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RELIABILITY ASSESSMENT OF OPTO-ELECTRONIC INTEGRATED CIRCUITS

Uniphase Telecommunications Products

Karl M. Kissa and Hogan Eng

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13. ABSTRACT (Maximum 200 words)
This effort examined the functionality of 30 emitter-coupled, logic, compatible phase modulators and 30 bias-controlled modulators under various environments. The devices were subjected to thermal cycling, vibration, and temperature/humidity to evaluate the long-term performance of the optical and electronic portions of the devices. Thermal cycling and vibration testing did not cause optical failures. Subjecting the devices to high temperatures combined with high humidity (85°C/90% relative humidity) resulted in failures in the lid and fiber seal. Once moisture is allowed to enter the package, the water vapor reacts with the epoxies in the package, which then soften and darken. Laser welding the package lid and newly developed humidity resistant fiber seals extend the survival range to over 2,000 hours at 100°C/100% humidity.

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1.0 EXECUTIVE SUMMARY

Packaged Opto-Electronic Integrated Circuits (OEIC's) were subjected to thermal cycling, vibration, and elevated temperature and humidity. OEIC's subjected to 700 temperature cycles over a range as large as -55° to 85°C did not experience any optical failures, an indication that screening procedures are adequate. Two types of OEIC's were used for this program: BCM (Bias Control Module) devices and ECL-compatible phase modulators. Thirty 1.3 μm BCM devices and fifteen 1.3 μm plus sixteen 1.5 μm ECL-compatible phase modulators were procured for the testing. The temperature range exceeded the design limit of the ECL package (0°C to 50°C), resulting in cracked ceramic electrical boards. No electrical or optical failures were observed in OEIC's undergoing vibration testing to the 20 G level. OEIC's subjected to 85°C and 90% Relative Humidity (RH) did not fail optically until after 500 hr. Newly developed humidity resistant fiber seals have survived for longer than 2000 hr at temperature and humidity levels of 100°C and 100% RH, while maintaining a leak rate of 6×10^{-9} cc/sec of He, an indication that the time before failure of packaged OEIC's can be dramatically increased. The only electrical failures observed in the elevated temperature/humidity testing were shorted Detector-On-Chip (DOC) components, which were affected by the humidity degraded epoxies in the package.

2.0 SUMMARY OF TESTING

Table 1 lists the lot allocation of ECL-compatible phase modulators (now referred to as simply the "ECL modulators") and BCM modulators. Functionality of devices after the program are also listed along with wavelength of operation for the ECL modulators. Lots 5 and 6 of the BCM modulators were originally intended for thermal cycling tests, however, information rendered from thermal cycling tests of ECL modulators was deemed adequate for determining reliability of OEIC's, therefore, those tests were eliminated from the program.

OEIC's were put through three screening tests prior to the actual reliability testing. No other screening tests took place prior to the ones conducted under this program. The screen tests for this program are summarized:

Temperature Cycle Screen

1) -25° to +75°C
2) 25 cycles
3) Ramp rate of 5°C/min
4) Soak times of 15 min at -25° and +75°C

Vibration Screen

1) MIL-STD-202 Condition 1
2) 5.2 G's (50 to 2000 Hz)
3) 15 minutes each axis

Burn-In Screen

1) 24 hour powered operation at maximum operable temperature (85°C)
2) No optical power is applied

The reliability testing took place after screening. The 3 lots of ECL modulators underwent thermal cycling tests. The devices were thermally cycled, removed from the oven, and then critical performance parameters were re-measured. The devices were then placed back in the oven for more thermal cycling. Each lot consisted of three 1.3 μm plus three 1.5 μm modulators. Table 2 lists the total number of thermal cycles before each performance test. The ramp rate was 5°C/min for Lots 2 and 3 and ≤ 5°C/min for Lot 4. Soak times at the temperature extremes were 15 min. Devices were not powered during cycling. The first oven used for Lot 4 had difficulty approaching the low temperature extreme (-55°C), causing the cycle times to be very long, which in turn caused the performance tests for that lot to fall far behind schedule. A better oven was substituted and one performance test at 200 cycles was eliminated in order to bring testing of Lot 4 back on schedule.

Table 1: Lot allocation and status.

30 BCM DEVICES					31 ECL DEVICES			
Serial #	Functionality				Serial #	Functionality		
LOT 1 (control)	Optical	Electrical			LOT 1 (control)	Optical	Electrical	Wavelength
1791	OK	OK			1720	OK	FAILED	1.3
1787	OK	OK			1721	OK	FAILED	1.3
1767	OK	FAILED			1736	OK	FAILED	1.5
1797	OK	OK			1737	OK	OK	1.5
1823	FAILED	----			1738	OK	OK	1.5
					1752	OK	OK	1.5
LOT 2 (60C & 90%RH)	Optical	Electrical						
1769	OK	FAILED			LOT 2 (0 to 70C)	Optical	Electrical	
1773	FAILED	FAILED			1722	OK	FAILED	1.3
1775	FAILED	FAILED			1723	OK	OK	1.3
1777	OK	FAILED			1724	FAILED	----	1.3
1819	OK	FAILED			1741	OK	FAILED	1.5
					1742	OK	FAILED	1.5
LOT 3 (75C & 90%RH)	Optical	Electrical			1751	OK	OK	1.5
1779	FAILED	----						
1783	FAILED	----			LOT 3 (-20 to 85C)	Optical	Electrical	
1785	FAILED	----			1725	OK	FAILED	1.3
1811	FAILED	----			1726	OK	OK	1.3
1821	FAILED	----			1743	OK	FAILED	1.5
					1744	OK	OK	1.5
LOT 4 (85C & 90%RH)	Optical	Electrical			1745	OK	OK	1.5
1789	FAILED	----			1734	OK	FAILED	1.3
1761	FAILED	----						
1765	FAILED	----			LOT 4 (-55 to 85C)	Optical	Electrical	
1793	FAILED	----			1729	OK	FAILED	1.3
1795	FAILED	----			1730	OK	FAILED	1.3
					1732	OK	FAILED	1.3
LOT 5 (not used)	Optical	Electrical			1746	OK	FAILED	1.5
1799	OK	OK			1747	OK	FAILED	1.5
1801	OK	OK			1748	OK	FAILED	1.5
1807	OK	OK			1735	OK	FAILED	1.3
1759	OK	OK						
1771	OK	OK			LOT 5 (vibration)	Optical	Electrical	
					1733	FAILED	----	1.3
LOT 6 (not used)	Optical	Electrical			1719	OK	OK	1.3
1813	OK	FAILED			1728	OK	FAILED	1.3
1815	OK	OK			1749	OK	OK	1.5
1817	OK	OK			1750	OK	OK	1.5
1781	OK	OK			1740	OK	OK	1.5
1803	OK	FAILED						

Table 2: Testing schedule for thermally cycled ECL modulators.

TEST #:	T1	T2	T3	T4
TOTAL CYCLES:	50	200	500	700
Lot 2: 0° to 70°C	X	X	X	X
Lot 3: -20° to 85°C	X	X	X	X
Lot 4: -55° to 85°C	X	NT	X	X

X = tested; NT = not tested

Two 1.3 μm and three 1.5 μm ECL modulators were subjected to two sets of vibration testing at the 16.4 G level, and then at the 20 G level. Vibration was applied to all three axis for 15 min per axis. Performance tests were made after each set of vibration testing. Devices were not powered during vibration.

Three lots of 5 BCM modulators were subjected to elevated temperature and humidity and performance tests were performed according to the schedule in Table 3. Devices were powered during exposure. Some performance tests were eliminated near the end of the schedule in order to prevent cost overrun.

Table 3: Testing schedule for BCM devices exposed to elevated temperature/humidity.

TEST #:	T1	T2	T3	T4	T5	T6	T7	T8
HOURS:	31	62	125	250	500	1000	1500	2000
Lot 2: 60°C / 90% RH	X	X	X	X	X	X	NT	X
Lot 3: 75°C / 90% RH	X	X	X	X	X	X	NT	X
Lot 4: 85°C / 90% RH	X	X	X	X	X	NT	X	NT

X = tested; NT = not tested

A control lot of four BCM modulators and a control lot of one 1.3 μm and four 1.5 μm ECL modulators was maintained at ambient temperature (+18° to +27°C) and humidity. The devices were tested according to the schedule of Table 4. Devices were powered for the entire duration. As with other lots, some performance tests were eliminated in order to prevent cost overrun of the program.

Table 4: Testing schedule for BCM and ECL control lots.

TEST#:	T1	T2	T3	T4	T5	T6
HOURS:	31	93	1000	1500	2000	3500
ECL control lot	NT	NT	X	NT	X	NT
BCM control lot	X	X	X	X	NT	X

X = tested; NT = not tested

Figures 1 and 2 show the test set-up used to evaluate the ECL modulators and BCM devices. A more detailed explanation of testing procedures can be found in the OEIC Reliability Test Plan.

