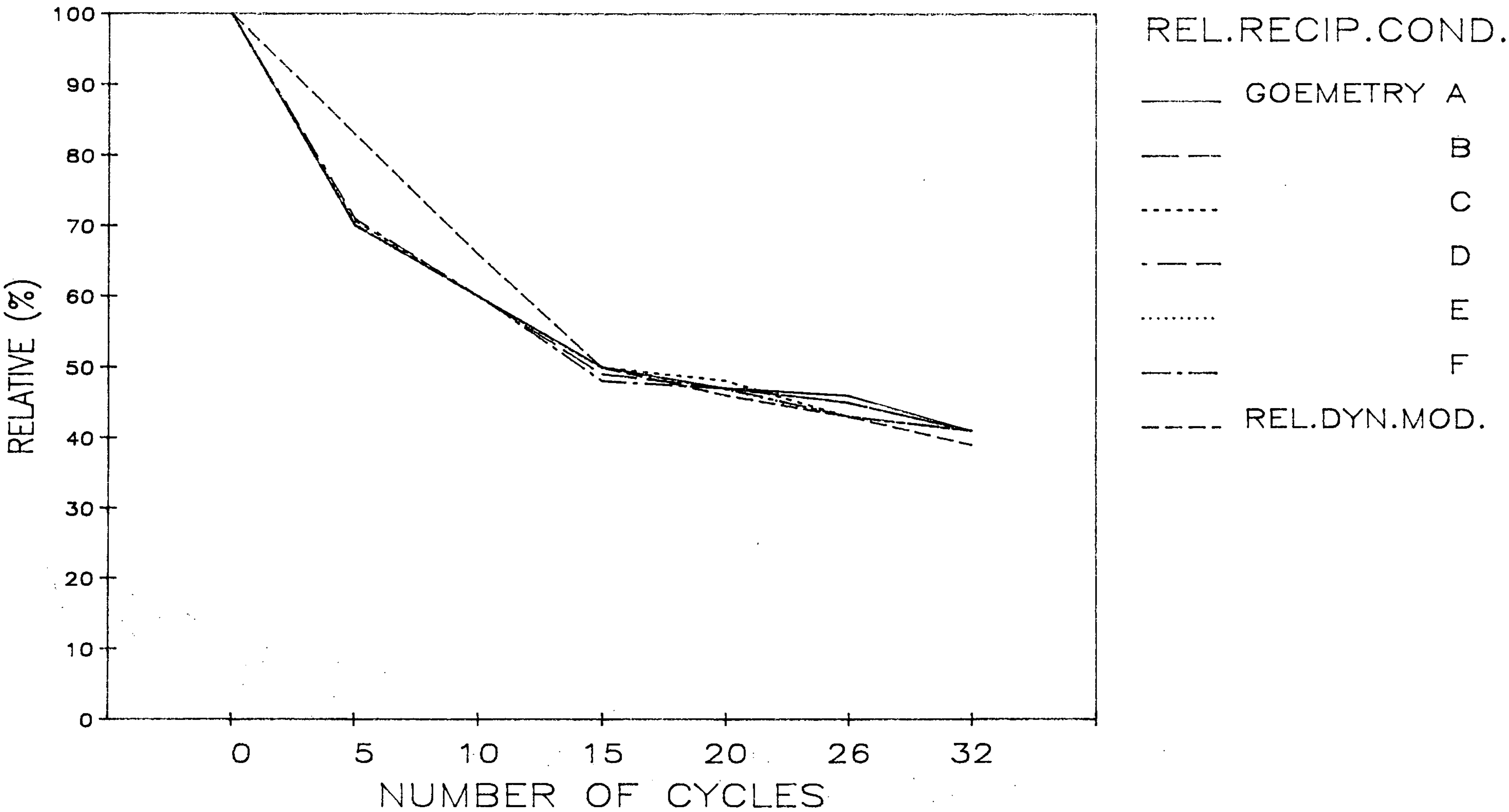


FIGURE 2

RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE–THAW CYCLES.

ALDEN_2LM1

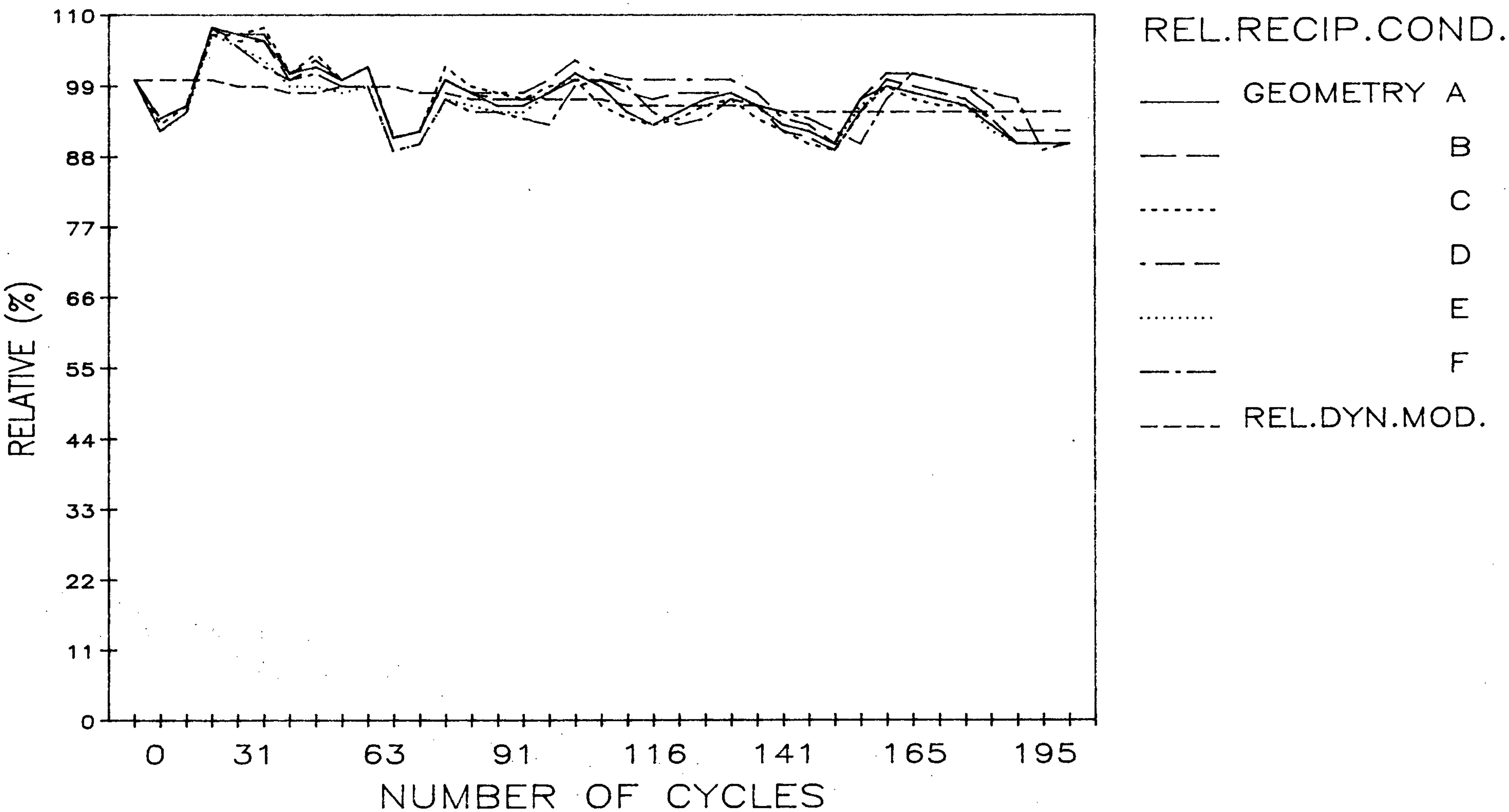


FIGURE 3

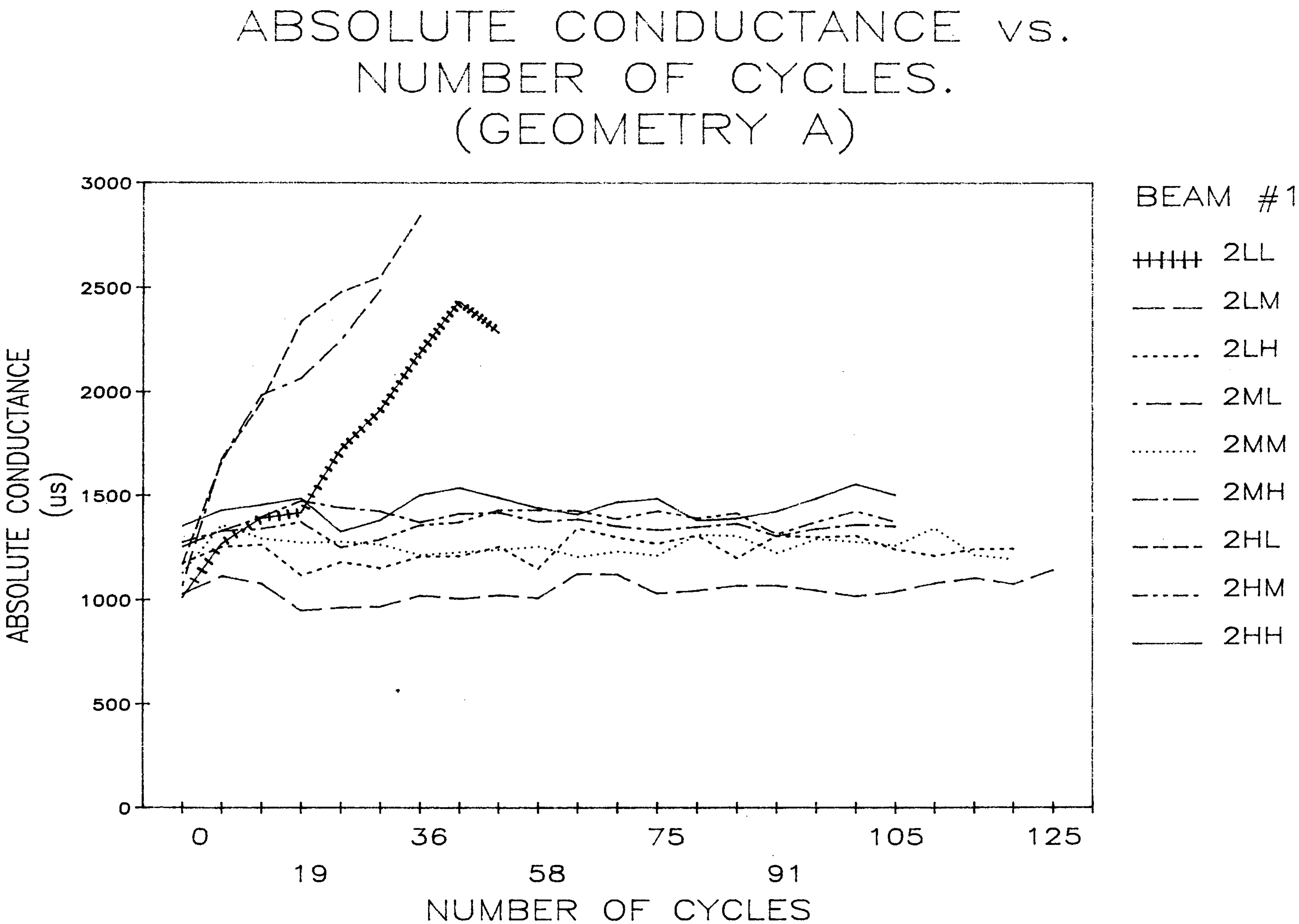
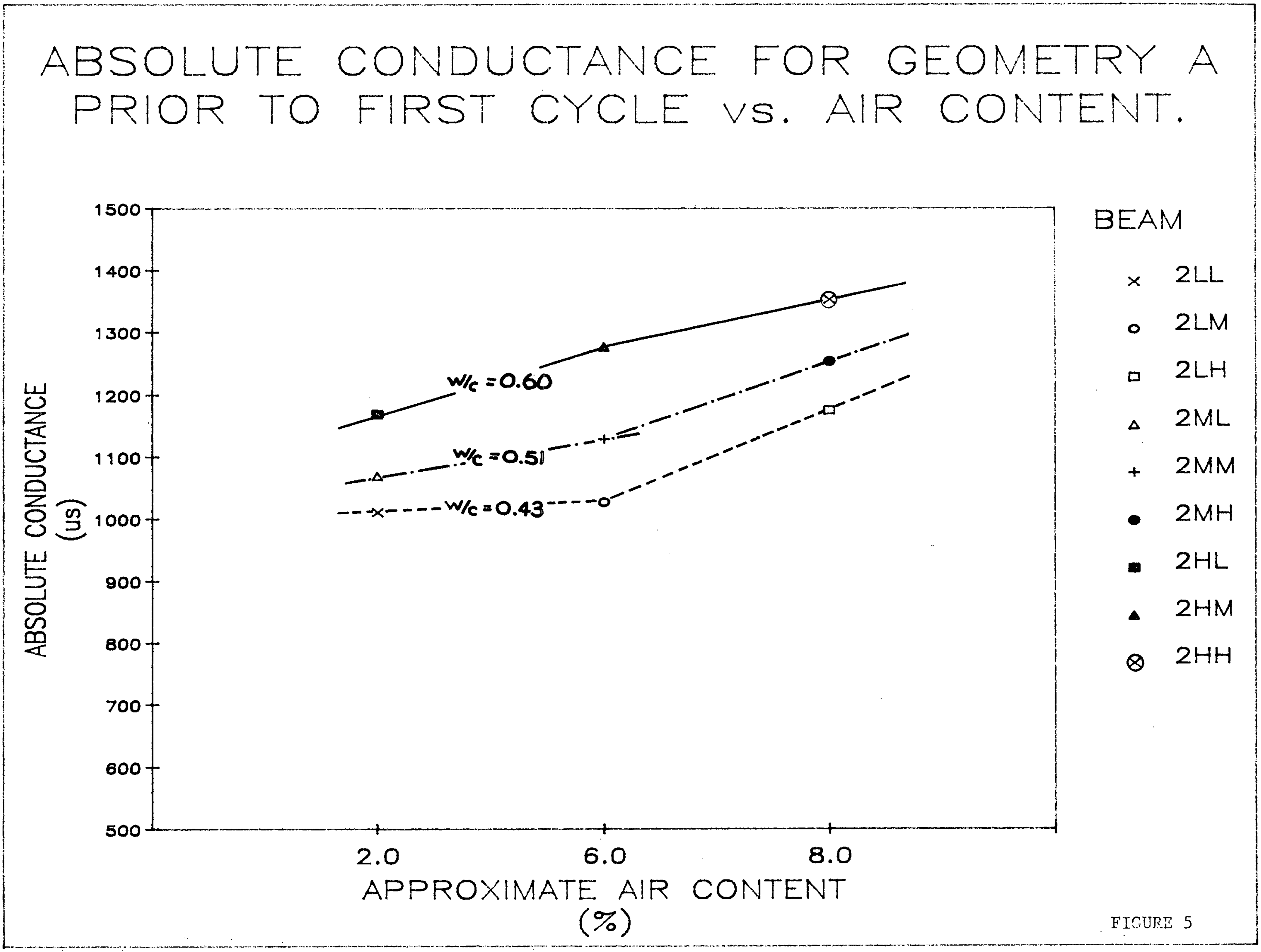

ABSOLUTE CONDUCTANCE vs.
NUMBER OF CYCLES.
(GEOMETRY A)
ABSOLUTE CONDUCTANCE
(us)
3000
2500
2000
1500
1000
500
0
0
19
36
58
75
91
105
125
NUMBER OF CYCLES
BEAM #1
2LL
2LM
2LH
2ML
2MM
2MH
2HL
2HM
2HH

FIGURE 4



ABSOLUTE CONDUCTANCE FOR GEOMETRY A
PRIOR TO FIRST CYCLE vs. AIR CONTENT.
ABSOLUTE CONDUCTANCE
(us)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
2.0
6.0
8.0
APPROXIMATE AIR CONTENT
(%)
w/c = 0.60
w/c = 0.51
w/c = 0.43
BEAM
2LL
2LM
2LH
2ML
2MM
2MH
2HL
2HM
2HH

FIGURE 5

ABSOLUTE CONDUCTANCE FOR GEOMETRY A PRIOR TO FIRST CYCLE vs. W\C RATIO.