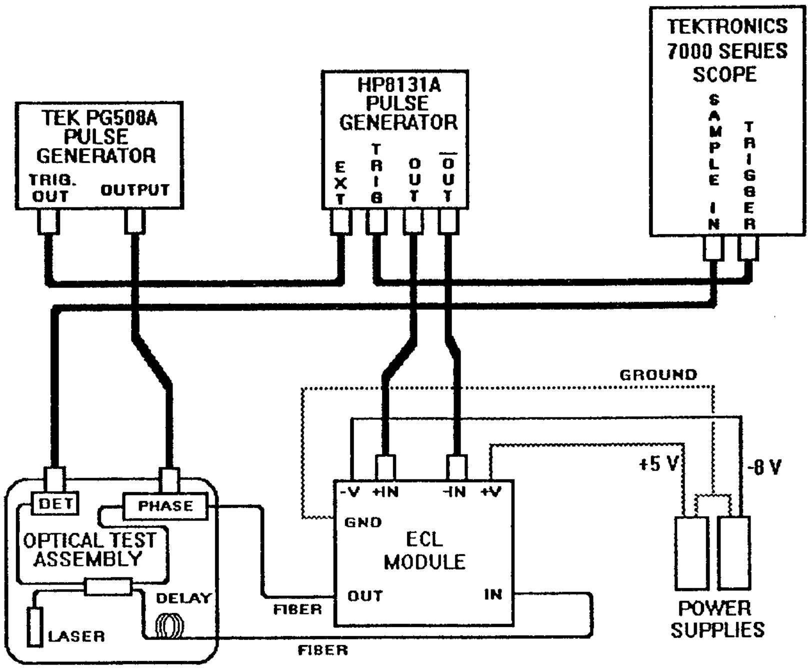


Figure 1: ECL modulator test set-up.

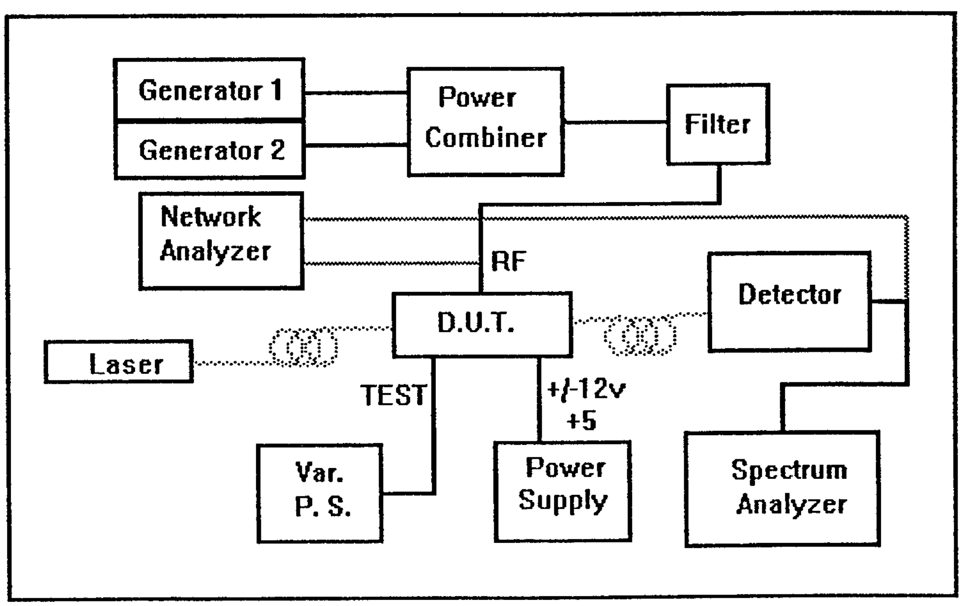


Figure 2: BCM device test set-up.

3.0 TESTING RESULTS

The test data is subdivided into two parts: failure data and performance data. Failure data relates to failures induced by the testing that make all or part of the device inoperable. Performance data contains information on degradation of critical performance parameters

3.1 ELECTRICAL AND OPTICAL FAILURES

Tables 5 through 11 list the number of failures occurring during each test. An "optical failure" is defined here to be a significant and sustained increase in optical insertion loss. As will be seen in the data, the loss increased dramatically when devices failed optically, either exceeding 10 dB or passing no light at all. An "electrical failure" refers to a failure of an electrical component within the ECL modulator that prevents operation of the modulator. Even though some devices failed electrically, they were still operational optically and could be tested since they did not require a bias voltage to pass light. "Electrical degradation" refers to degradation in electrical components within the BCM device that prevent proper operation of the bias control loop. A phase error of 10° is the threshold above which a BCM device is considered electronically degraded. This phase error did not affect the accuracy of optical measurements such as insertion loss. The bias point was set manually when measuring insertion loss. It should be noted that 10 ECL modulators originally intended for elevated temperature/humidity testing were removed after screening and did not undergo any further testing.

Table 5: ECL modulator screening test failures

TEST	Thermal Cycling	Vibration	Burn-in
TOTAL DEVICES	31	30	28*
TOTAL FAILURES	5	3	0
ELECTRICAL FAILURES	5	2	0
OPTICAL FAILURES	0	0	0
HANDLING DAMAGE	0	1	0
REPAIRS	5	1	0
ELIMINATIONS	1	2	0

*CONTAINS ELECTRICALLY FAILED DEVICES

Table 6: BCM screening test failures

TEST	Thermal Cycling	Vibration	Burn-in
TOTAL DEVICES	30	30	30
TOTAL FAILURES	4	0	5
ELECTRICAL DEGRADATION	4	0	4
OPTICAL FAILURES	0	0	0
HANDLING DAMAGE	0	0	1
REPAIRS	4	0	4
ELIMINATIONS	0	0	1

Table 7: ECL modulator temperature cycling failures

CYCLES	50	200	500	700
TOTAL DEVICES	18*	18*	17*	16*
TOTAL FAILURES	4	1	3	3
ELECTRICAL FAILURES	4	1	2	3
OPTICAL FAILURES	0	0	0	0
HANDLING DAMAGE	0	0	1	0
REPAIRS	0	0	0	0
ELIMINATIONS	0	1	1	0

*CONTAINS ELECTRICALLY FAILED DEVICES

Table 8: ECL modulator vibration testing failures

TEST NUMBER	1	2
TOTAL DEVICES	5	5
TOTAL FAILURES	0	0
ELECTRICAL FAILURE	0	0
OPTICAL FAILURES	0	0
HANDLING DAMAGE	0	0
REPAIRS	0	0
ELIMINATIONS	0	0

Table 9: BCM temperature/humidity testing failures

TIME (HOURS)	31	93	124	250	500	1000	1500	2000
TOTAL DEVICES	15	15	15	14	14	14	14	10
TOTAL FAILURES	0	0	1	0	0	1	4	6
ELECTRICAL DEGRADATION	4	5	2	4	4	3	0	5
OPTICAL FAILURES	0	0	0	0	0	1	4	6
HANDLING DAMAGE	0	0	1	0	0	0	0	0
REPAIRS	0	0	0	0	0	0	0	0
ELIMINATIONS	0	0	1	0	0	0	4	6

Table 10: ECL modulator control lot failures

TIME (HOURS)	1000	2000
TOTAL DEVICES	5	5
TOTAL FAILURES	0	2
ELECTRICAL FAILURES	0	2
OPTICAL FAILURES	0	0
HANDLING DAMAGE	0	0
REPAIRS	0	0
ELIMINATIONS	0	0

Table 11: BCM control lot failures

TIME (HOURS)	31	93	1000	1500	3500
TOTAL DEVICES	4	4	4	4	4
TOTAL FAILURES	0	0	0	0	0
ELECTRICAL DEGRADATION	2	2	3	3	1
OPTICAL FAILURES	0	0	0	0	0
HANDLING DAMAGE	0	0	0	0	0
REPAIRS	0	0	0	0	0
ELIMINATIONS	0	0	0	0	0

No optical failures were experienced by any of the ECL modulators, with the exception of two devices that failed from handling damage (broken optical fibers). None of the BCM modulators failed optically either until the last few tests (1000 hr or more), with the exception of two which also had an optical fiber accidentally broken by handling. The lack of optical failures during the thermal cycling reliability testing demonstrates the adequacy of the screening tests in stimulating optical failure mechanisms causing infant mortality.

Several ECL modulators experienced electrical failures, during both screening and reliability testing. The ceramic board used for mounting of electrical components cracked as a result of stress induced by the thermal cycling, causing a break in the metal traces on the board. This is not surprising since the ECL modulator was designed for a temperature range of only 0° to 50°C. Several of these modulators were repaired during screening by placing wire bonds across the breaks in the metal traces; however, none were fixed during the reliability testing because of the prohibitive cost. These failures can be eliminated in the future by using a different board material, such as Duroid, which can survive the wide temperature range.

Several BCM modulators experienced electrical degradation, during both screening and after exposure to elevated temperature/humidity. Failure analysis after all the testing was complete revealed two problems. First, the settling time for the bias control loop was as long as 10 min for some devices, even one in the control lot. Since the BCM devices were only given approximately one minute to warm-up and acquire bias control, it is not surprising that many devices exhibited bias errors. The cause of the long settling time is currently unknown.

A second cause of the electrical degradation in BCM modulators was failure of the DOC on devices that were exposed to elevated temperature/humidity. On five devices, the voltage on the PD pin of the package became unusually high (> 1V), an indication that the DOC became shorted. Failure analysis of two devices confirmed the suspicion that the DOC itself was shorted, as opposed to the electronics surrounding the DOC. Further examination of the devices revealed degradation of the epoxies used to mount the DOC and the pigtail to the OEIC. These epoxies not only became soft and changed color from transparent to slightly brown, but became airborne and deposited themselves on the surface of the OEIC and the wire bonds. It is possible that the airborne material contaminated the DOC causing a short. Hydrolysis of the epoxy may have also created harmful chemical by-products which leached out and attacked the DOC. Once the DOC's performance was degraded, the bias control loop either functioned poorly or not at all.

3.1 CRITICAL PERFORMANCE PARAMETERS

Figures in Appendices A through F show critical performance parameters for the ECL modulators, as a function of temperature cycles for Lots 2 through 4, and as a function of time for Lot 1, the control lot. The critical performance parameters are listed:

<u>ECL modulator critical performance parameters</u>

1) optical insertion loss
2) input and output polarization crosstalk
3) phase modulation index
4) modulator rise and fall times

A brief description of each parameter is given. Optical insertion loss is the loss of optical power through the device. Polarization crosstalk refers to the crosstalk that occurs outside of the OEIC die, such as that occurring at the fiber-OEIC interface due to fiber pigtail misalignment, or due to stress on the fiber itself produced by the packaging. There are two values since the OEIC die is made with APE™ polarizing waveguides, which permit independent measurement of the crosstalk in each fiber pigtail. Phase modulation index is the amount of phase modulation normalized to π rad, e.g., phase modulation index of 1.0 implies π rad phase shift. Modulator rise and fall time refer to the response time of the modulator at the leading and trailing edge of an applied voltage step, like a digital signal.

Figures in Appendix G through L show critical performance parameters for the BCM devices, as a function of exposure time to elevated temperature/humidity for Lots 2 through 4. These parameters are also plotted for Lot 1, the control lot. The parameters are listed:

<u>BCM device critical performance parameters</u>

1) optical insertion loss
2) modulator on/off ratio
3) half-wave voltage (V_π)
4) DOC coupling
5) system gain (S_{21})
6) electrical return loss (S_{11})

The BCM devices have some critical parameters that are different from the ECL modulator. Modulator on/off ratio is simply the extinction of the modulator. Half-wave voltage, V_π, is the voltage applied to the modulator that creates a π phase shift between the two legs of the Mach-Zehnder within the OEIC. DOC coupling is the percentage of power coupled out of the waveguide and into the DOC. It was measured by checking the voltage on the 'PD' pin of the package at the same time that the optical power exiting the modulator, P_{out}, was measured. The DOC photocurrent was calculated from the voltage on the PD pin using knowledge of the DOC circuit. Optical power entering the DOC, P_{DOC}, was then calculated from the manufacturer specified responsivity. The optical power in the waveguide before the DOC, P_{guide}, is simply the sum of P_{out} and P_{DOC}; therefore, the DOC coupling, η, is given by

$$\eta = \frac{P_{DOC}}{P_{guide}} = \frac{P_{DOC}}{P_{out} + P_{DOC}} \tag{1}$$

System gain, S_{21}, is the gain through the optical link used to test the BCM module, consisting of BCM device, optical fiber, and a high-speed photodetector (see Figure 2). The absolute value of S_{21} is of less significance than changes in S_{21} that occur as a result of reliability testing. The sixth parameter, electrical return loss, S_{11}, is the amount of electrical power that is reflected by the RF port of the BCM device. S_{11} is primarily a function of input impedance of the BCM RF port. The closer the impedance is to 50Ω, the lower S_{11} will be.

3.3 SUMMARY OF TEST DATA

The test results are summarized for all thermally cycled lots, vibration lot, and ECL control lot:

1) All polarization crosstalk values were better (less) than -25 dB by the end of testing except for one device which had an output with -17 dB crosstalk. The -25 dB value corresponds to a maximum of 3° error in rotational alignment between the OEIC and the fiber. Often the crosstalk improved with cycling, probably the result of stresses being relieved within the epoxy used to hold the fiber. The measured value dropped significantly in only one instance, where it went from an value of -17 to -5 to -27 dB crosstalk (see figure in appendix). The -5 dB value may have been the result of measurement error. Another possible explanation is that the stress on the fiber imparted by the strain relief was relieved by thermal cycling.

2) Insertion loss was always measured to be less than 4.0 dB. Measured insertion loss did change on some devices, though not more than 1.5 dB for thermally cycled units, or not more than 1.7 dB for vibration lot. There was no trend with cycling or vibration. Sometimes the measured value increased and then decreased. Some of the perceived change in loss is probably measurement error. For example, note the increase in measured loss of all units in Lot 5 after the first round of vibration (Appendix A.5). This increase disappears after the second round of vibration after which all loss values return to their initial values within 0.4 dB.

Polarization alignment errors during insertion loss measurement probably caused the variation. Before each insertion loss test, light is launched into one of the optical fibers from the OEIC and the fiber is rotated to align it with the polarization of the optical source. The APE™ waveguides used in the OEIC device pass only one polarization; therefore, it was assumed that when the fiber is rotated for maximum power throughput, alignment has been achieved. Recent experience indicates that the fiber position is sometimes unintentionally translated at the same time this alignment is performed, deceiving the operator as to the proper rotational position for polarization alignment. This error results in a measured value that is higher than actual loss. Procedures have been developed to eliminate this source of error, and are now a part of standard testing procedure.

3) Phase modulation index was always measured to be between 0.8 and 1.0 for all devices that didn't fail electrically. Furthermore, for all but three of those devices, phase modulation index was always measured to be between 0.9 and 1.0 at any point in the reliability testing.

4) Rise and fall times were always measured to be less than 800 psec.

The test results are summarized for all BCM lots:

1) Up until the 1000 hr performance test, at which point optically failed devices were discovered, losses were always less than 6.25 dB except for one device that started at 6.8 dB and then failed from handling. There was a 2.2 dB variation in the measured loss for all BCM units. Note that the control lot also had one device with 1.5 dB variation in measured loss; therefore, the perceived variability is likely to have been caused by the measurement artifact discussed earlier. No trends were observed with exposure time until devices failed.

Several optical failures were observed towards the end of the test schedule and are summarized below:

<u>Lot 2 (60°C / 90% RH):</u>
1) 1 failure between 500 and 1000 hr (loss increased by 6 dB)
2) 1 failure between 1000 and 2000 hr (loss increased by 6 dB)

<u>Lot 3 (75°C / 90% RH):</u>
1) all failed between 1000 and 2000 hr (does not pass light)

<u>Lot 4 (85°C / 90% RH):</u>
1) all failed between 500 and 1500 hr (does not pass light)

Note that the measured loss of one device in Lot 4 increased to 8.9 dB at 250 hr and then returned to 4.8 dB at 500 hr. The fluctuation was probably caused by the measurement error problem discussed earlier.

Opening the packages and examining the epoxy revealed that the cause of these failures was hydrolysis of the epoxy, a chemical reaction between water vapor and the epoxies used inside the package. The epoxy at the pigtail became soft and darkened in color.

2) On/off ratio was always higher than 23 dB for all devices, even those that failed optically, but still passed light. Those that started above 30 dB, remained above 30 dB. There were no trends observed with exposure time.

3) The amount of light coupled out of the waveguide by the DOC varied by as much as 5.6% in the control lot and 8.6% in the other lots; however, DOC failures occurred only on devices exposed to elevated temperature/humidity. The failures are summarized:

Lot 2 (60°C / 90% RH):
1) 1 failure between 1000 and 2000 hr

Lot 3 (75°C / 90% RH):
1) 2 failures between 500 and 1000 hr

Lot 4 (85°C / 90% RH):
1) 1 failure between 124 and 250 hr
2) 1 failure between 31 and 124 hr
3) 1 failure between 31 and 93 hr

4) Half-wave voltage, V_π, was always measured to be below 1.06 V for all BCM devices. No trend was observed for V_π vs. exposure time. In some cases, the measured V_π dropped to abnormally low values. For example, in Lot 2 the V_π was measured to be 0.4 V at 250 hr and then returned to approximately 1.0 V at 500 hr. These dropouts in V_π are likely to be an artifact of measurement. V_π is measured from the relative level of the 3rd order IMP's (Inter-Modulation Products), which are illustrated in Figure 3. The formula used to calculate V_π from the 3rd order IMP, given by Equation 2, assumes an ideal bias point. In that equation, *Vrms* is the RMS voltage of the applied tones and *D* is the level of the 3rd order IMP relative to the main tones. The level of the 3rd order IMP increases when the bias point moves away from the ideal, causing *D* and the measured value of V_π to both decrease. The bias point was off by 76° when V_π was at its measured value of 0.4 V; therefore, the V_π drop is probably a measurement artifact. Another contributor to measurement error is noise which creates uncertainty in the small signals levels of the IMP's. These error sources can be eliminated in the future by using a more direct means of V_π measurement. For example, V_π can be measured at the same time that the modulator extinction measurement is made, by recording the difference in applied voltages for the on and off states.