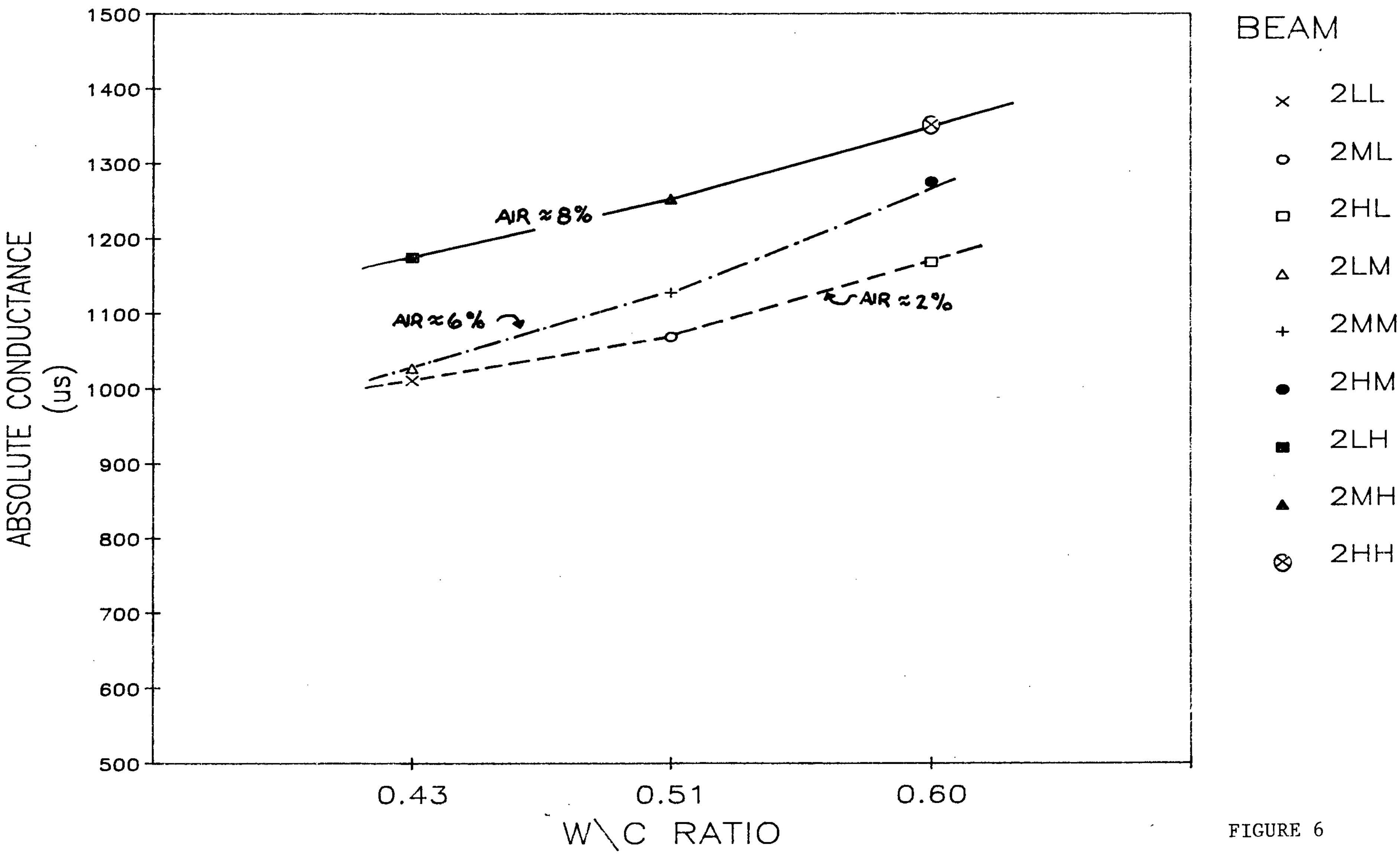


FIGURE 6

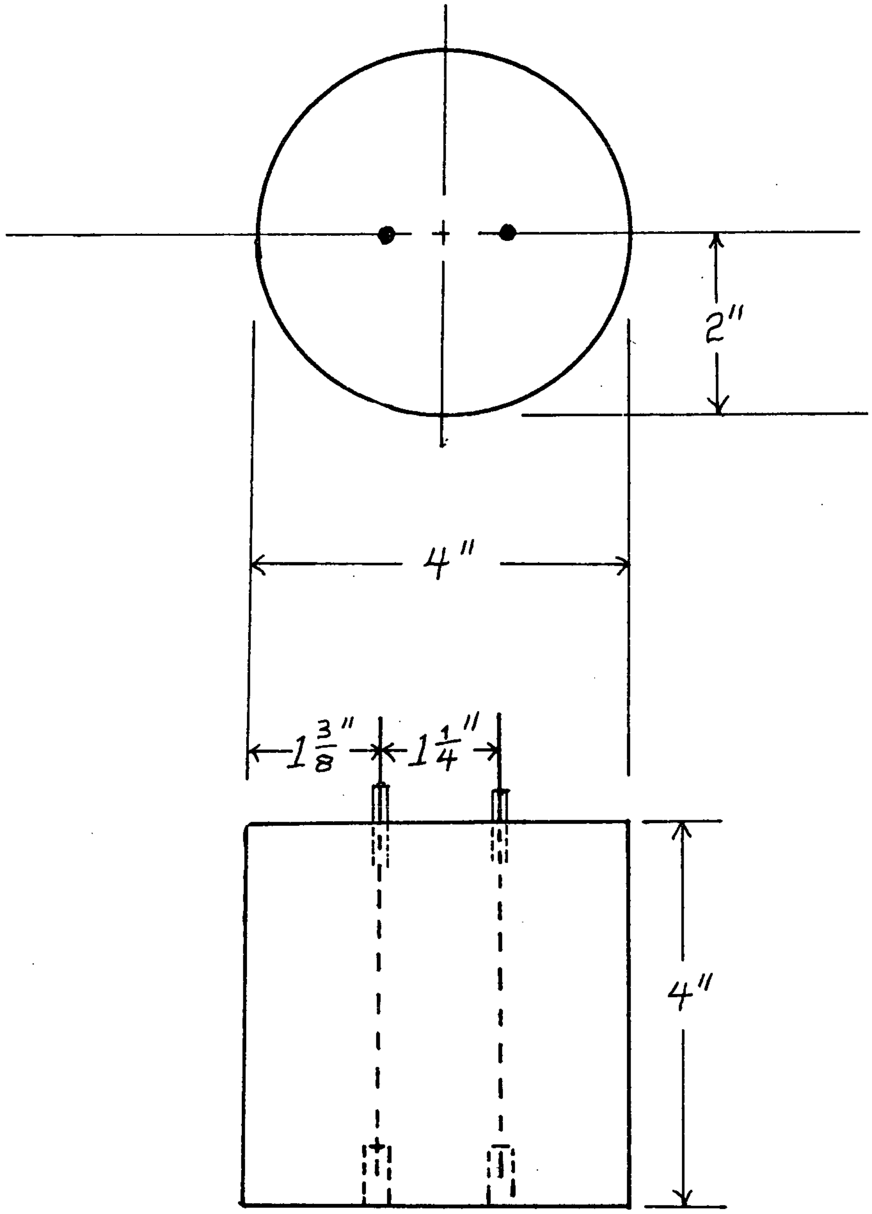


Figure 7. Electrode geometry for cylindrical samples.

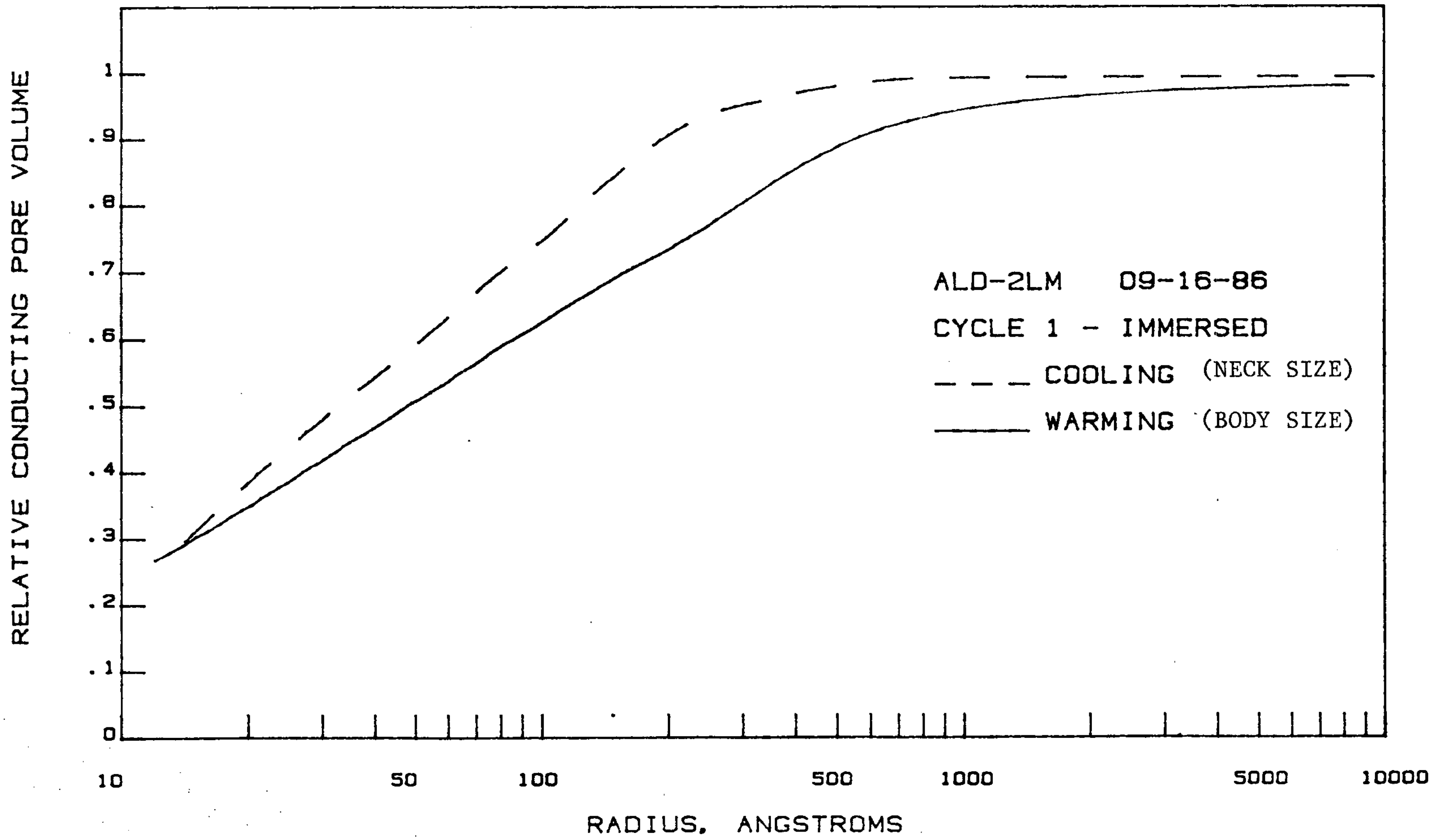


Figure 8. Pore size distribution of Ald.2LM beam.

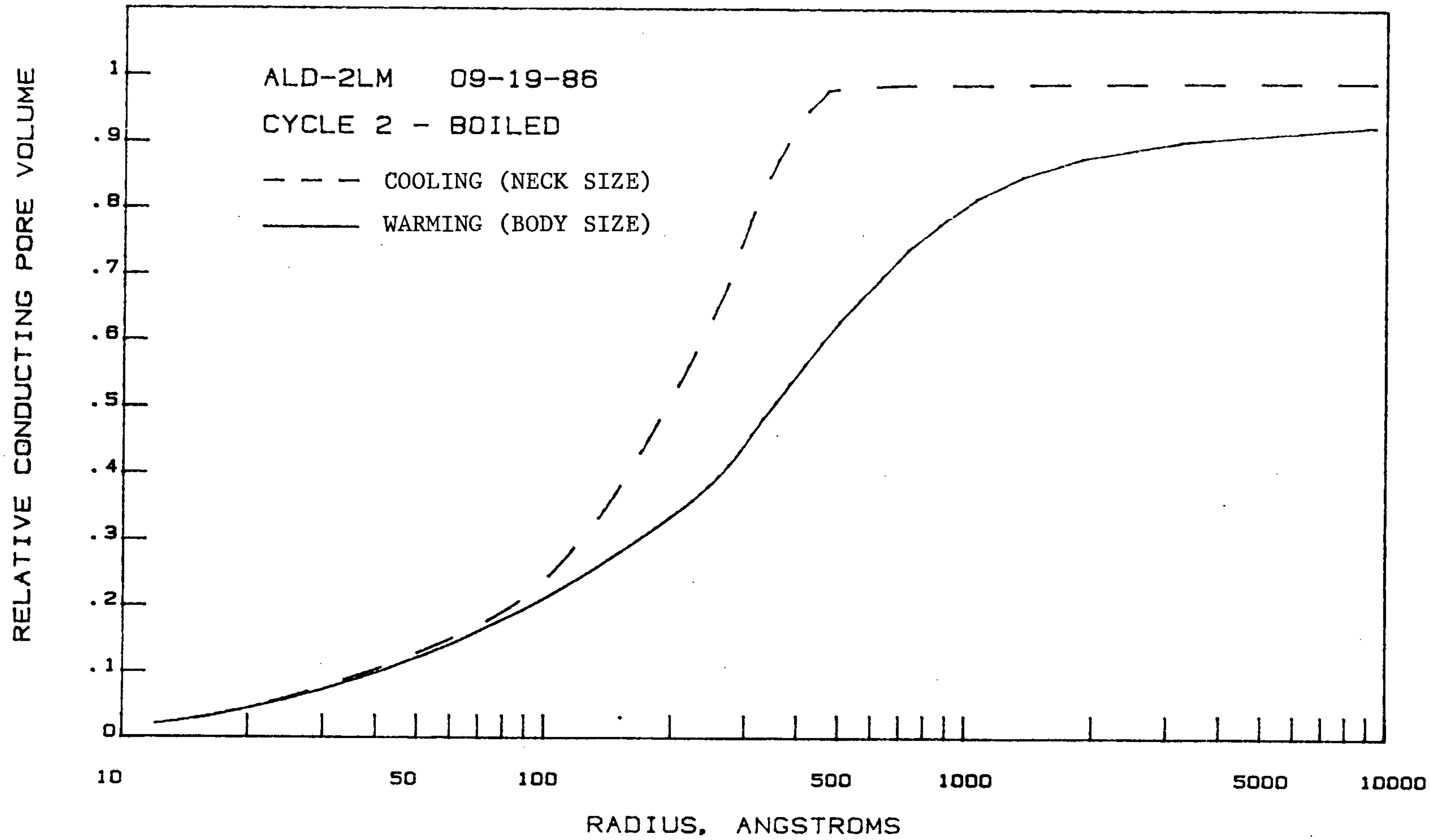


Figure 9. Pore size distribution of Ald.2LM beam.

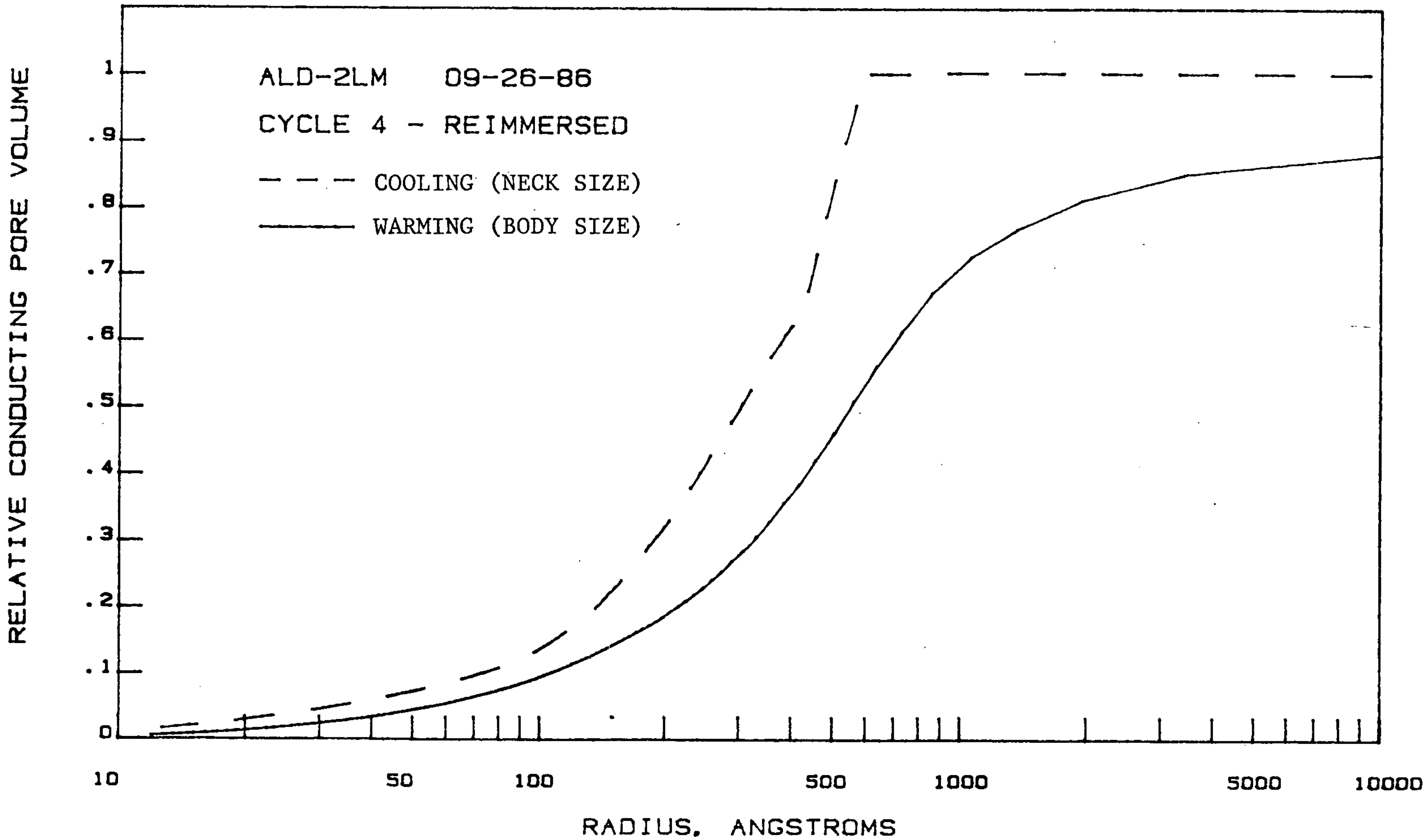


Figure 10. Pore size distribution of Ald.2LM beam.