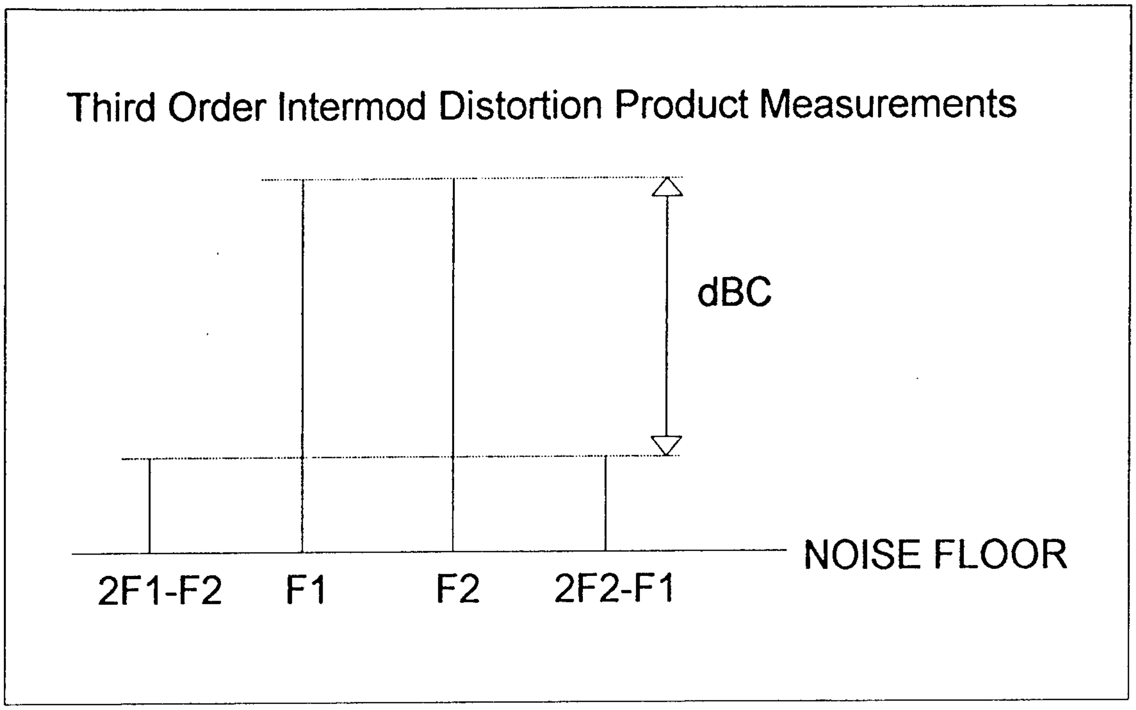


Figure 3: Intermodulation measurement.

$$V_\pi = \frac{\pi \cdot Vrms}{2 \times 10^{-D/40}} \qquad (2)$$

5) The system gain, S_{21}, varied by as much as 11 dB. Variations in S_{21} are likely to be caused by errors in the bias control circuitry, which were discussed earlier. No dramatic changes in gain flatness (S_{21} vs. frequency) were observed.

6) The electrical return loss, S_{11}, always remained between -8 and -9.2 dB.

4.0 MEAN TIME BETWEEN FAILURE (MTBF) ANALYSIS

The only optical or electrical failures of significance are those occurring from exposure to elevated temperature/humidity. The epoxy used to bond the fiber pigtail to the OEIC degraded causing optical failure of the device. An MTBF was estimated for optical failure of the BCM device. An MTBF was not estimated for the DOC since data on DOC failures is incomplete. Testing was stopped on devices once they failed optically. It is not possible to test the operation of the DOC once the pigtails have failed and light cannot be made to enter the device.

The optical failures were assumed to follow an Arrhenius model for thermally activated processes. It should be noted that this simple model maybe an oversimplification of the failure mechanism. The BCM optical failure may occur in two steps, the first being package seal failure; the second being pigtail failure. In this case, the overall MTBF is simply the sum of the MTBF's corresponding to seal failure and pigtail failure. The epoxies used for package sealing and pigtailing are different and are likely to have different MTBF and activation energies. If one step occurs much faster than the other than the MTBF will be approximately determined by the activation energy of the slower process. It is possible that in the temperature range where testing was performed, one process (say package seal failure) is the slower step, while at room temperature the other step (say pigtail failure) is the slower step. As can be seen in Figure 4, extrapolating to room temperature can lead to an erroneous result; however, the error creates an MTBF that is more conservative (shorter) than actual. In this analysis, it was not possible to separate seal failure MTBF from pigtail failure MTBF; therefore, one activation energy was used in the model.

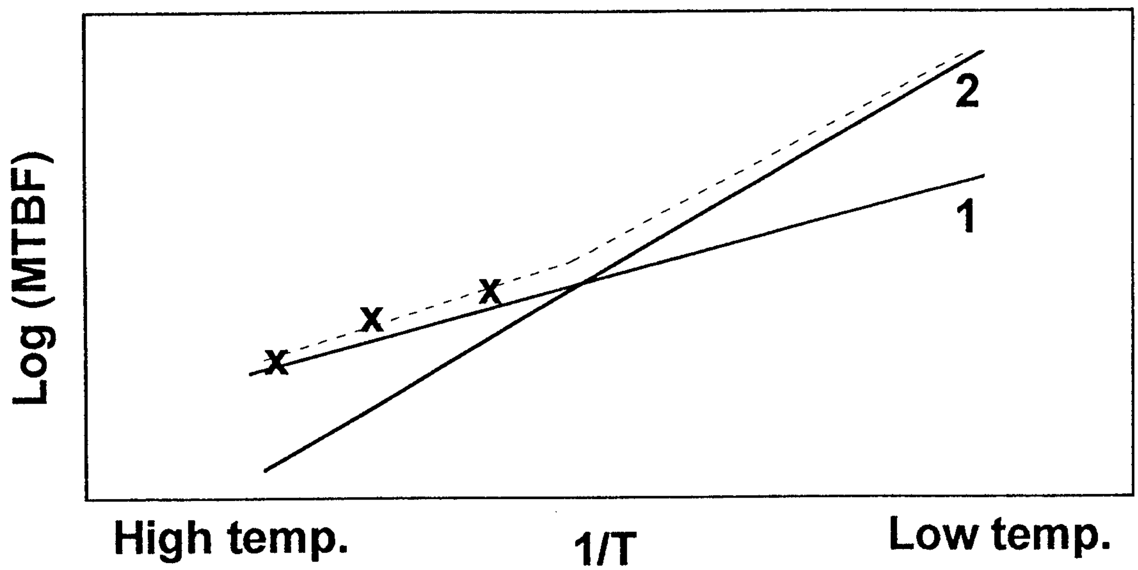


Figure 4: Illustration of two step failure mechanism. Solid lines represent Arrhenius plots of actual MTBF for each failure mechanism. Dashed line represents overall MTBF, which is sum of MTBF's from each step. Crosses represent measured data from which extrapolations are made.

Another potential source of error in the MTBF calculation is the Arrhenius model itself. The mechanism of degradation, hydrolysis of the epoxy, is a complex chemical reaction which may not fit the simple Arrhenius model all the way to room temperature.

Ideally, the exact time of failure would be known for each device, in which case the times could be averaged to provide a measured MTBF. The performance parameters were measured at periodic intervals, hence the uncertainty in time of failure equals the time interval between measurements. In Lot 2, 2 out of 5 devices or 40% of the units failed between 1000 and 2000 hr. Restating another way, 60% of the devices survived 2000 hr. If it is assumed that the distribution of failures with exposure time is symmetric about the MTBF, then the MTBF for Lot 2 is longer than 2000 hr. Without further data it is difficult to determine the exact MTBF for Lot 2; therefore, its MTBF was assumed to be 2000 hr. In Lot 3, which was exposed to 75°C / 90% RH, all devices failed between 1000 and 2000 hr. The devices of Lot 4, which were exposed to 85°C / 90% RH, failed between 500 and 1500 hr.

The MTBF can be estimated at lower temperatures, by making an Arrhenius plot of the data, performing a least squares straight line fit, and extrapolating the least squares fit to lower temperatures. Uncertainty in measured MTBF at the higher temperatures can have a dramatic impact on the estimated MTBF; therefore, the extrapolation is performed for two extreme cases. Case #1 uses the minimum values for MTBF for Lots 3 and 4, whereas Case #2 uses the maximum values for those lots. It should be noted that the uncertainty in the MTBF at 75°C / 90% RH actually has a minor effect on the least squares fit, influencing the value at 25°C by less than 1%. The estimated MTBF at lower temperatures is mainly influenced by the values assumed for Lots 2 and 4. Figure 5 contains the Arrhenius plots of the MTBF data including the least squares fits. The measured and straight line fit MTBF are given in Tables 12 and 13 for the two cases and the activation energies are listed in Table 14. The MTBF from 25°C to 85°C is plotted in Figure 6. Note that the uncertainty in measured MTBF at higher temperatures creates large uncertainty in the estimated MTBF at lower temperatures. For example, MTBF at 25°C / 90% RH is estimated to be between 3200 hr and 20600 hr (2.3 yr).

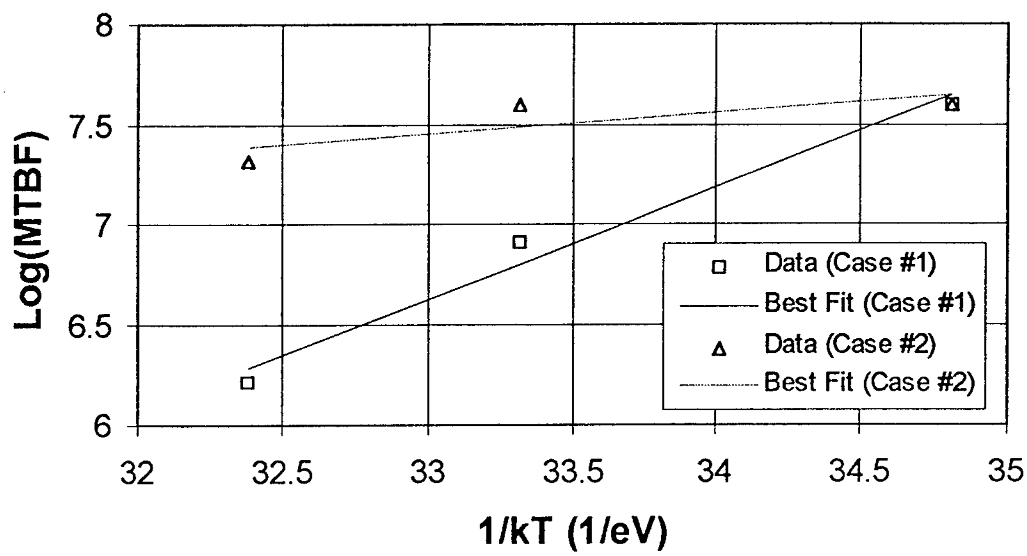


Figure 5: Arrhenius plot of MTBF data and least squares straight line fit. Case #1 and #2 use minimum and maximum possible values MTBF at high temperature, respectively.

Table 12: MTBF data and least squares fit (case #1: maximum possible MTBF at 25°C / 90% RH)

LOT #	TEMP./RH	MEASURED MTBF (hr)	LEAST SQUARES FIT MTBF (hr)
4	85°C / 90% RH	500	534
3	75°C / 90% RH	1000	899
2	60°C / 90% RH	2000	2083
----	25°C / 90% RH	----	20563 (2.3 yr)

Table 13: MTBF data and least squares fit (case #2: minimum possible MTBF at 25°C / 90% RH)

LOT #	TEMP./RH	MEASURED MTBF (hr)	LEAST SQUARES FIT MTBF (hr)
4	85°C / 90% RH	1500	1612
3	75°C / 90% RH	2000	1781
2	60°C / 90% RH	2000	2091
----	25°C / 90% RH	----	3240

Table 14: Activation energy of MTBF

Case #1	0.56 eV
Case #2	0.11 eV

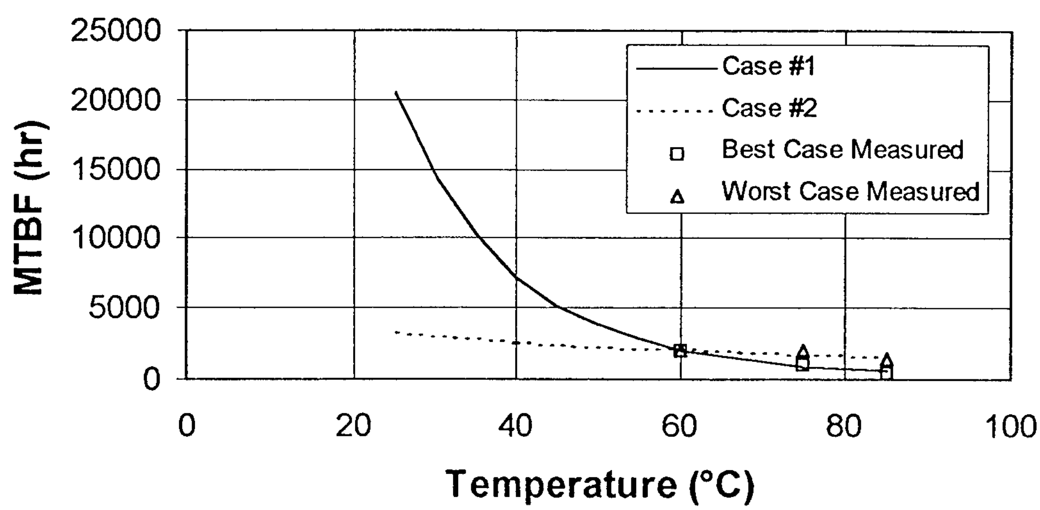


Figure 6: Plot of estimated MTBF at 90% RH for case #1 and #2, two extremes of possible values for MTBF, along with measured data. See text for explanation of large uncertainty in estimated MTBF at low temperatures.

The statistical impact of the small number of devices in each lot needs to be addressed. If the failure time for each device was accurately known, the distribution of failures with time would also be known, allowing an uncertainty in each measured MTBF to be determined. Given the small lot sizes and large time between measurements, this issue can only be addressed qualitatively. All of the devices in Lots 3 and 4 went from completely functional, with no detectable loss, to completely non-functional, that is, not passing light. The similarity of behavior suggests that the statistical effect of small lot size is much smaller than the uncertainty caused by the large sampling interval (1000 hr). It is possible that all the failures occurred abruptly over a period of a few hundred hours or less. Stated differently, increasing the size of the lots would not have changed the result much. All would have been functional at the start of the exposure period. All would have failed at the end. Lot 2 behaved differently in that the degradation occurred more gradually. One failure took place between 500 and 1000 hr and another failure occurred between 1000 and 2000 hr. The failures are likely to occur over a much larger period of time, perhaps 1000 hr. The impact on MTBF is significant. An uncertainty of 500 hr in the MTBF for Lot 2 translates into a factor of 2 uncertainty in the MTBF at 25°C / 90% RH.

5.0 CONCLUSIONS

Thermal cycling and vibration testing did not cause any optical failures, an indication that screening procedures are adequate. The only infant mortalities discovered were the cracked ceramic electrical boards in the ECL modulators. These failures do not represent a serious reliability problem for OEIC's, because electrical boards made from other materials can be used in place of ceramic.

The only serious failure mechanisms that were uncovered were epoxy failures in the package due to the effects of elevated levels of temperature and humidity. These include epoxies used for pigtailing as well as those used for the DOC. The MTBF of optical failure of the BCM device was estimated to be between 3200 hr and 20600 hr (2.3 yr) at 25°C and 90% RH, though, a clearer understanding of the failure mechanism is needed to validate the model used for MTBF extrapolations.