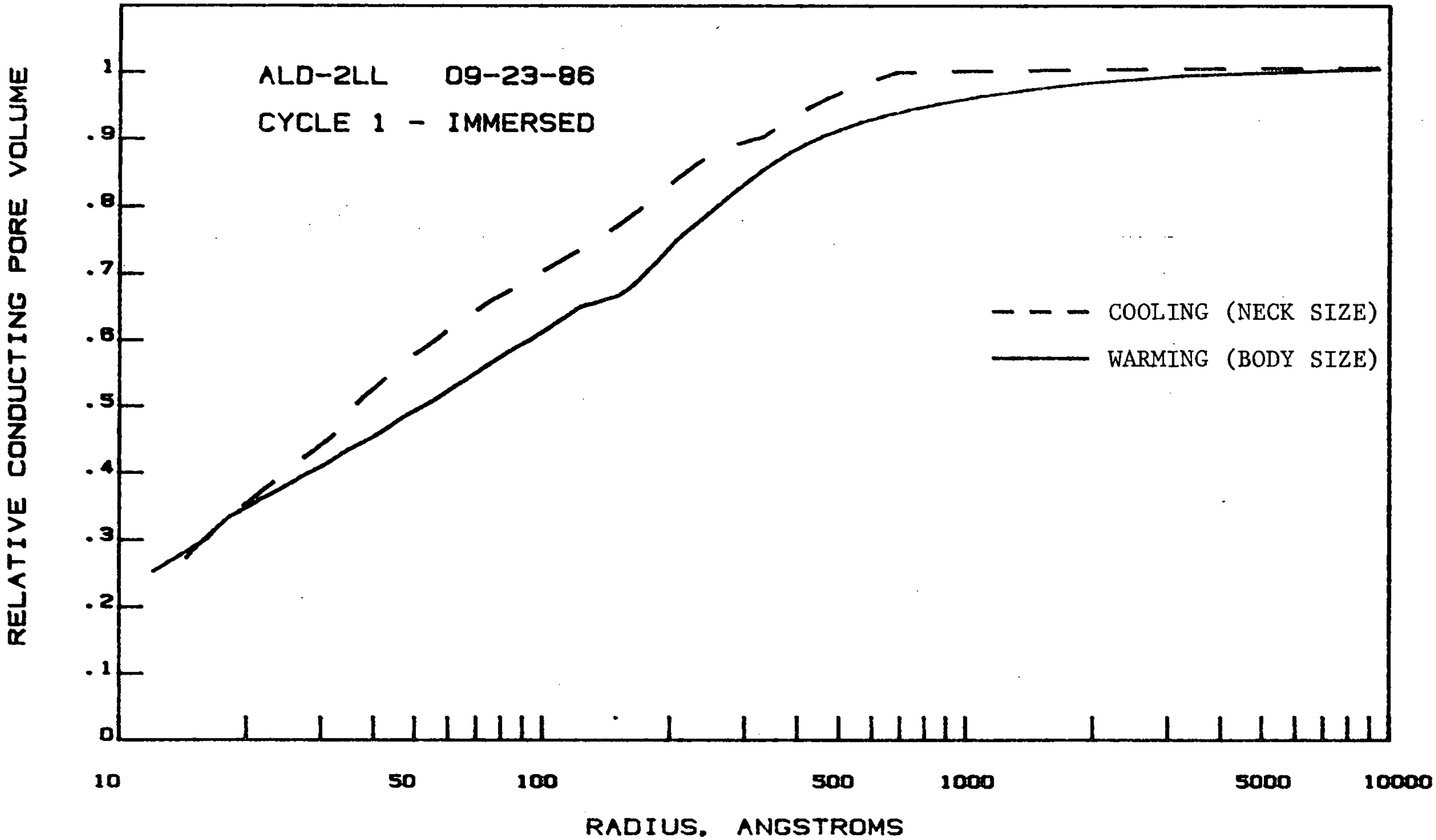


Figure 11. Pore size distribution of Ald.2LL beam.

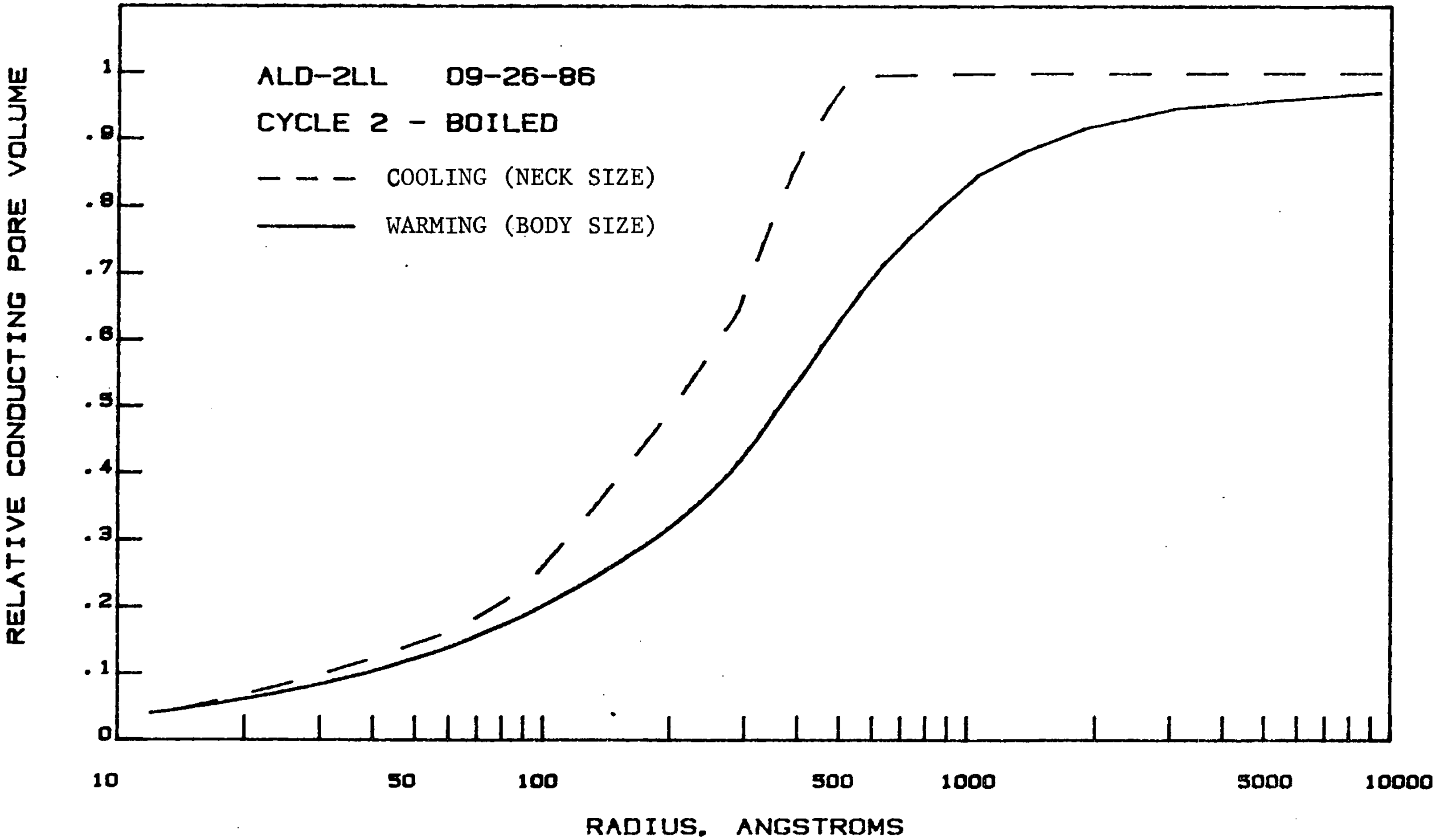


Figure 12. Pore size distribution of Ald.2LL beam.

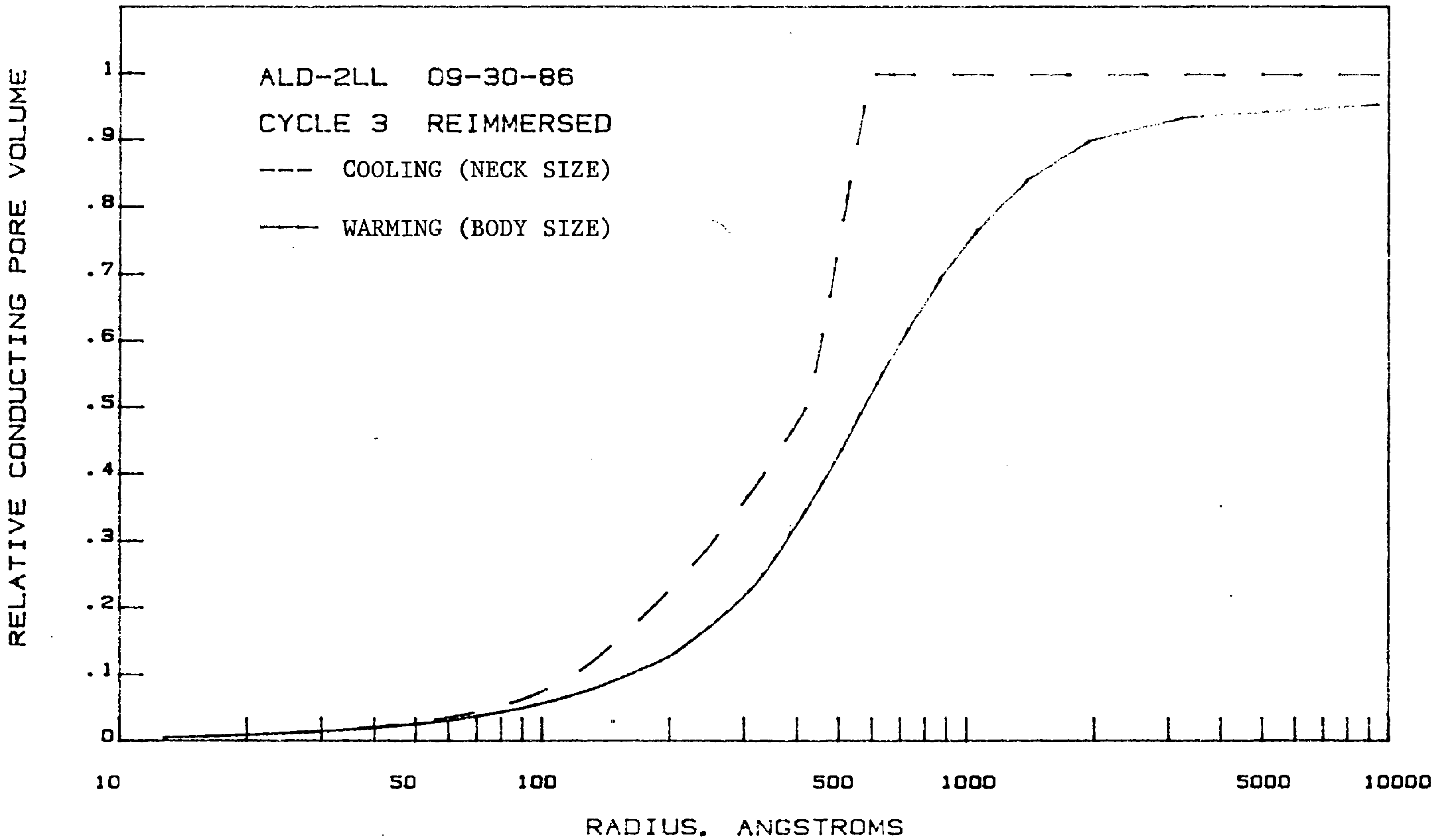


Figure 13. Pore size distribution of Ald.2LL beam.

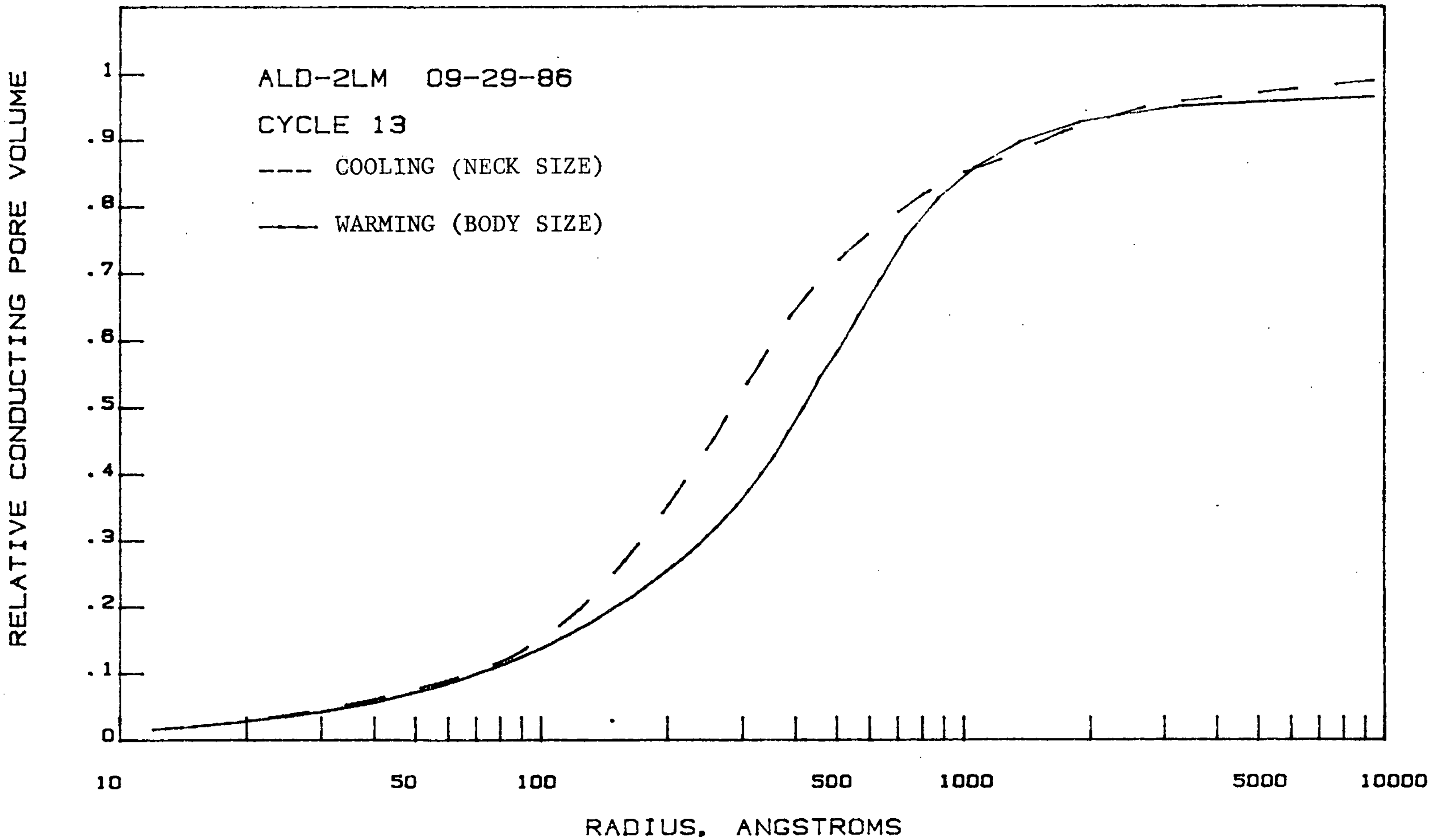


Figure 14. Pore size distribution of Ald.2LM beam.

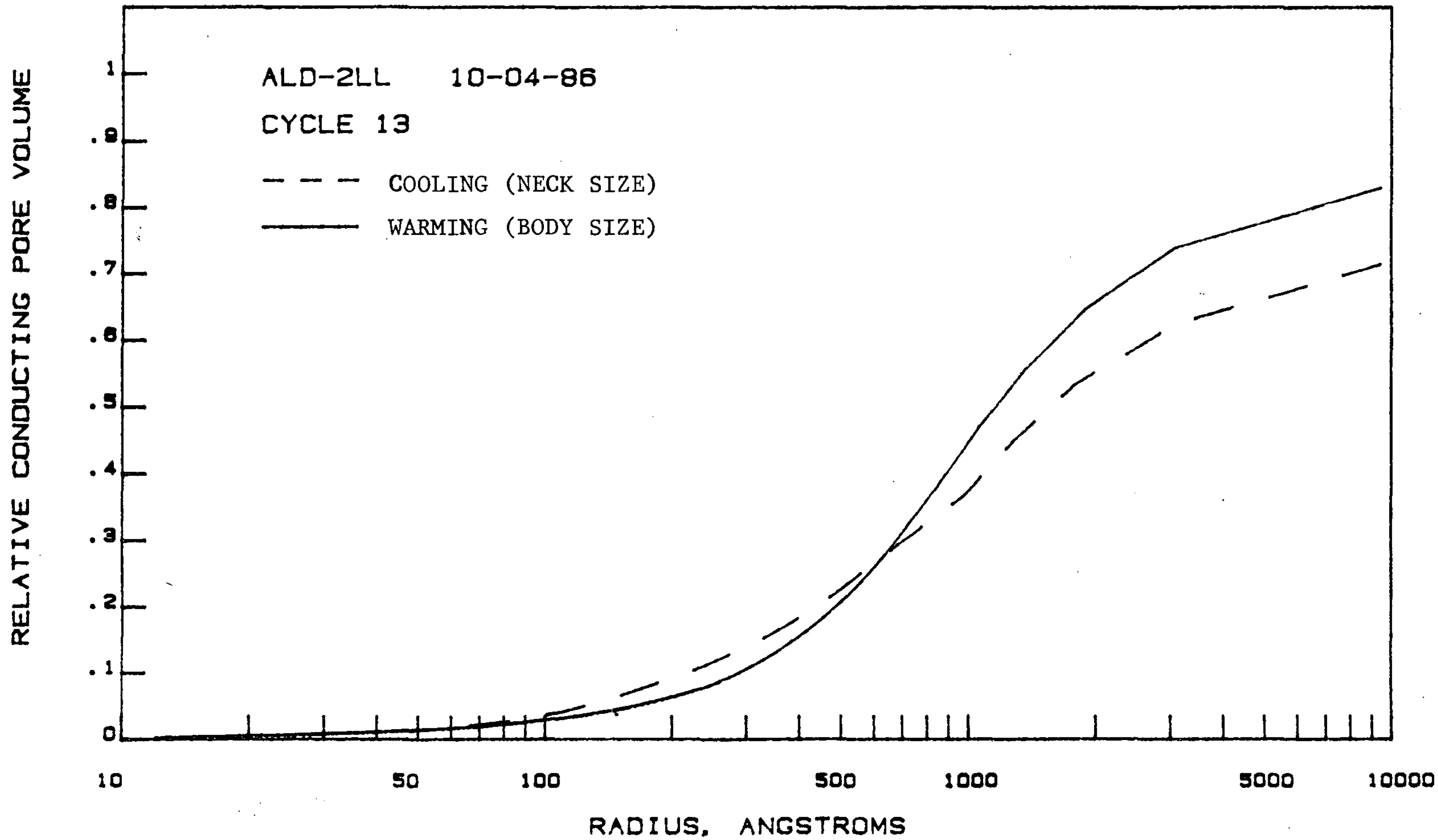
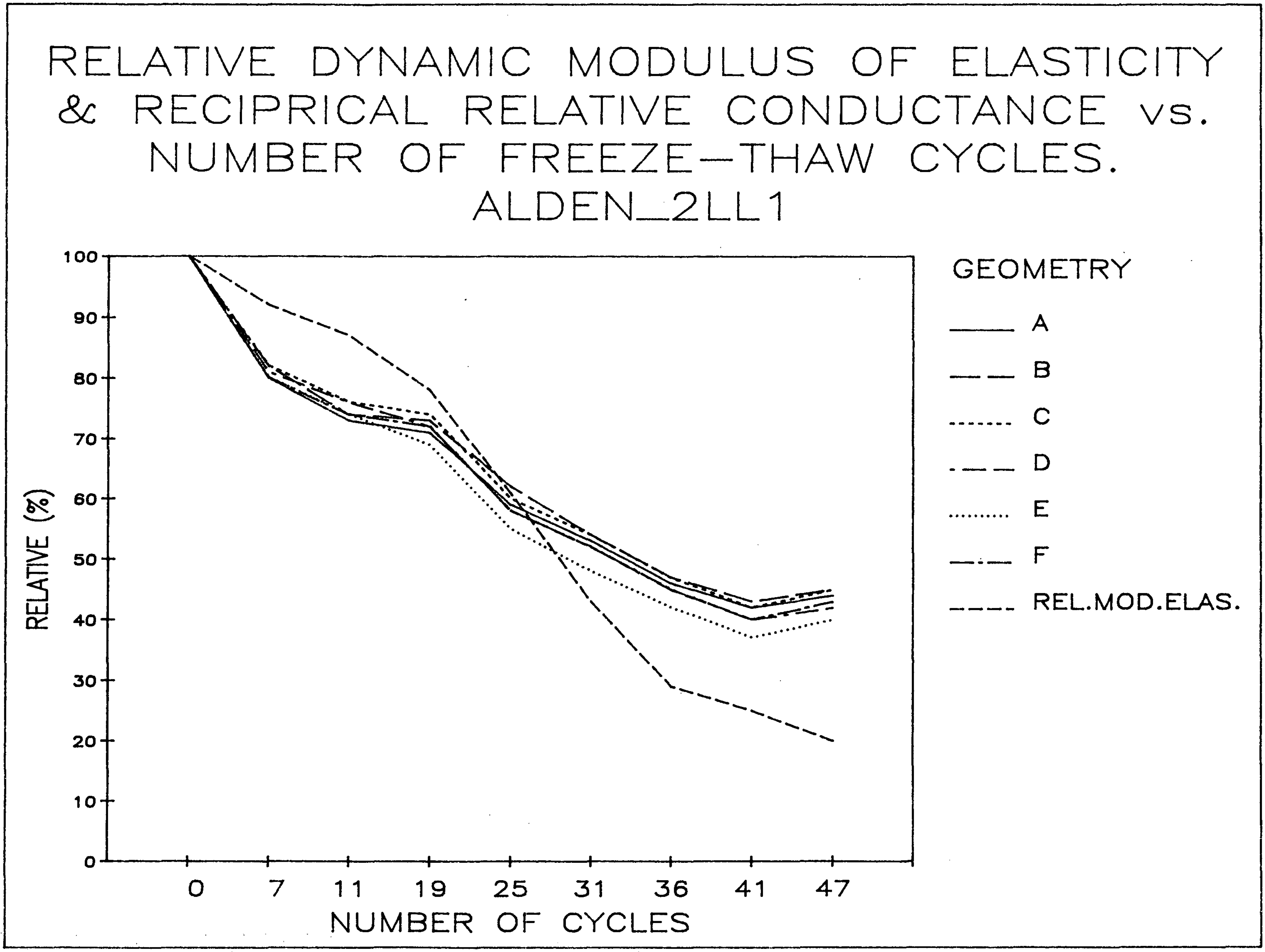
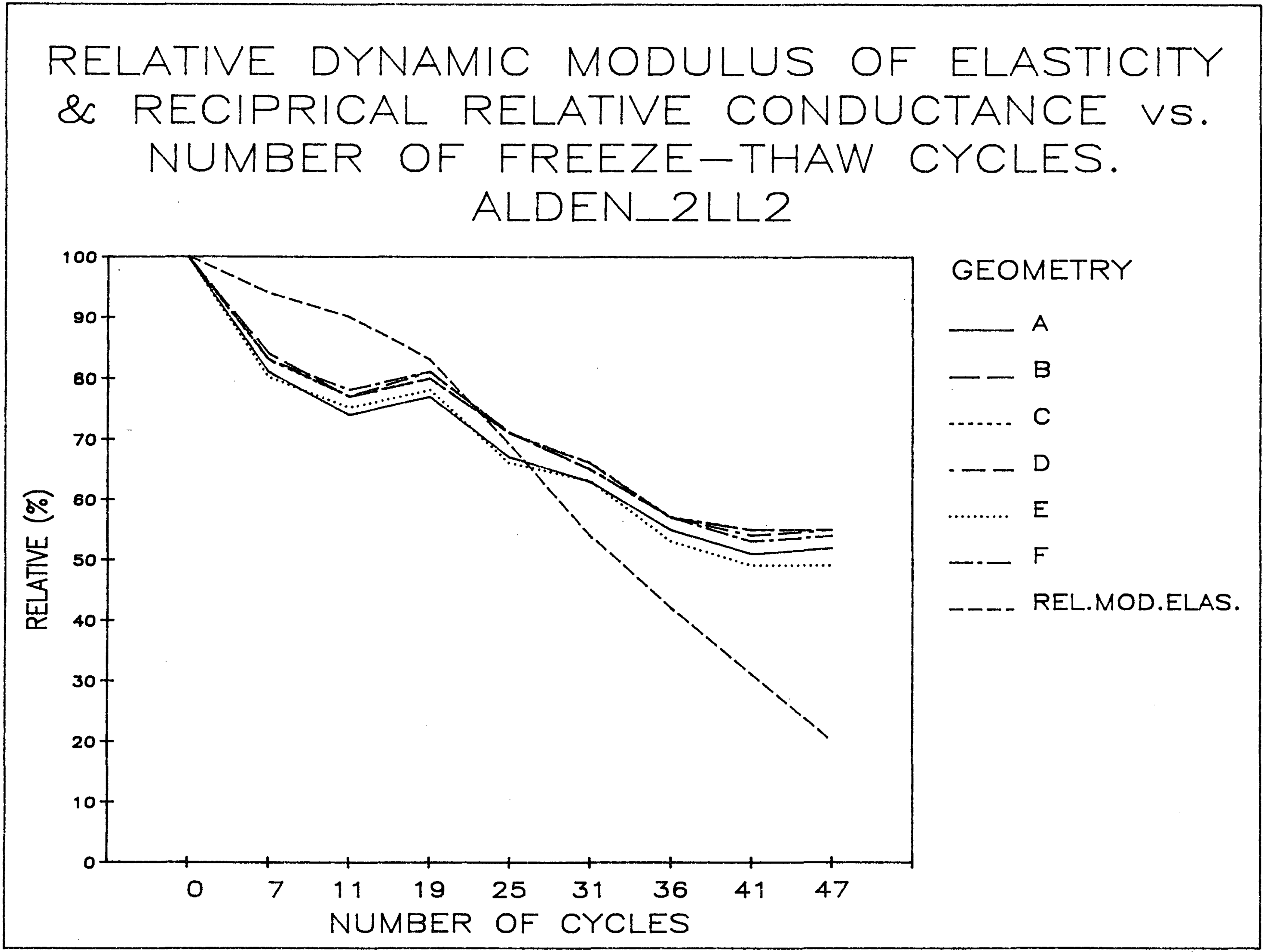
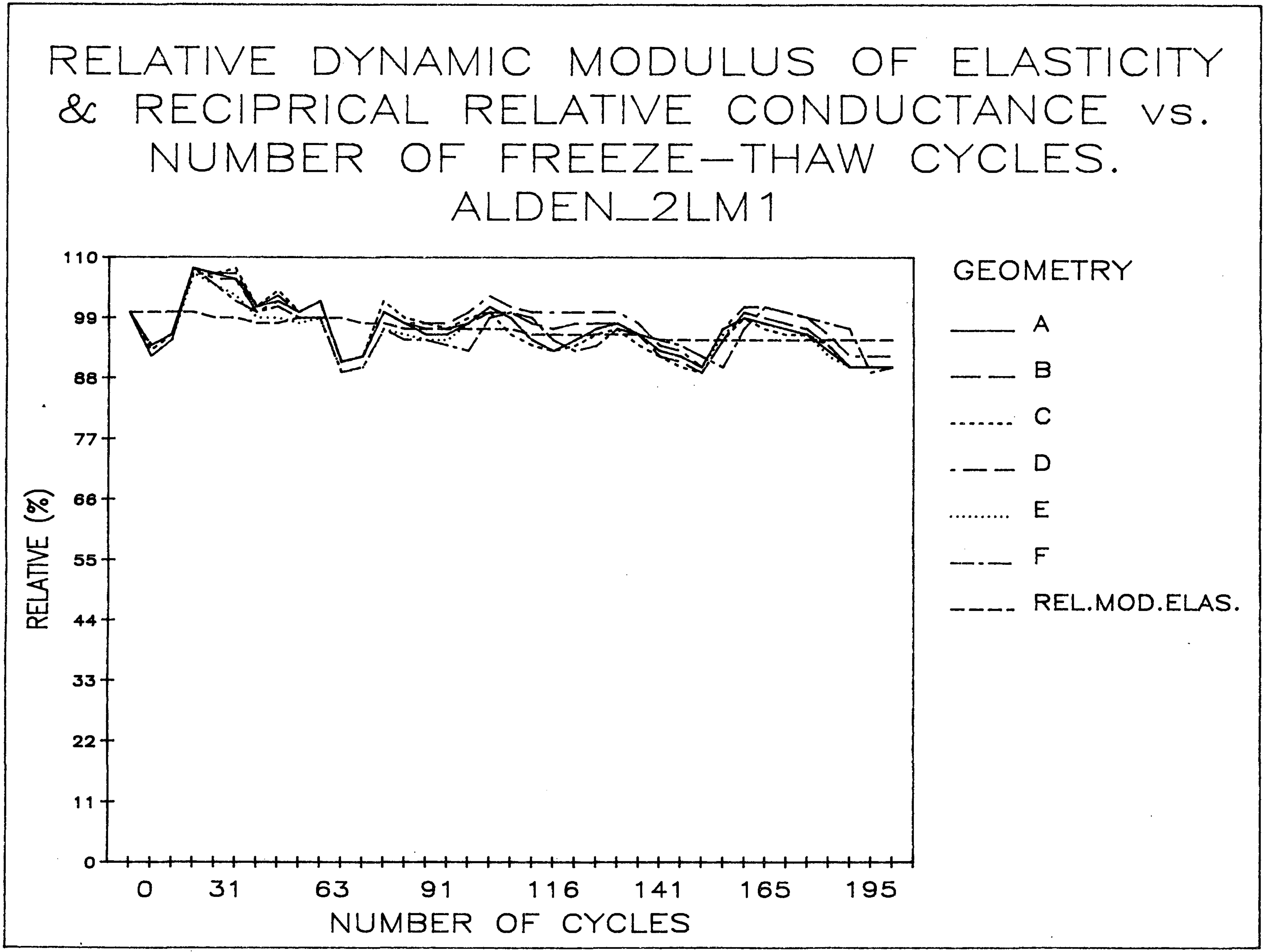


Figure 15. Pore size distribution of Ald.2LL beam.