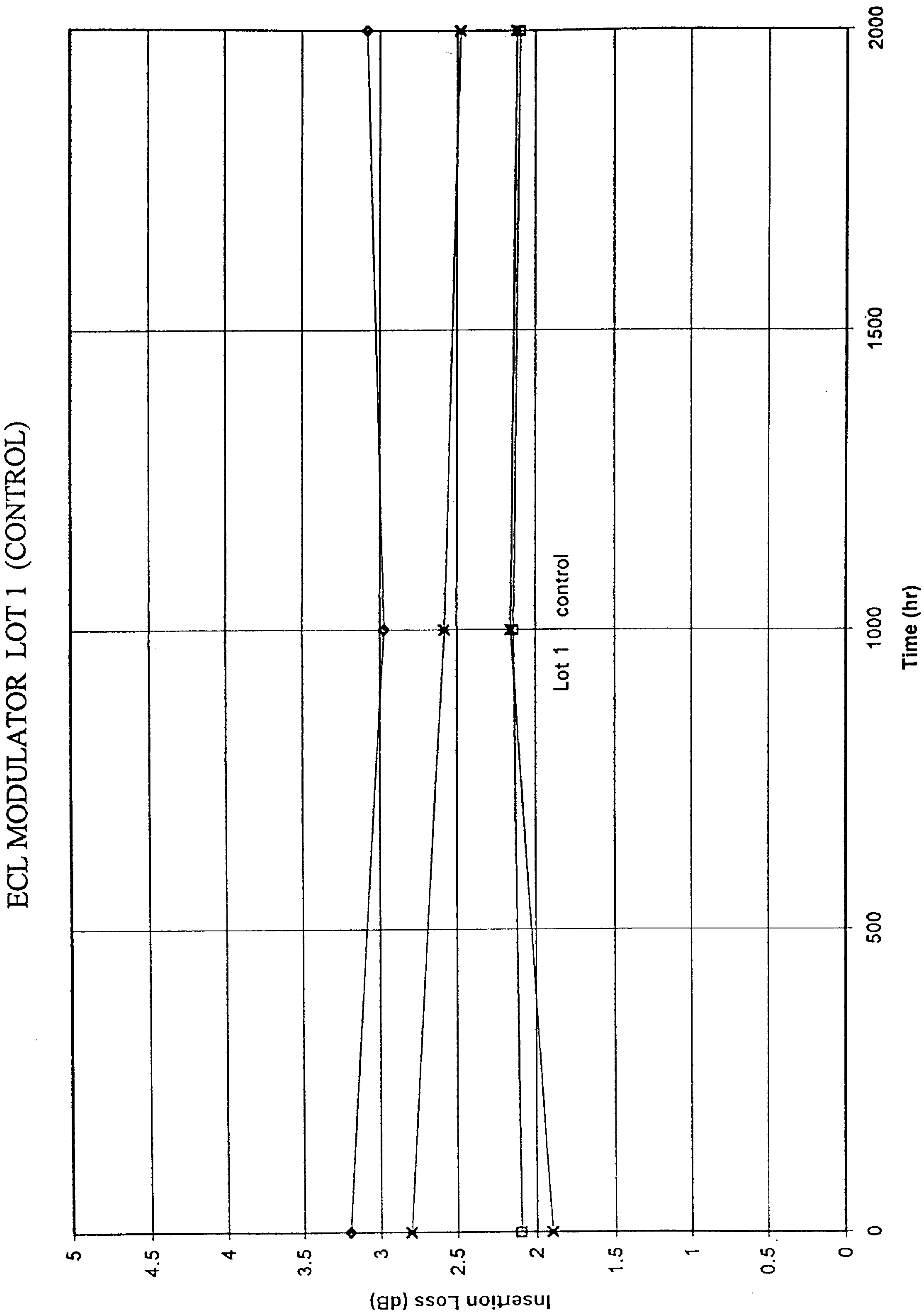
The MTBF can be increased dramatically through several simple improvements in fiber and cover seals. Laser welding package covers can eliminate leaks around the cover. Newly developed humidity resistant fiber seals have survived for longer than 2000 hr at temperature and humidity levels of 100°C and 100% RH, while maintaining a leak rate of 6×10^{-9} cc/sec of He. They already have surpassed the lifetime of the fiber seals used in this program by a factor of two, while being subjected to extreme environmental conditions. In addition to better fiber and cover seals at the package, using a re-coated splice to attach the fiber ends to other optical components can eliminate the fiber buffer/glass interface as a path for humidity intrusion.

Some improvements can be made to the testing procedures for any future tests of OEIC devices. The large uncertainty in MTBF values for optical failure can be reduced by reducing the performance testing interval or by making *in-situ* measurements in which insertion loss is monitored at all times during exposure. However, *in-situ* measurements would require the ends of the fiber to be in a benign environment, potentially eliminating a path for humid air to enter the package. Having the fiber ends in the environmental chamber during exposure makes the test a worst case scenario for reliability.

Elevated temperature/humidity testing over a wider range of temperature can increase the level of confidence in the Arrhenius model for optical failure. Leak testing the package at every performance test may show a correlation between package seal failure and pigtail failure, in order to determine which failure is most relevant to MTBF estimations. Tests at different humidity levels can be used to develop an empirical model for MTBF vs. humidity.

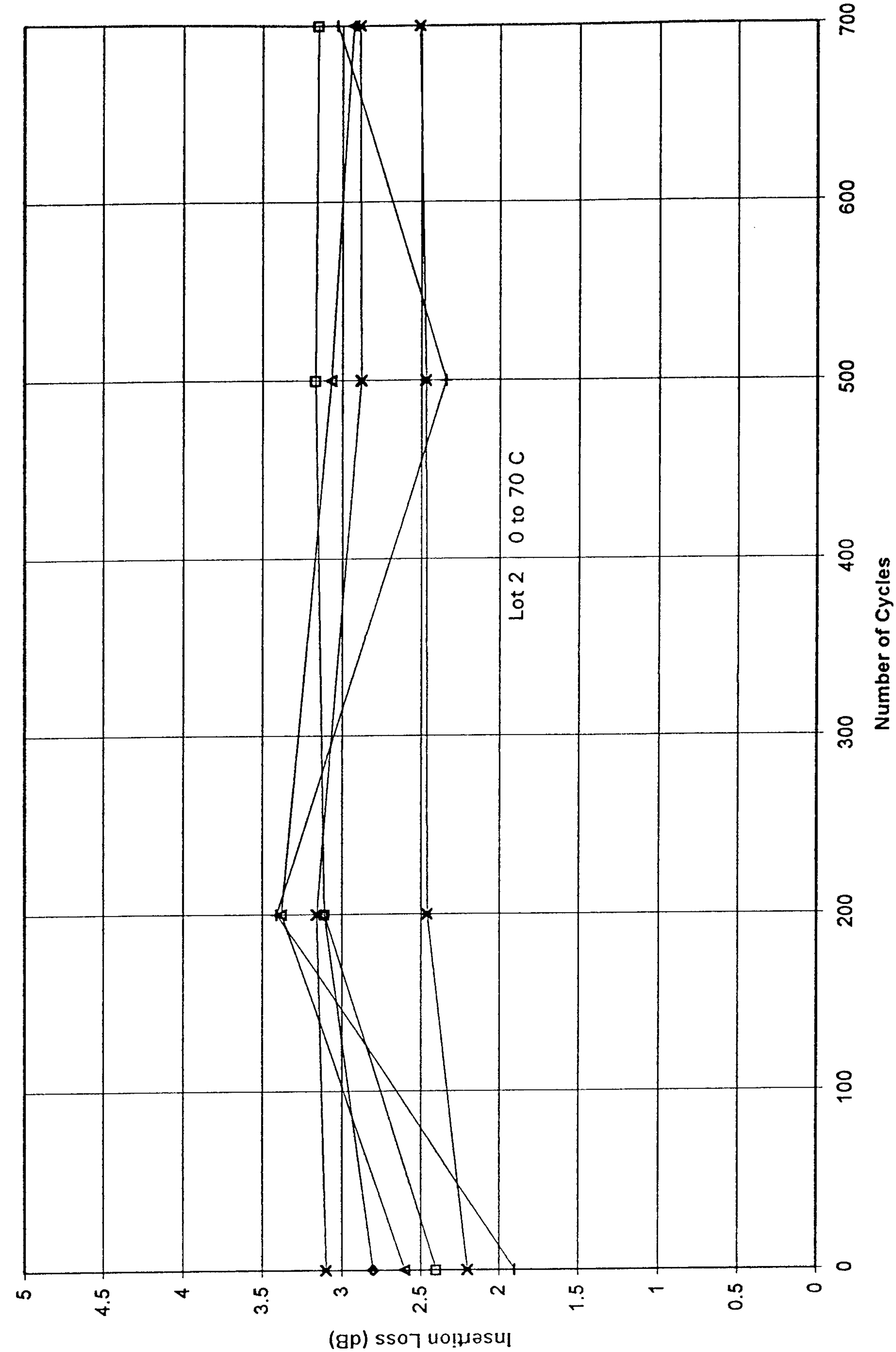
V_π should be measured directly when the modulator extinction is determined. Deducing V_π from 3rd order IMP's introduces errors that cause the measured value to be smaller than it really is.

Careful attention must be paid to polarization alignment of fiber with optical source when making insertion loss measurements. Errors in alignment cause the measured value to be larger than actual.


ECL MODULATOR LOT 1 (CONTROL)
Insertion Loss (dB)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Time (hr)
0
500
1000
1500
2000
Lot 1 control