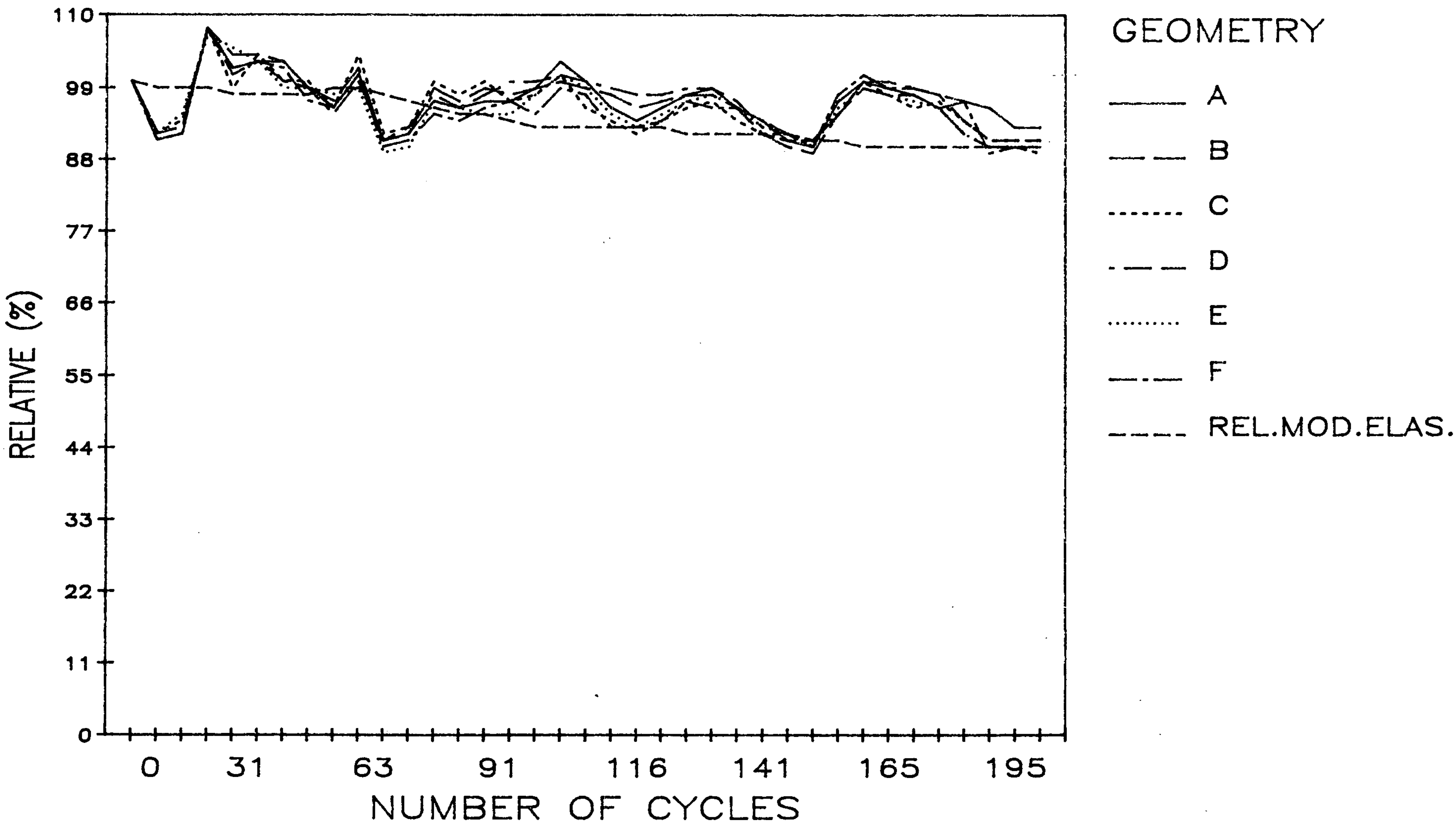
APPENDIX A

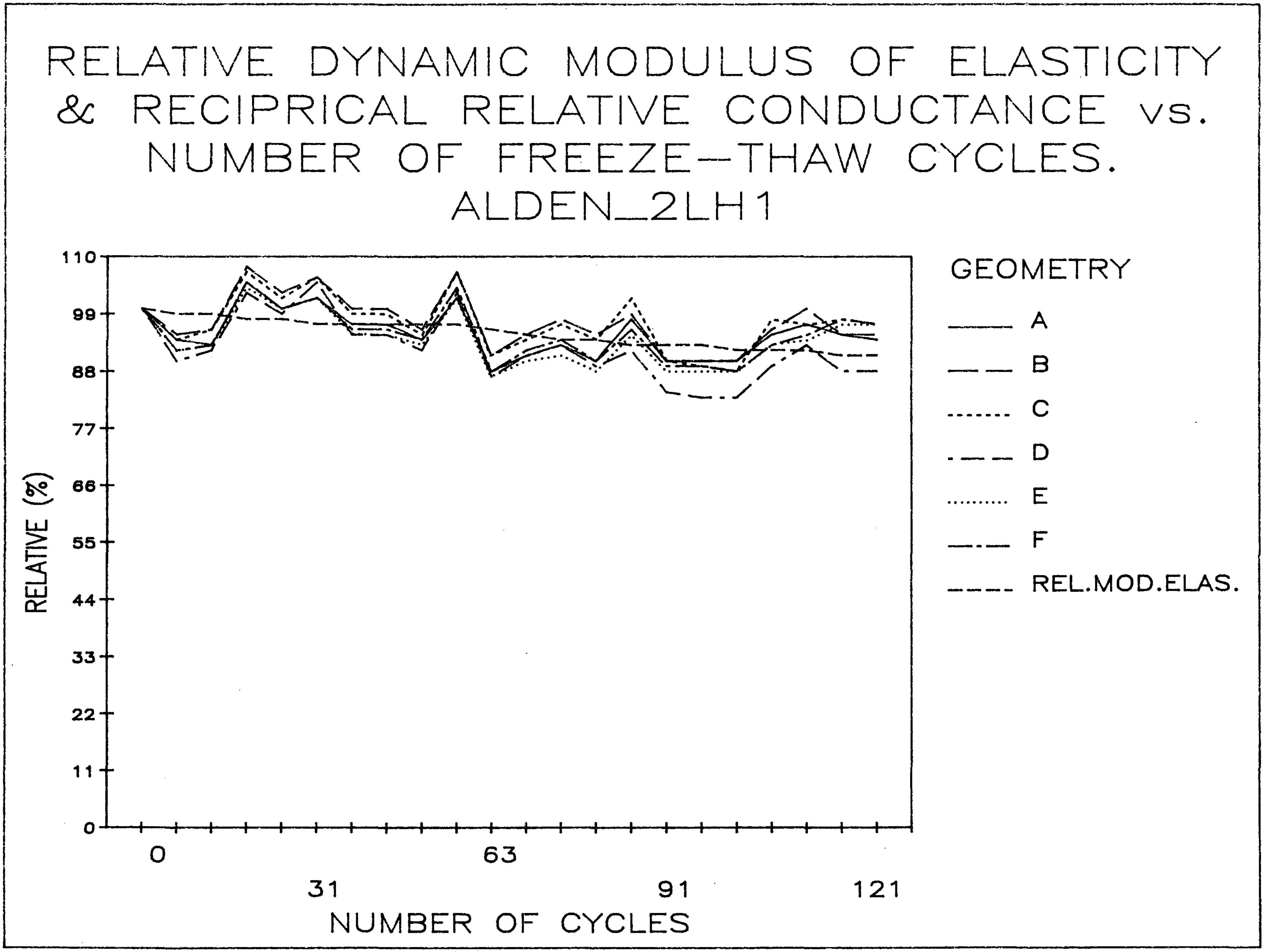

RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2LL1
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.
RELATIVE (%)
100
90
80
70
60
50
40
30
20
10
0
0
7
11
19
25
31
36
41
47
NUMBER OF CYCLES

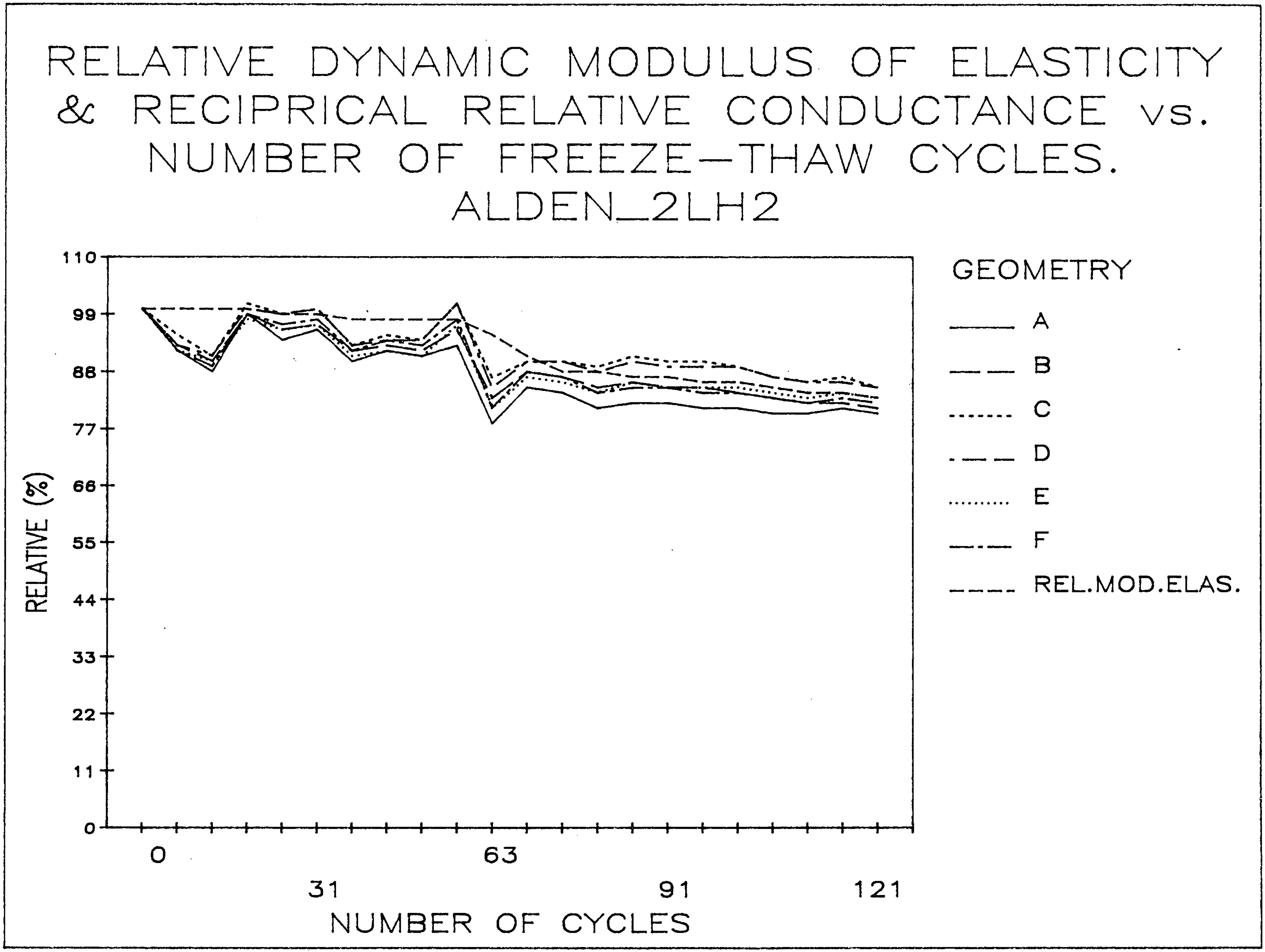

RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2LL2
RELATIVE (%)
100
90
80
70
60
50
40
30
20
10
0
0
7
11
19
25
31
36
41
47
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

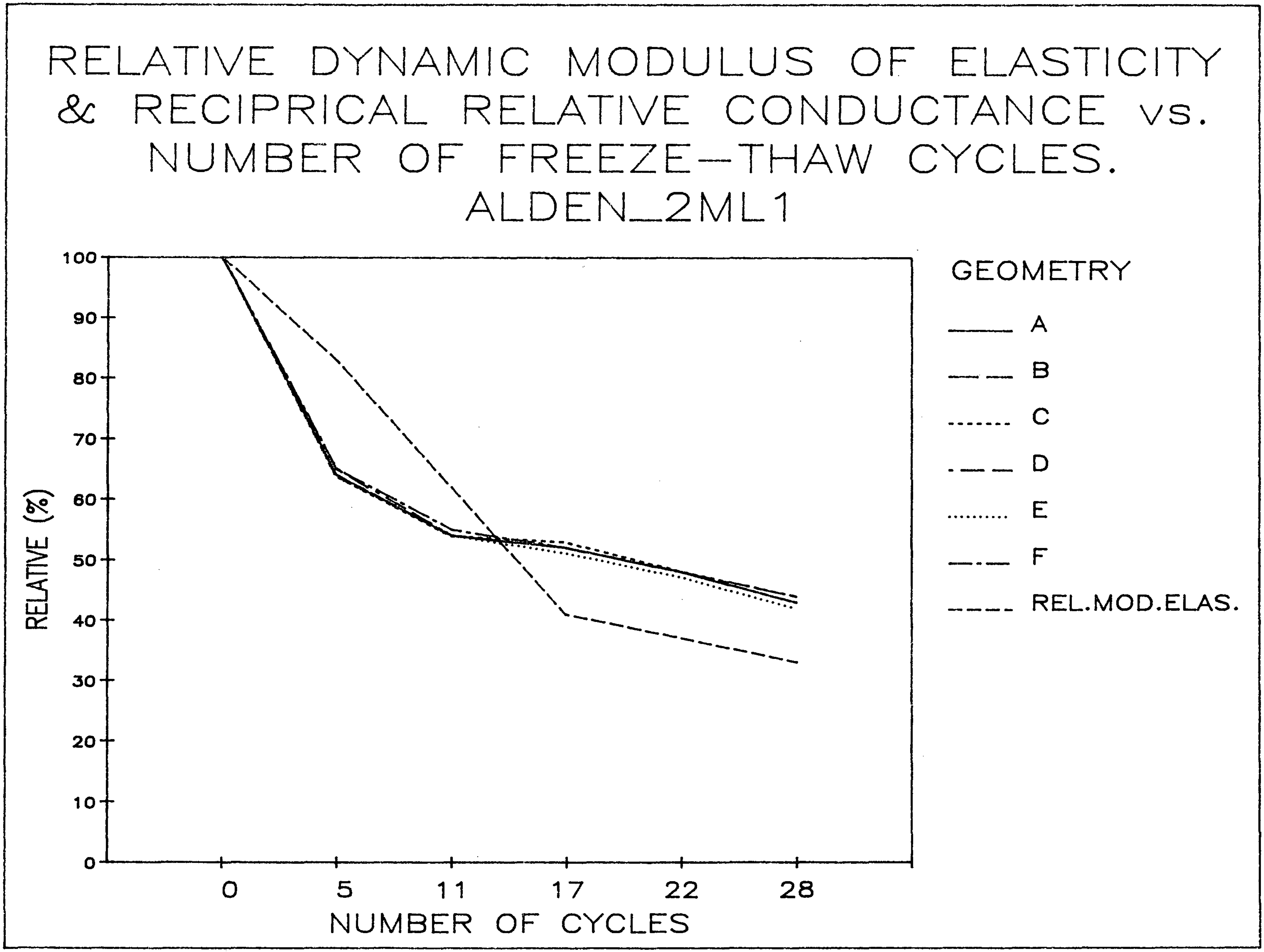

RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2LM1
110
99
88
77
66
55
44
33
22
11
0
RELATIVE (%)
0
31
63
91
116
141
165
195
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES. ALDEN_2LM2

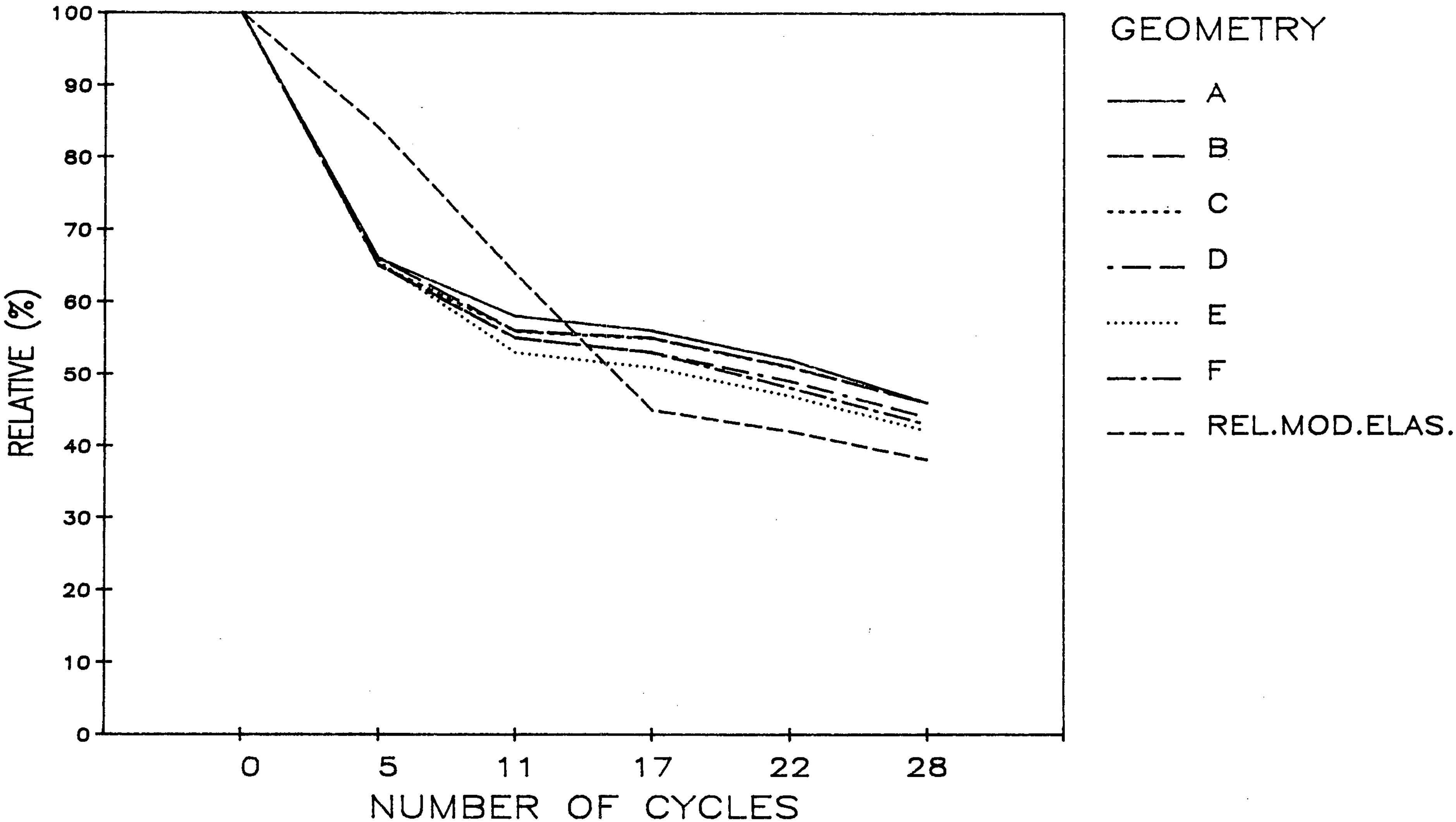



RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2LH1
110
99
88
77
66
55
44
33
22
11
0
RELATIVE (%)
0
31
63
91
121
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.


RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2LH2
RELATIVE (%)
110
99
88
77
66
55
44
33
22
11
0
0
31
63
91
121
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

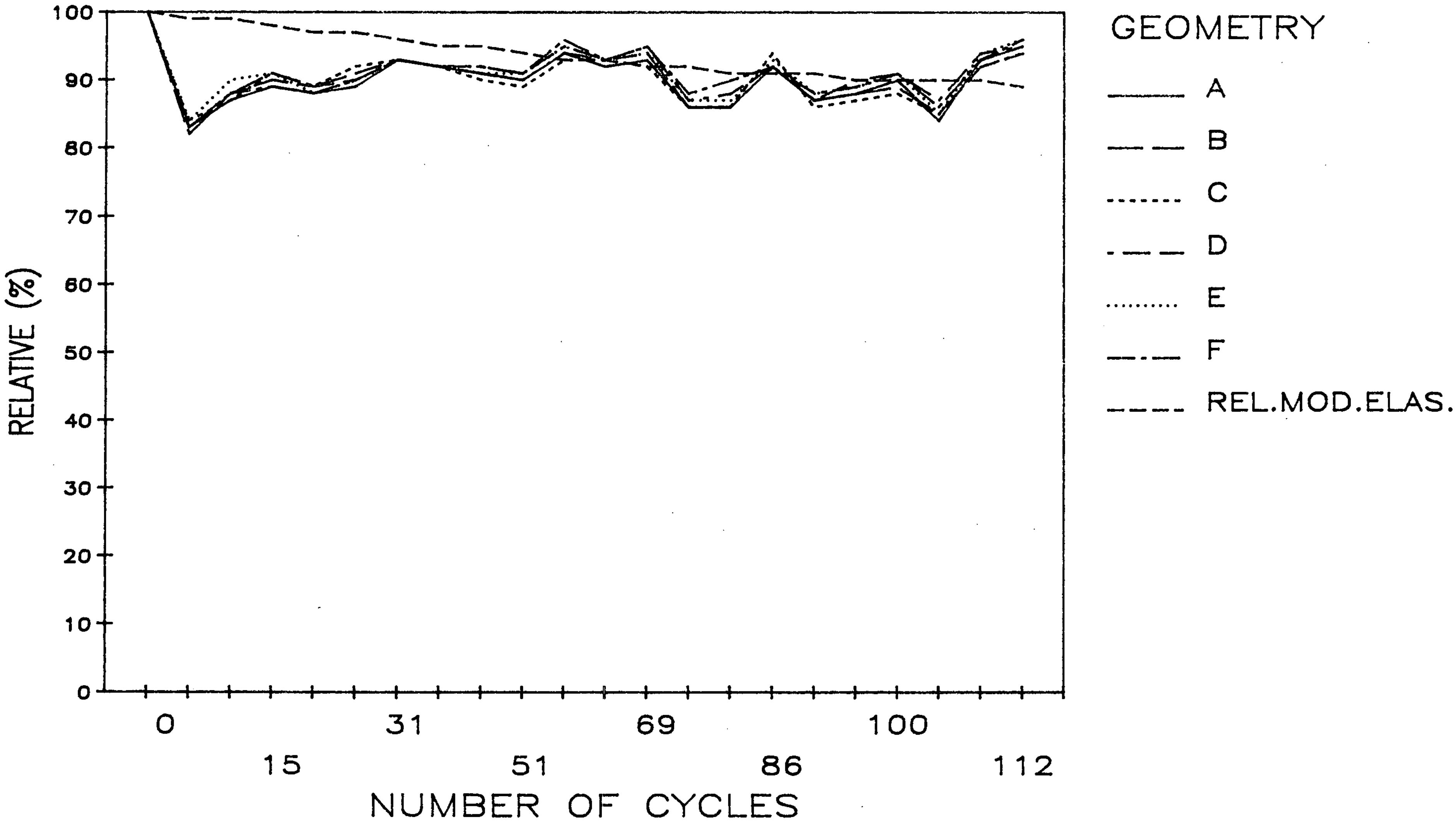

RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2ML1
100
90
80
70
60
50
40
30
20
10
0
RELATIVE (%)
0
5
11
17
22
28
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES. ALDEN_2ML2

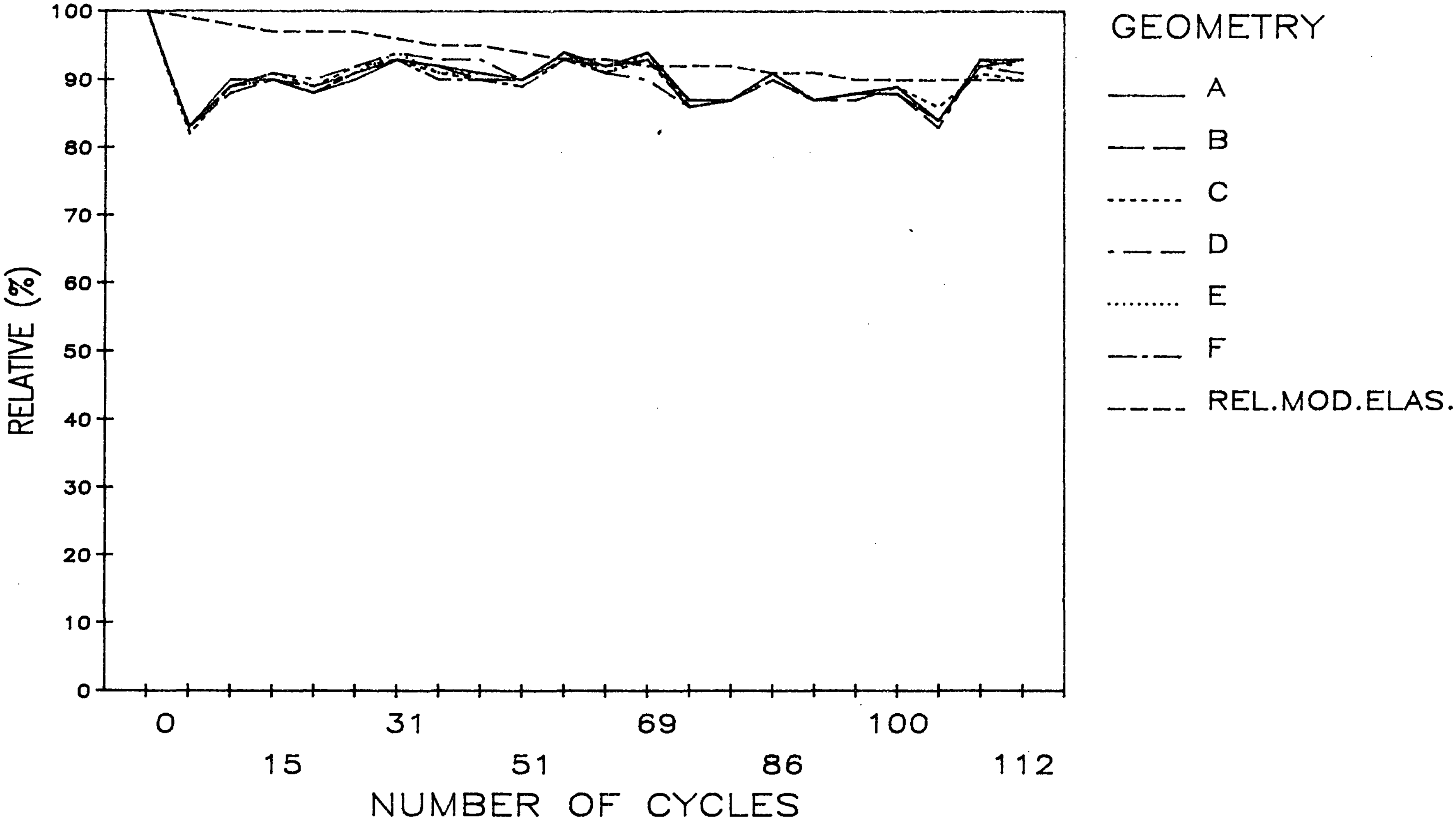


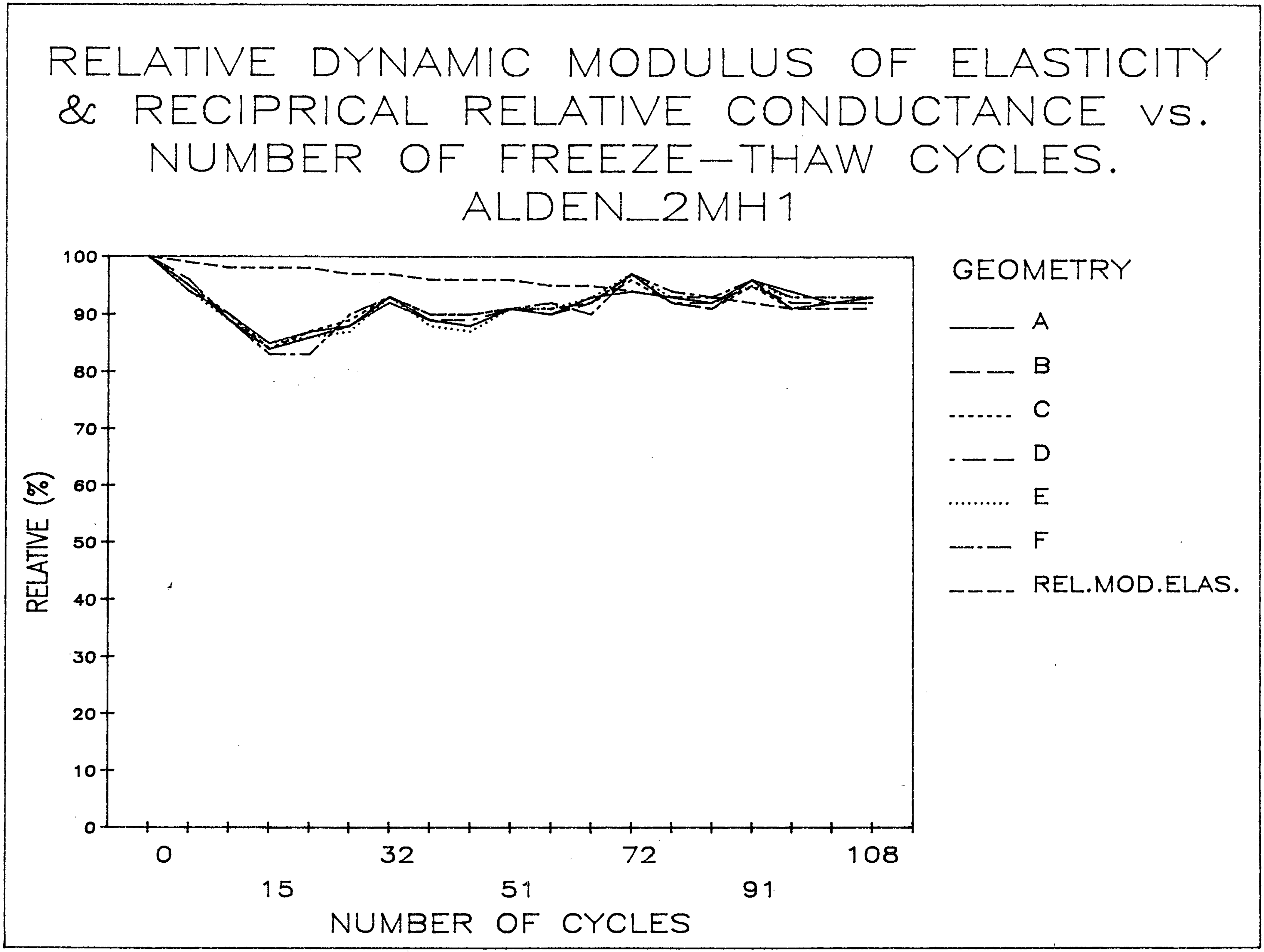
RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE–THAW CYCLES.