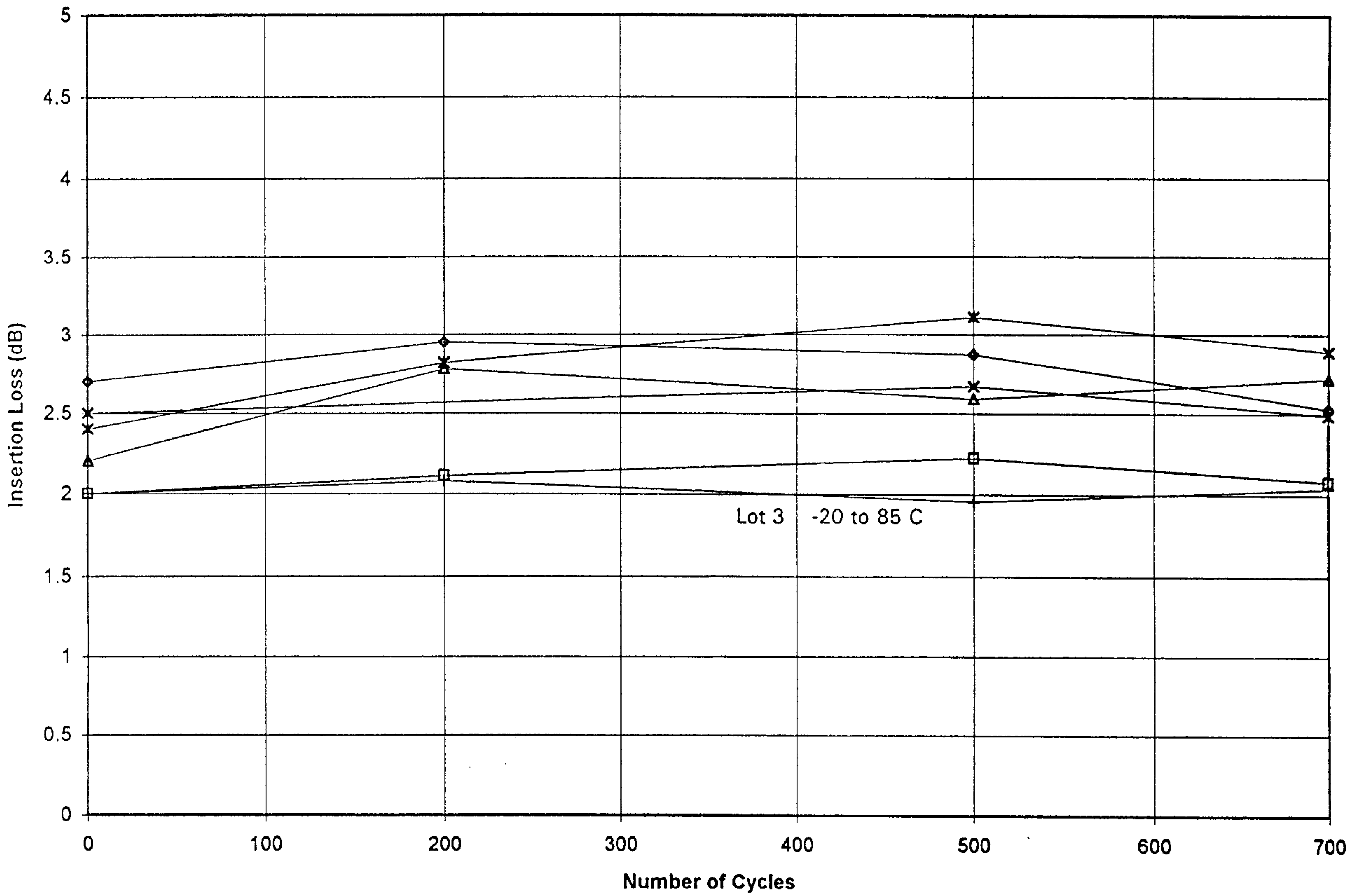
Appendix A.1

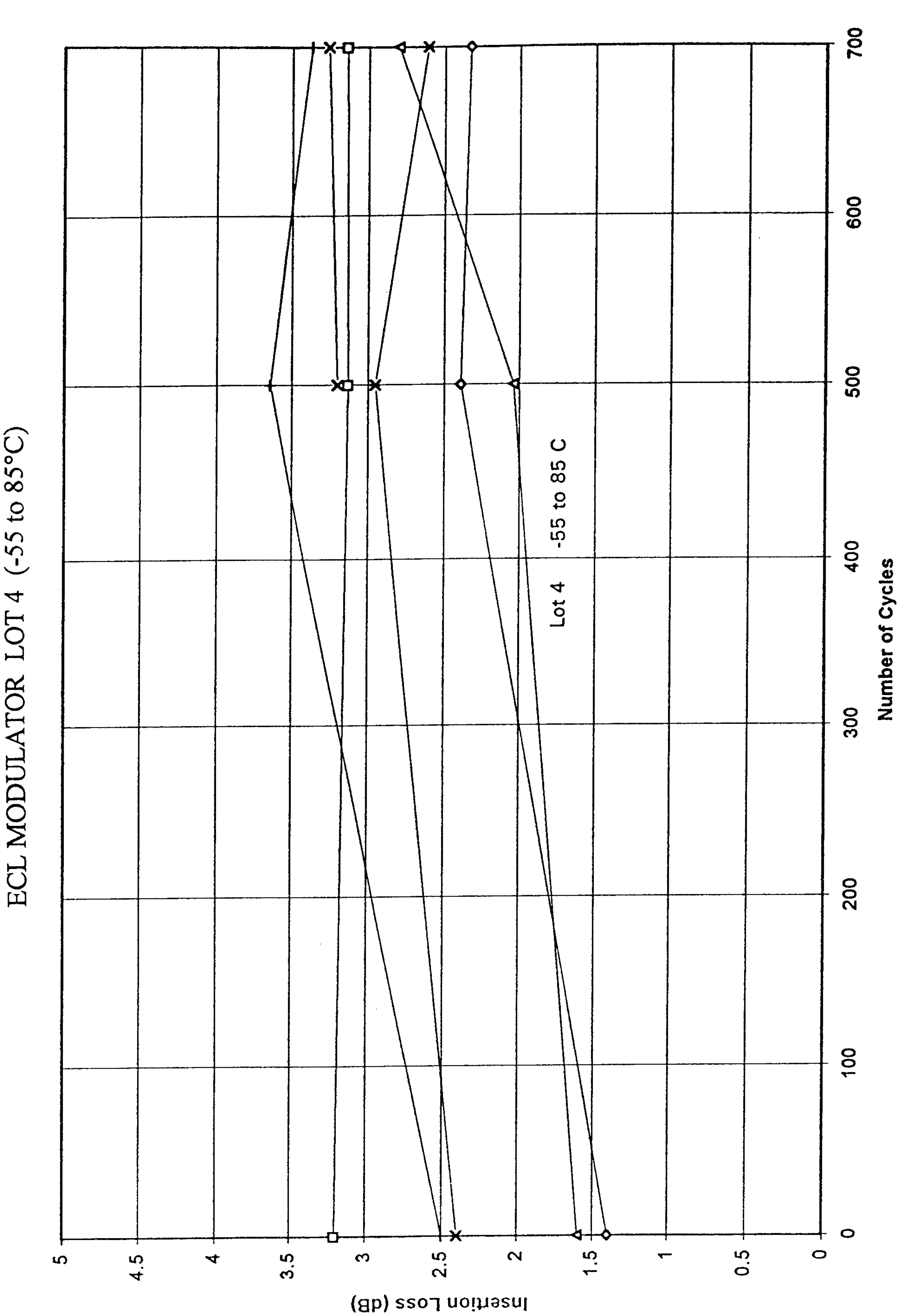
ECL MODULATOR LOT 2 (0 to 70°C)



Appendix A.2

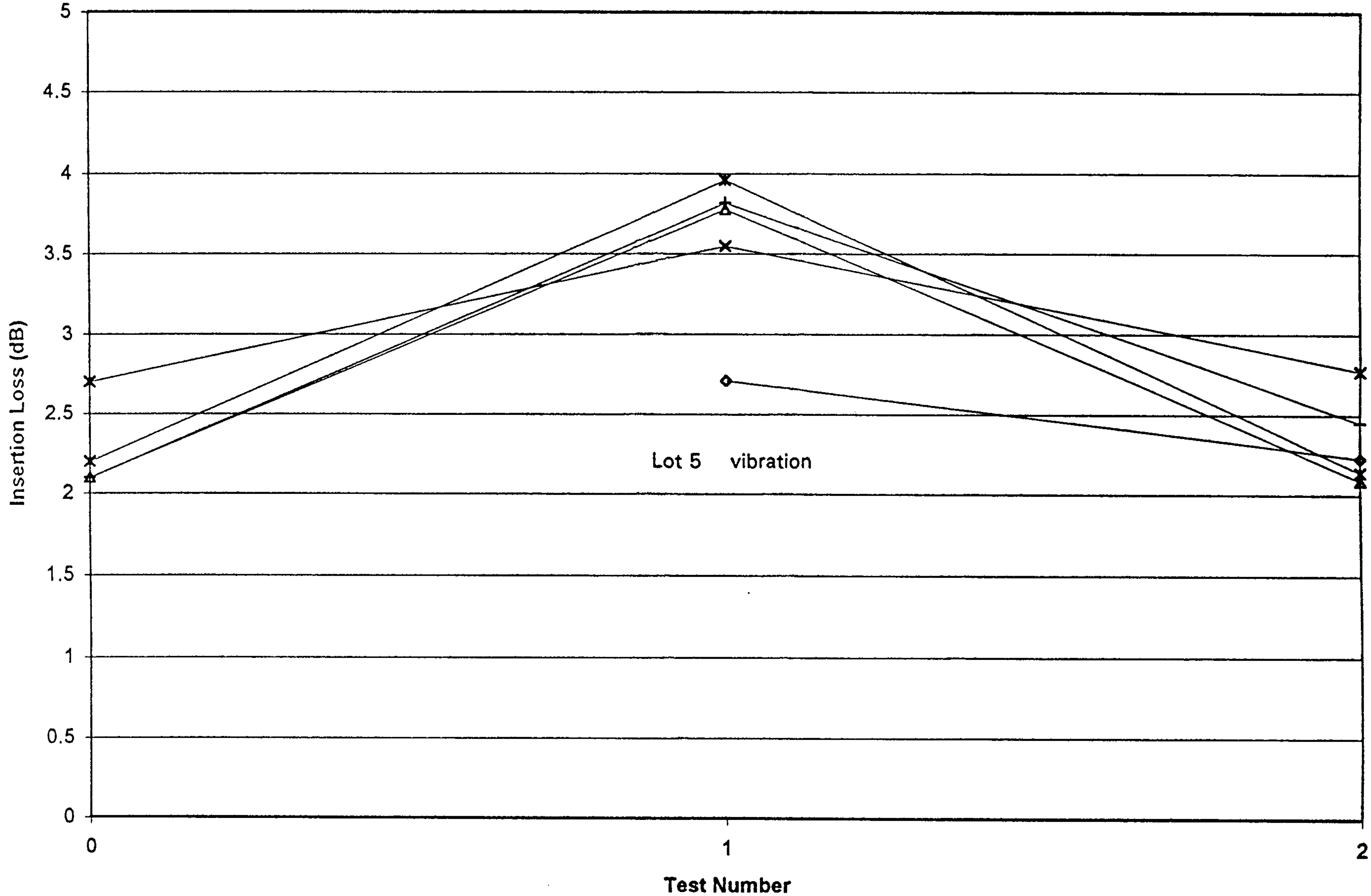
ECL MODULATOR LOT 3 (-20 to 85°C)