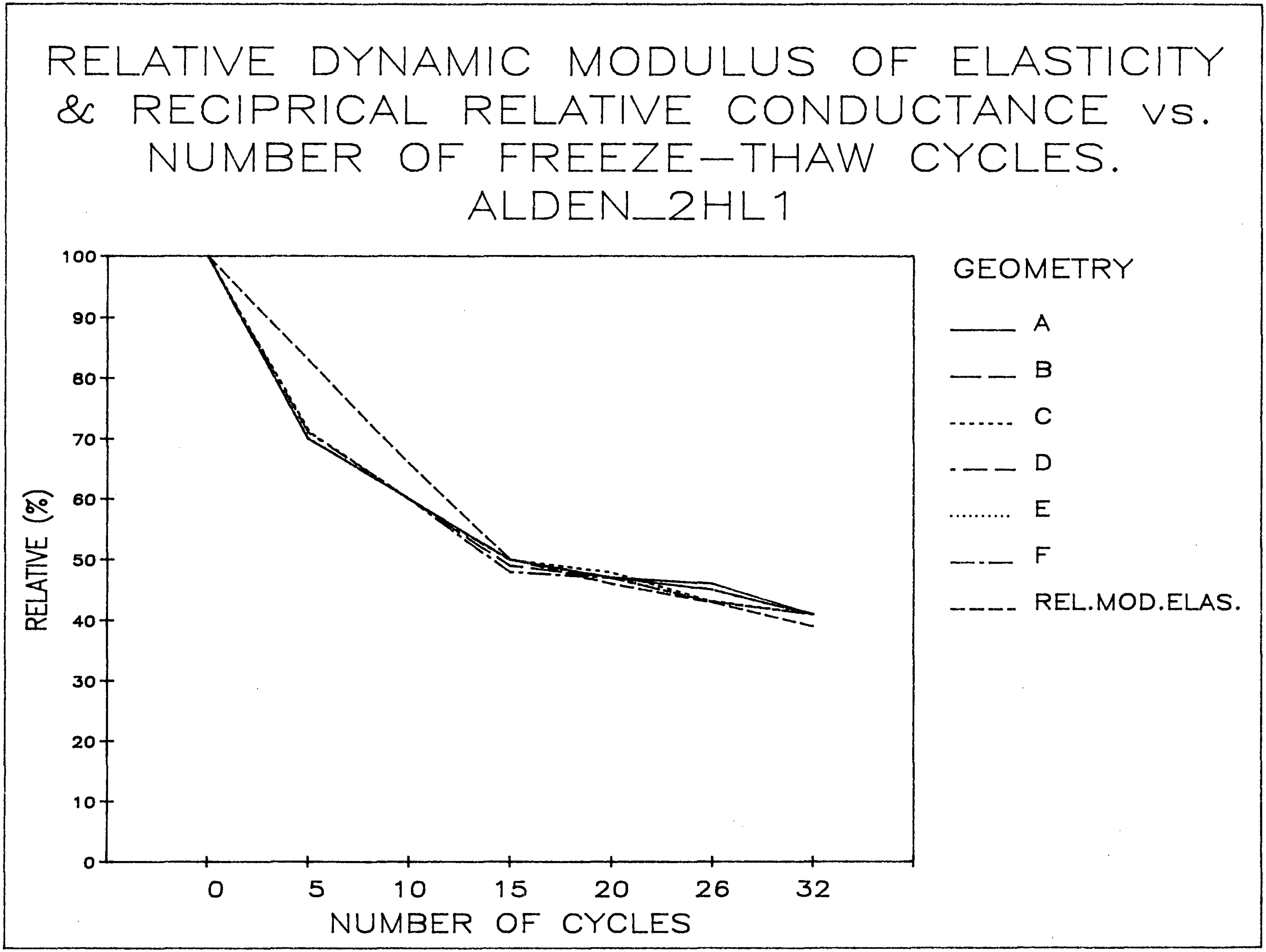
ALDEN_2MM1

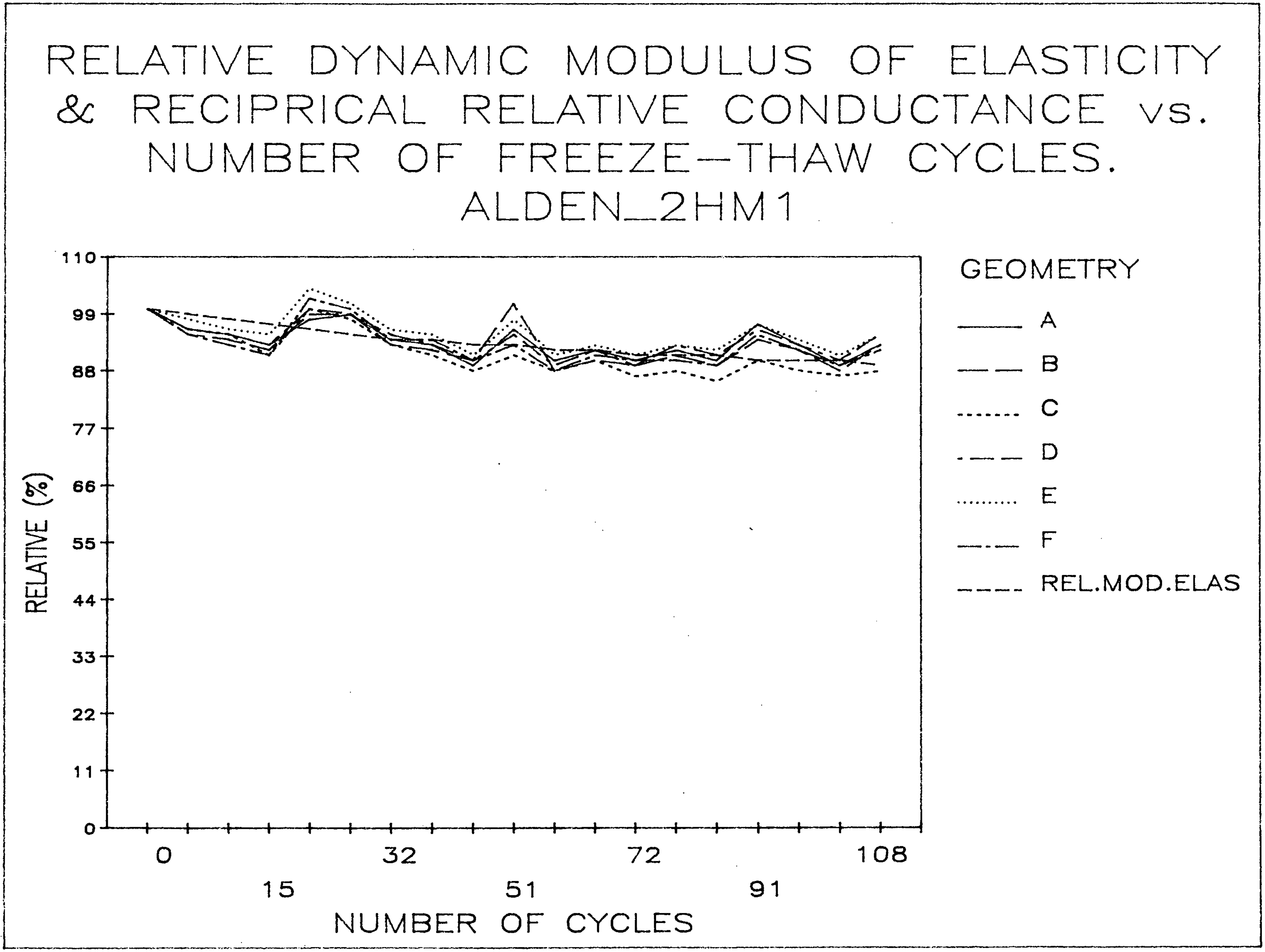


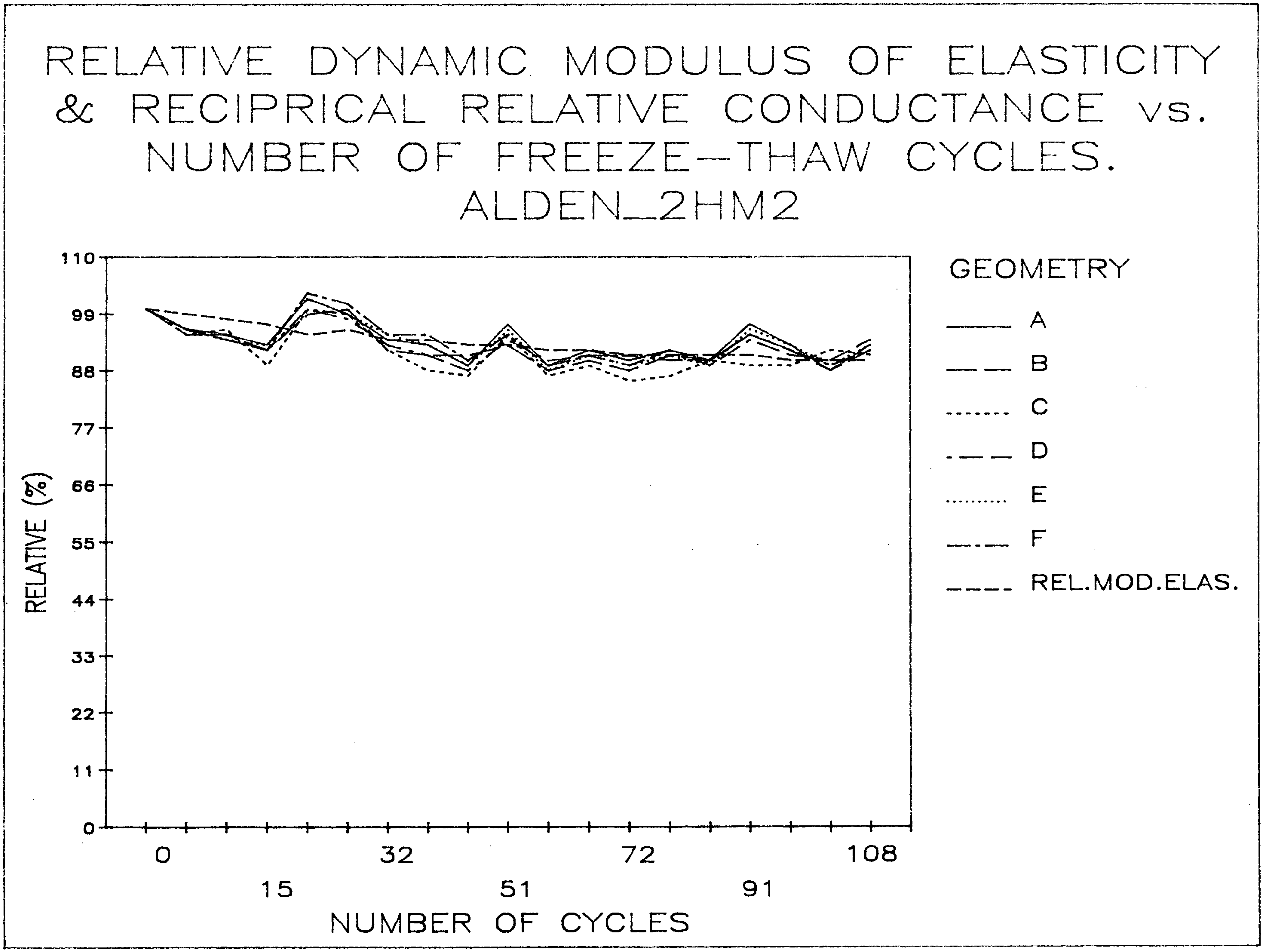
RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES. ALDEN_2MM2




RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2MH1
100
90
80
70
60
50
40
30
20
10
0
RELATIVE (%)
0
15
32
51
72
91
108
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

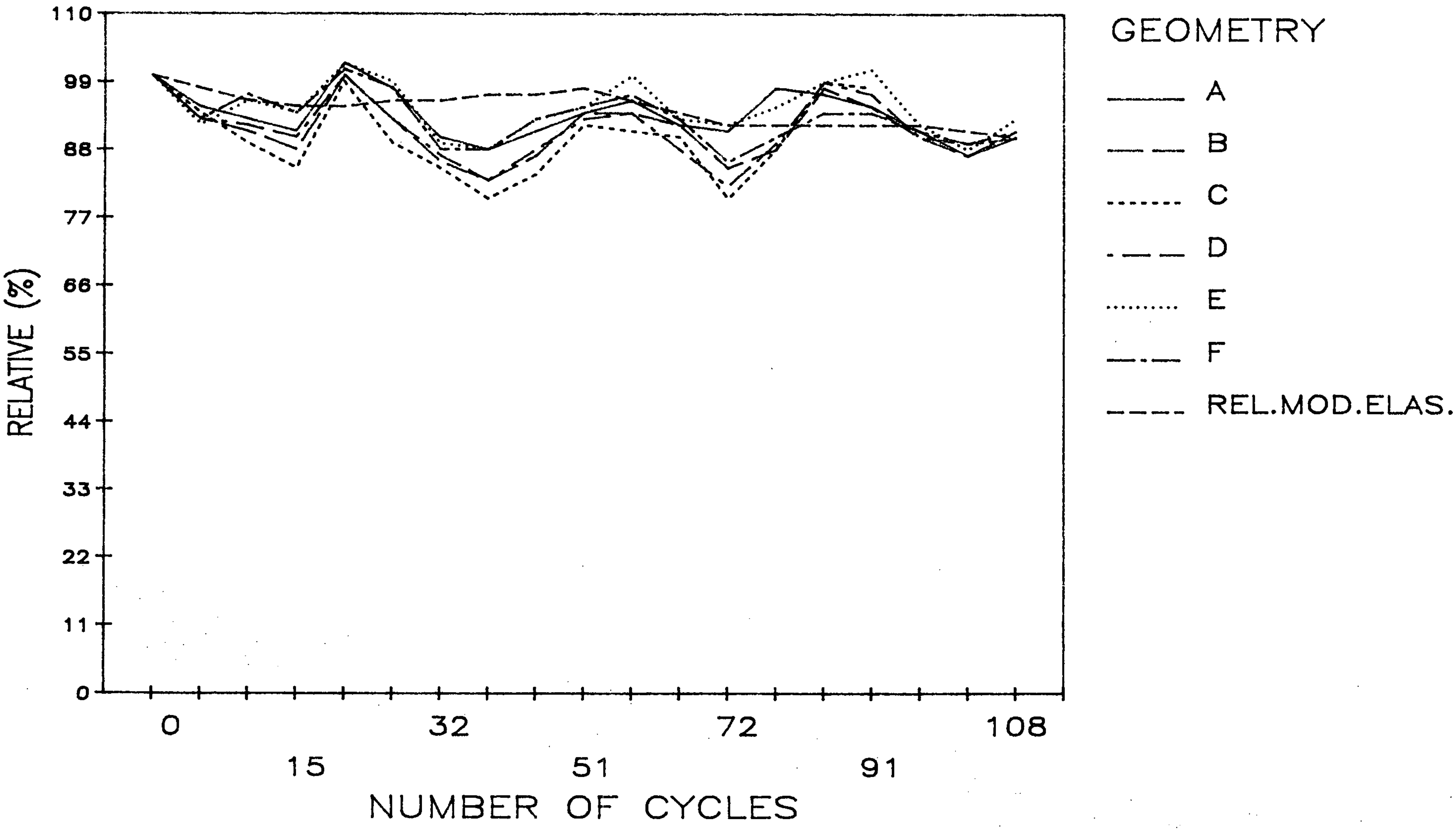

RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2HL1
RELATIVE (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
26
32
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.


RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2HM1
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS
RELATIVE (%)
110
99
88
77
66
55
44
33
22
11
0
0
15
32
51
72
91
108
NUMBER OF CYCLES



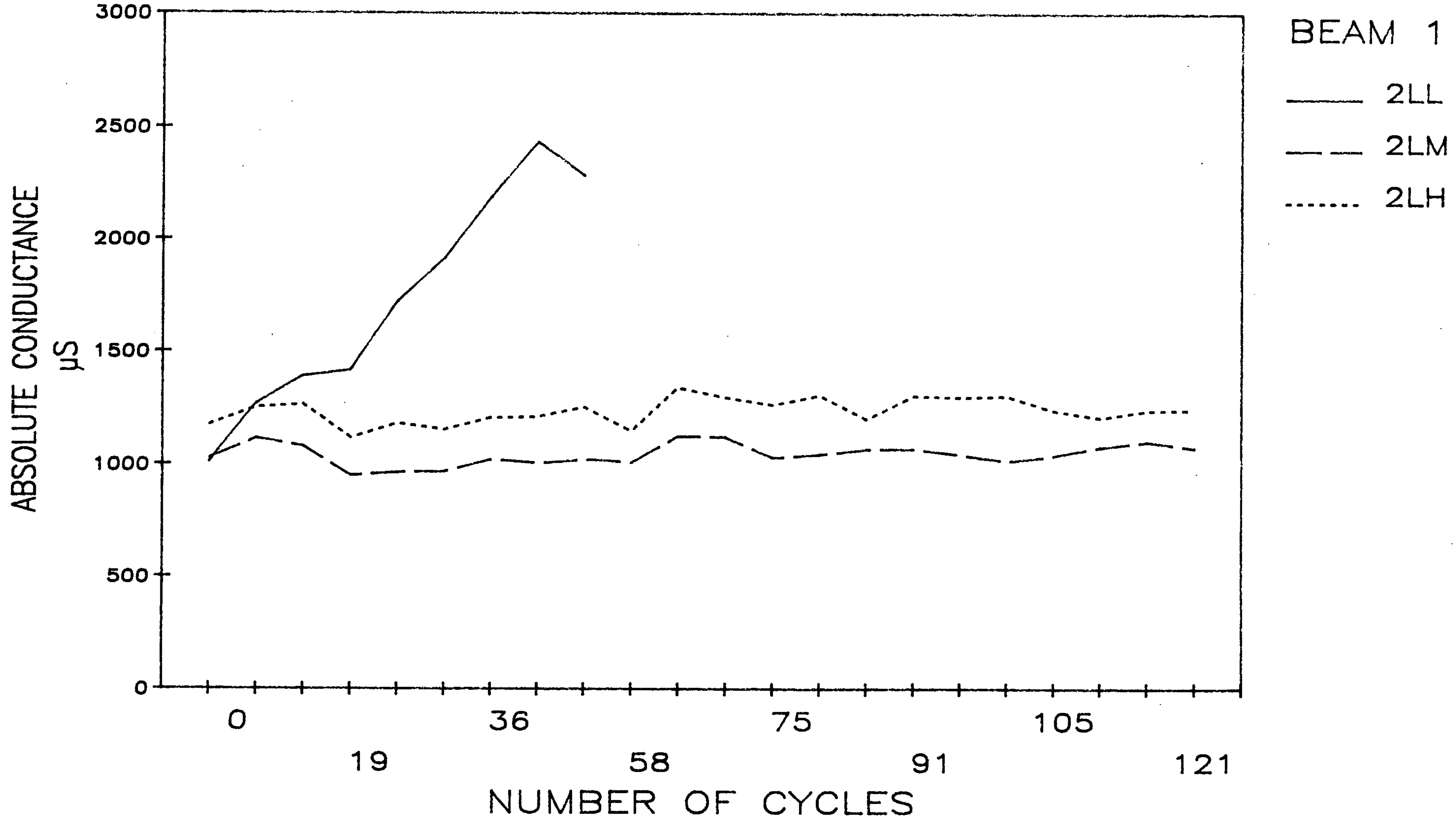
RELATIVE DYNAMIC MODULUS OF ELASTICITY
& RECIPRICAL RELATIVE CONDUCTANCE vs.
NUMBER OF FREEZE-THAW CYCLES.
ALDEN_2HM2
110
99
88
77
66
55
44
33
22
11
0
RELATIVE (%)
0
15
32
51
72
91
108
NUMBER OF CYCLES
GEOMETRY
A
B
C
D
E
F
REL.MOD.ELAS.

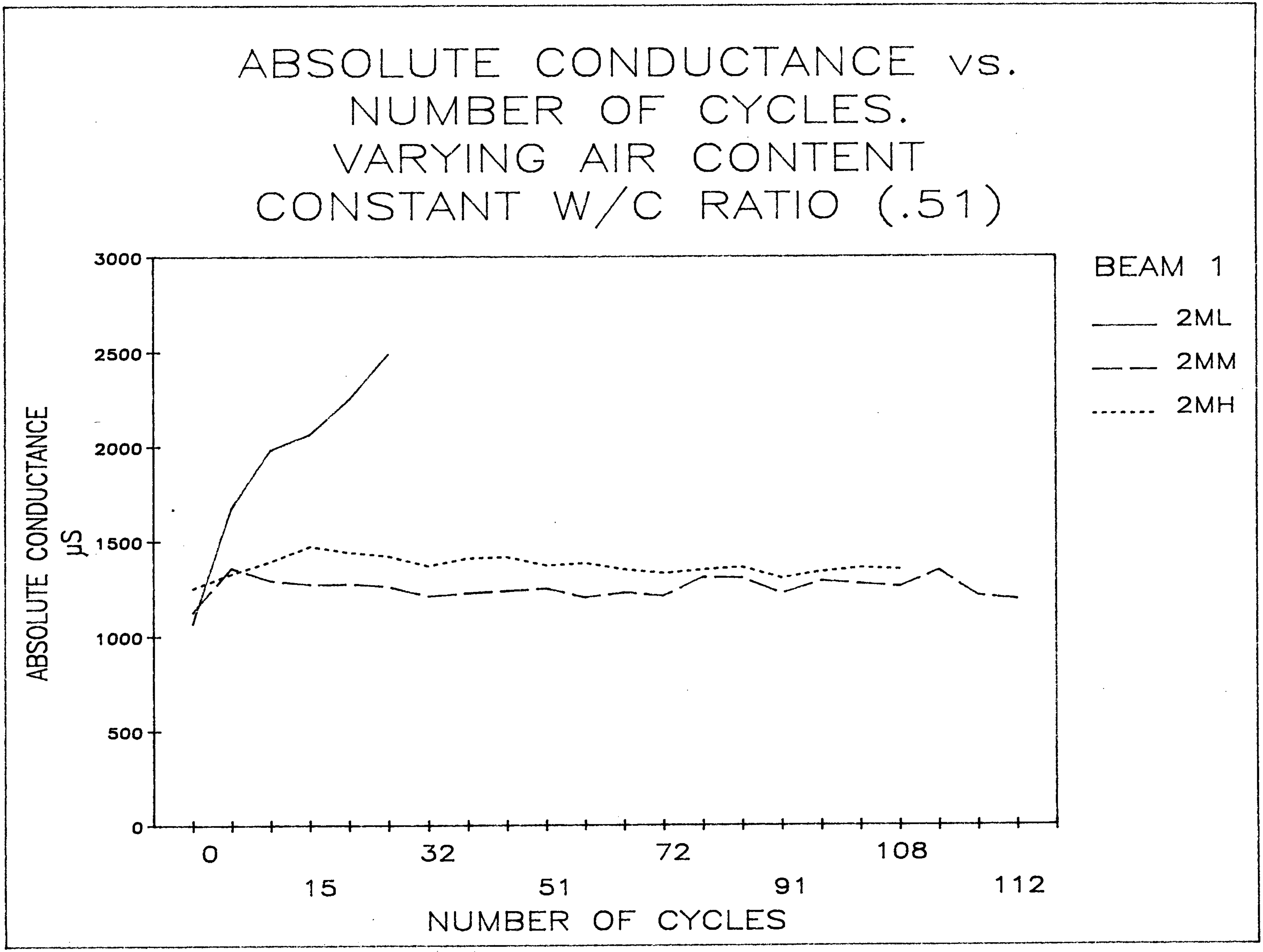
RELATIVE DYNAMIC MODULUS OF ELASTICITY & RECIPRICAL RELATIVE CONDUCTANCE vs. NUMBER OF FREEZE-THAW CYCLES. ALDEN_2HH1



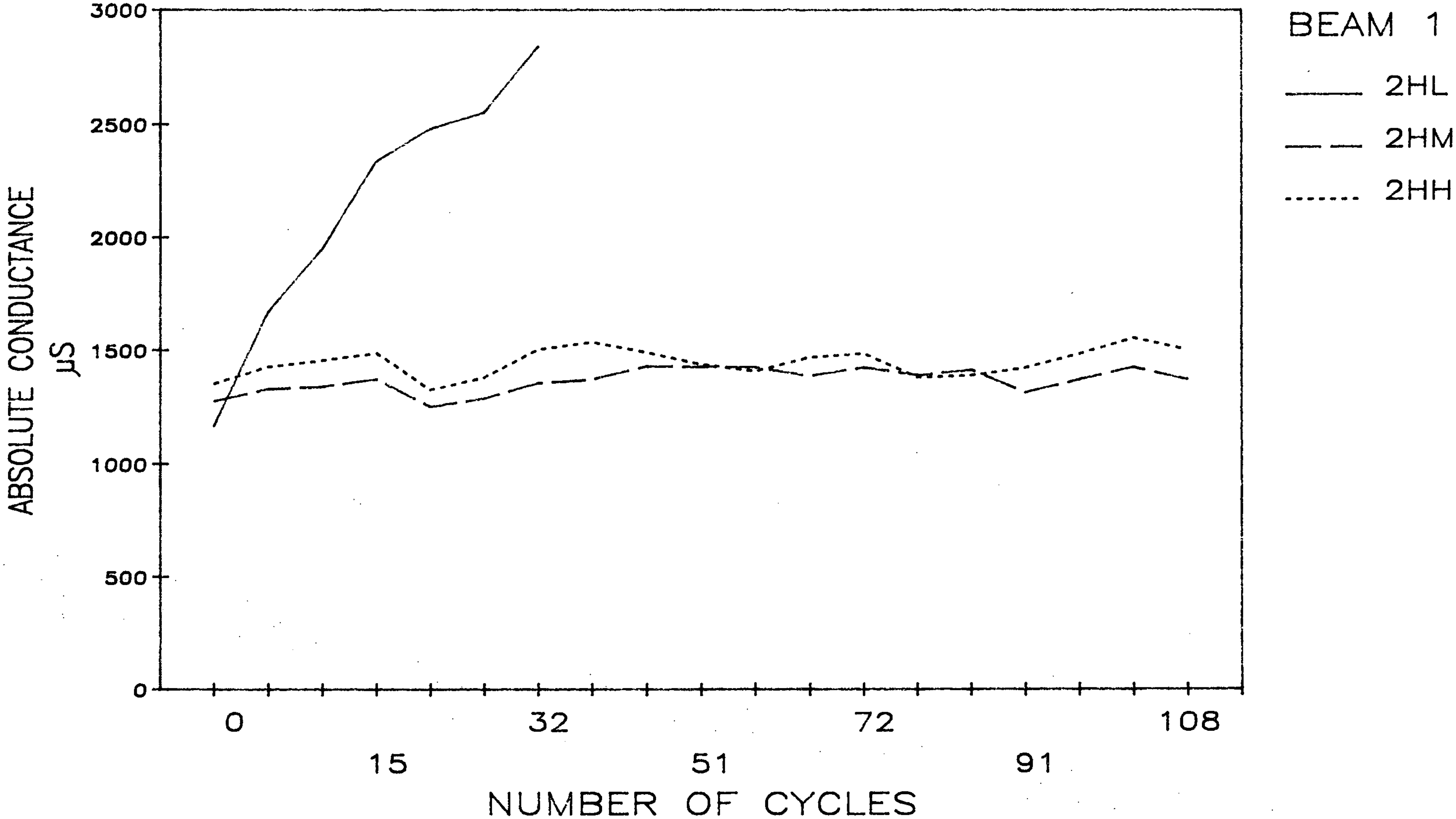
APPENDIX B

ABSOLUTE CONDUCTANCE vs. NUMBER OF CYCLES. VARYING AIR CONTENT CONSTANT W/C RATIO (.43)

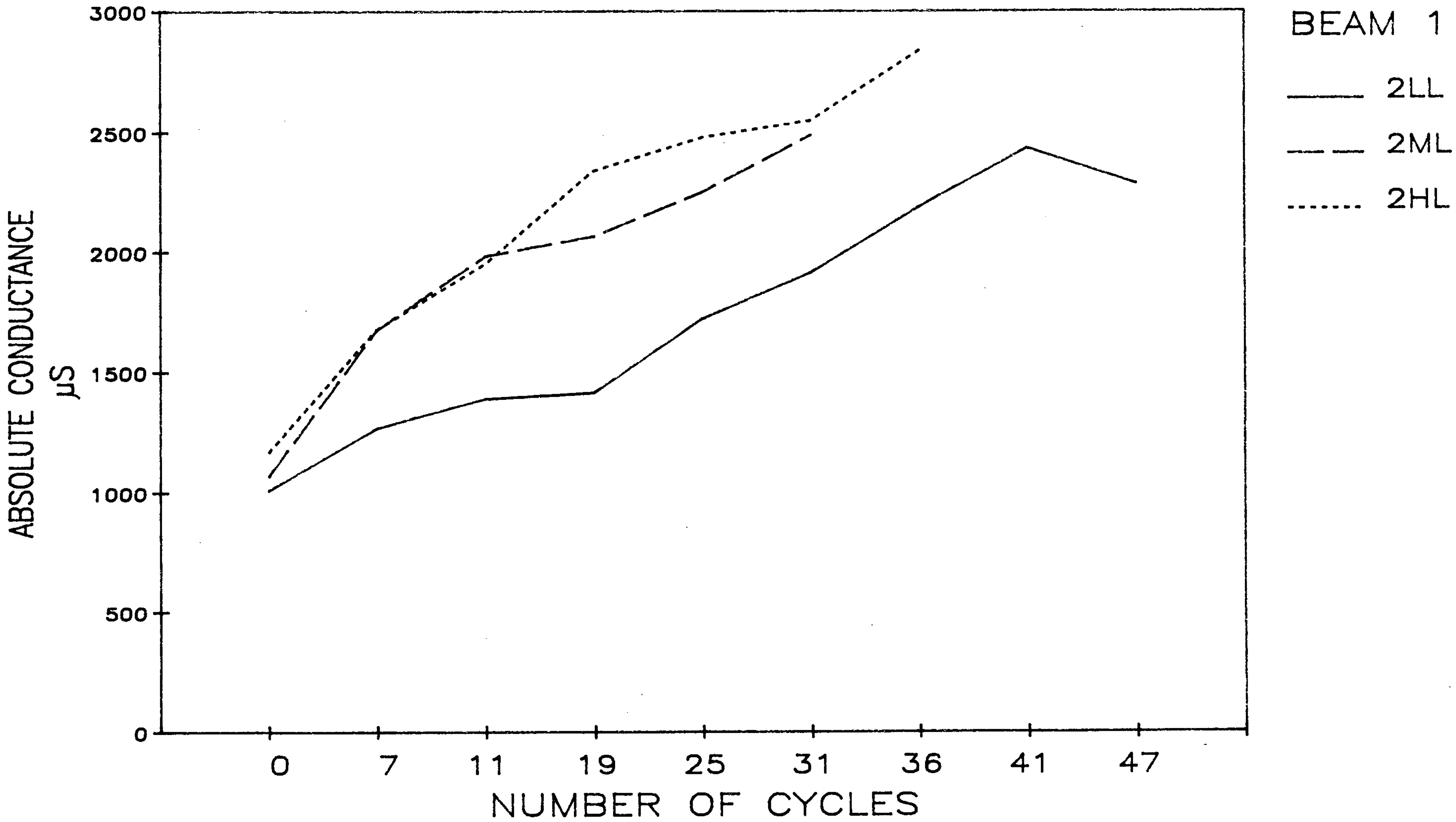


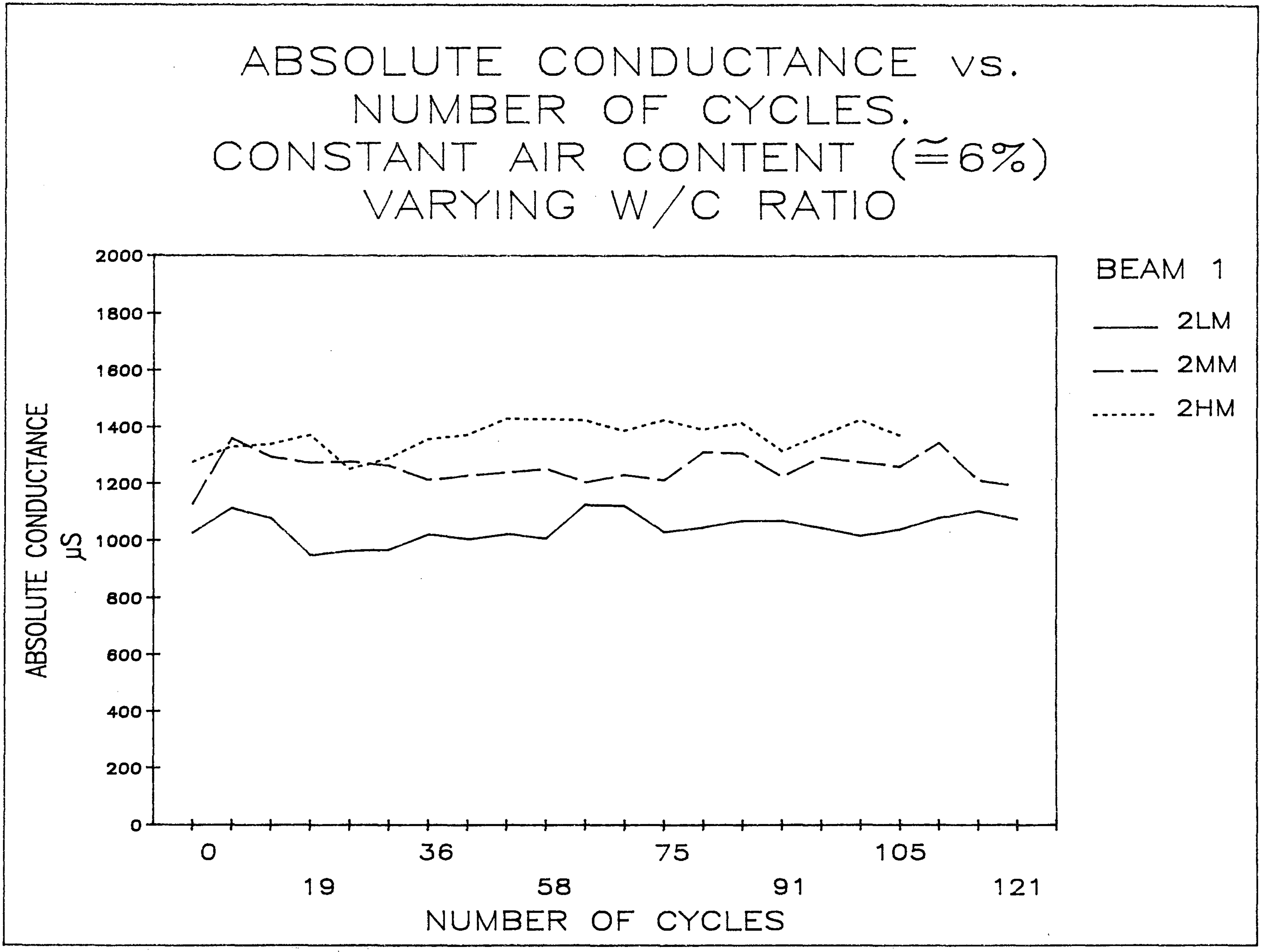

ABSOLUTE CONDUCTANCE vs.
NUMBER OF CYCLES.
VARYING AIR CONTENT
CONSTANT W/C RATIO (.51)
ABSOLUTE CONDUCTANCE
μS
3000
2500
2000
1500
1000
500
0
0
15
32
51
72
91
108
112
NUMBER OF CYCLES
BEAM 1
2ML
2MM
2MH

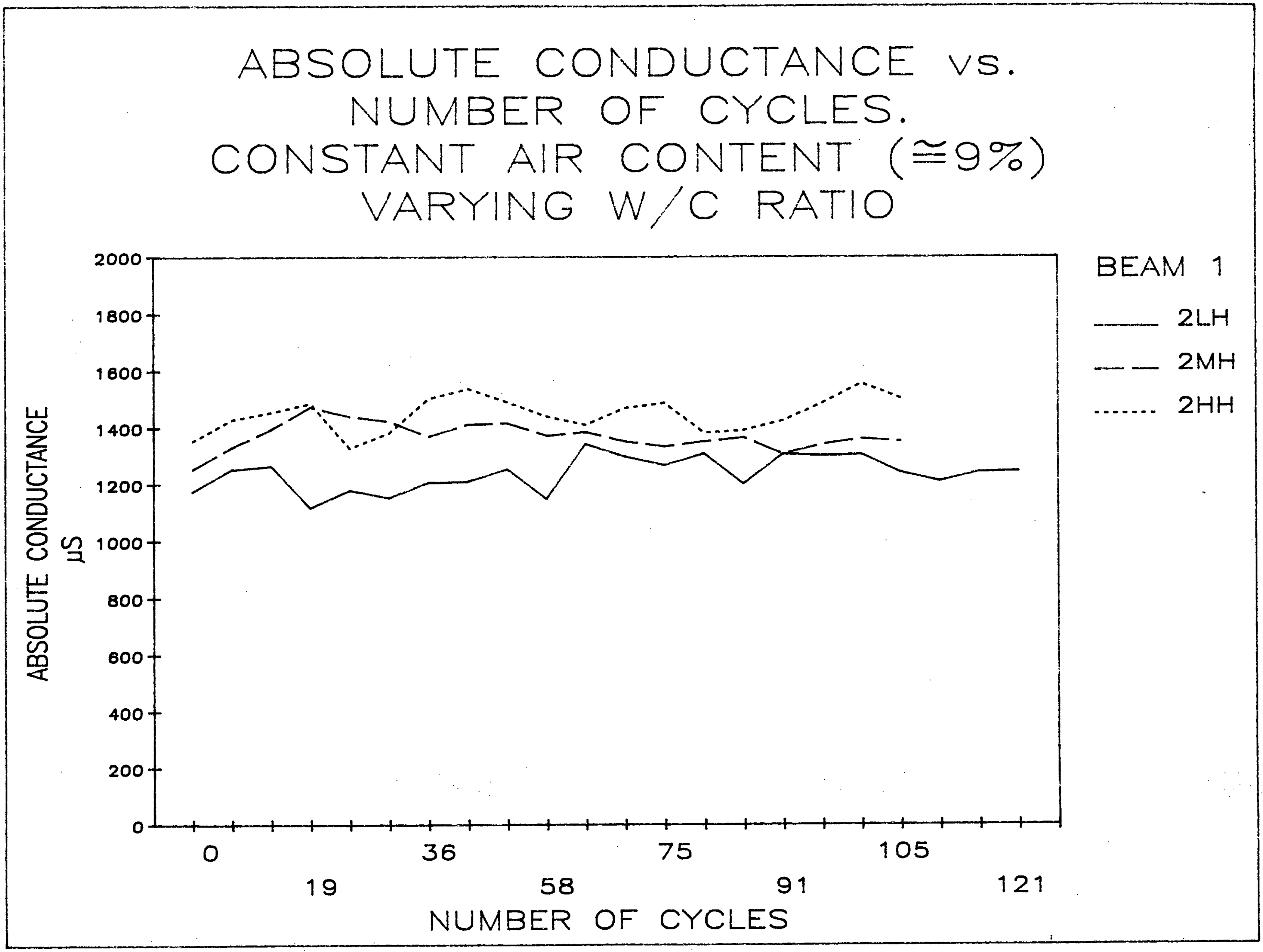
ABSOLUTE CONDUCTANCE vs. NUMBER OF CYCLES. VARYING AIR CONTENT CONSTANT W/C RATIO (.60)



ABSOLUTE CONDUCTANCE vs. NUMBER OF CYCLES. CONSTANT AIR CONTENT (≅2%) VARYING W/C RATIO




ABSOLUTE CONDUCTANCE vs.
NUMBER OF CYCLES.
CONSTANT AIR CONTENT (≅6%)
VARYING W/C RATIO
BEAM 1
2LM
2MM
2HM
ABSOLUTE CONDUCTANCE
μS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
19
36
58
75
91
105
121
NUMBER OF CYCLES



ABSOLUTE CONDUCTANCE vs.
NUMBER OF CYCLES.
CONSTANT AIR CONTENT (≅9%)
VARYING W/C RATIO
BEAM 1
2LH
2MH
2HH
ABSOLUTE CONDUCTANCE
µS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
19
36
58
75
91
105
121
NUMBER OF CYCLES