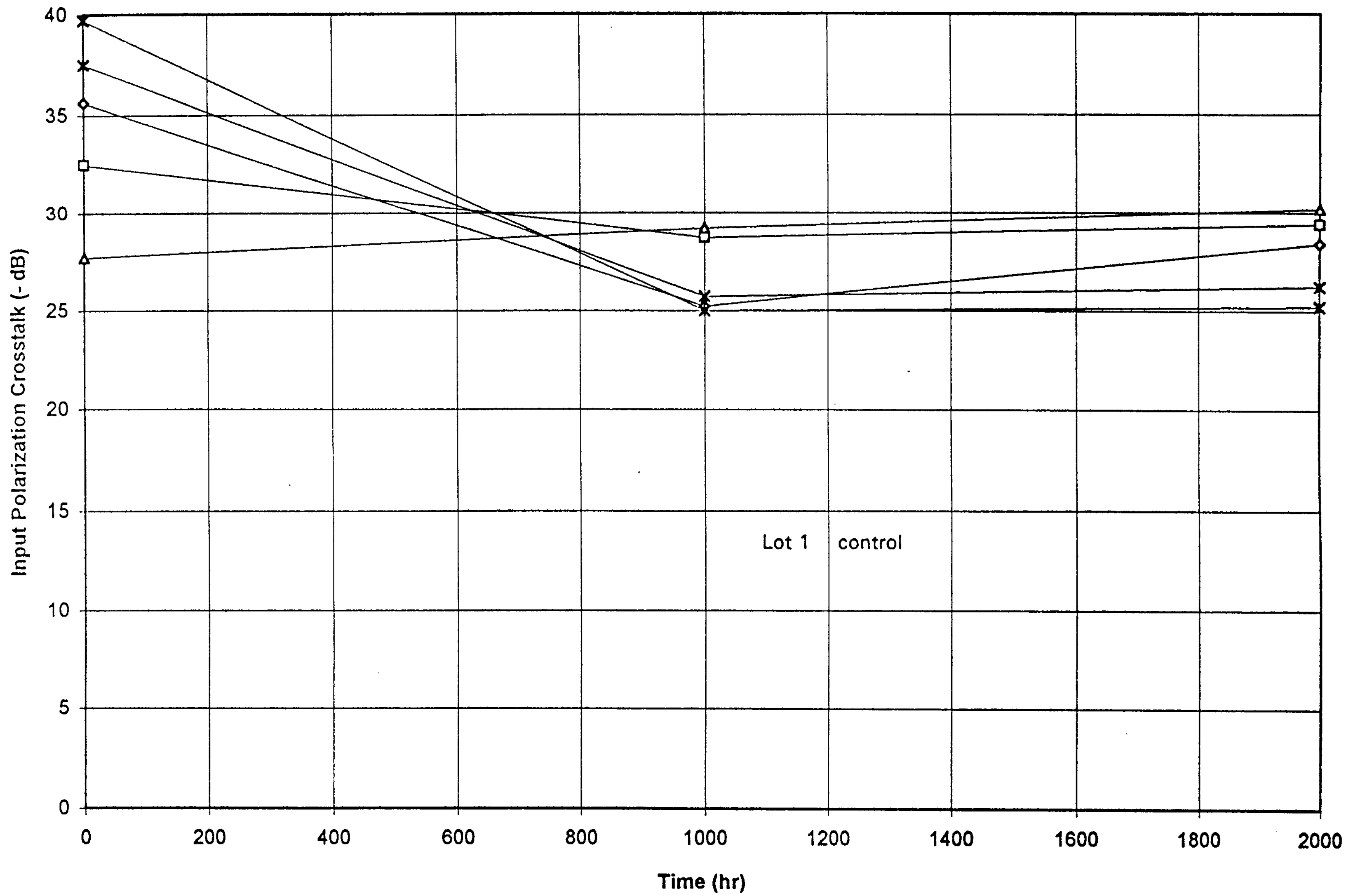


ECL MODULATOR LOT 4 (-55 to 85°C)
Lot 4 -55 to 85 C
Insertion Loss (dB)
Number of Cycles
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
100
200
300
400
500
600
700

ECL MODULATOR LOT 5 (VIBRATION)

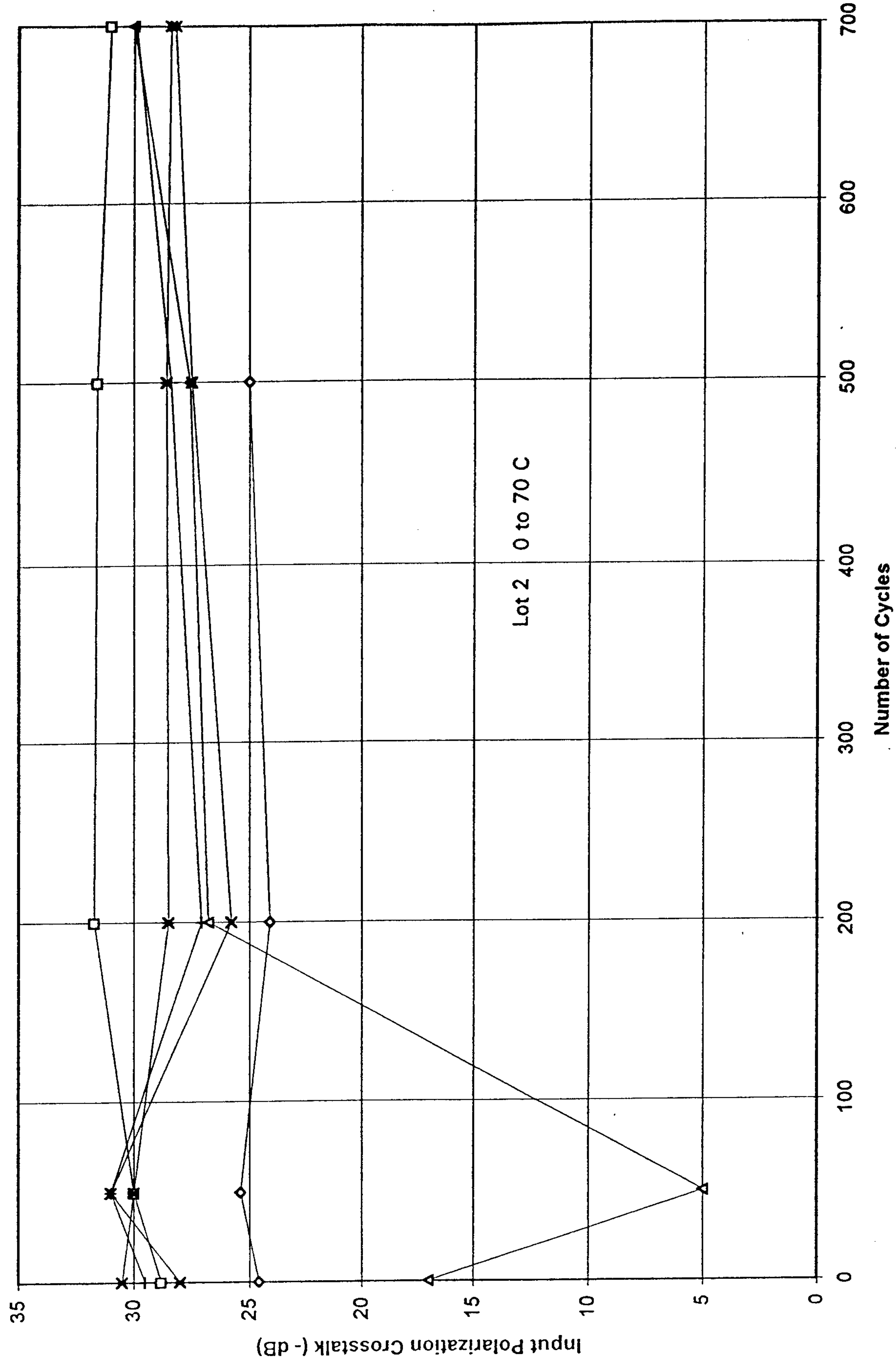


ECL MODULATOR LOT 1 (CONTROL)

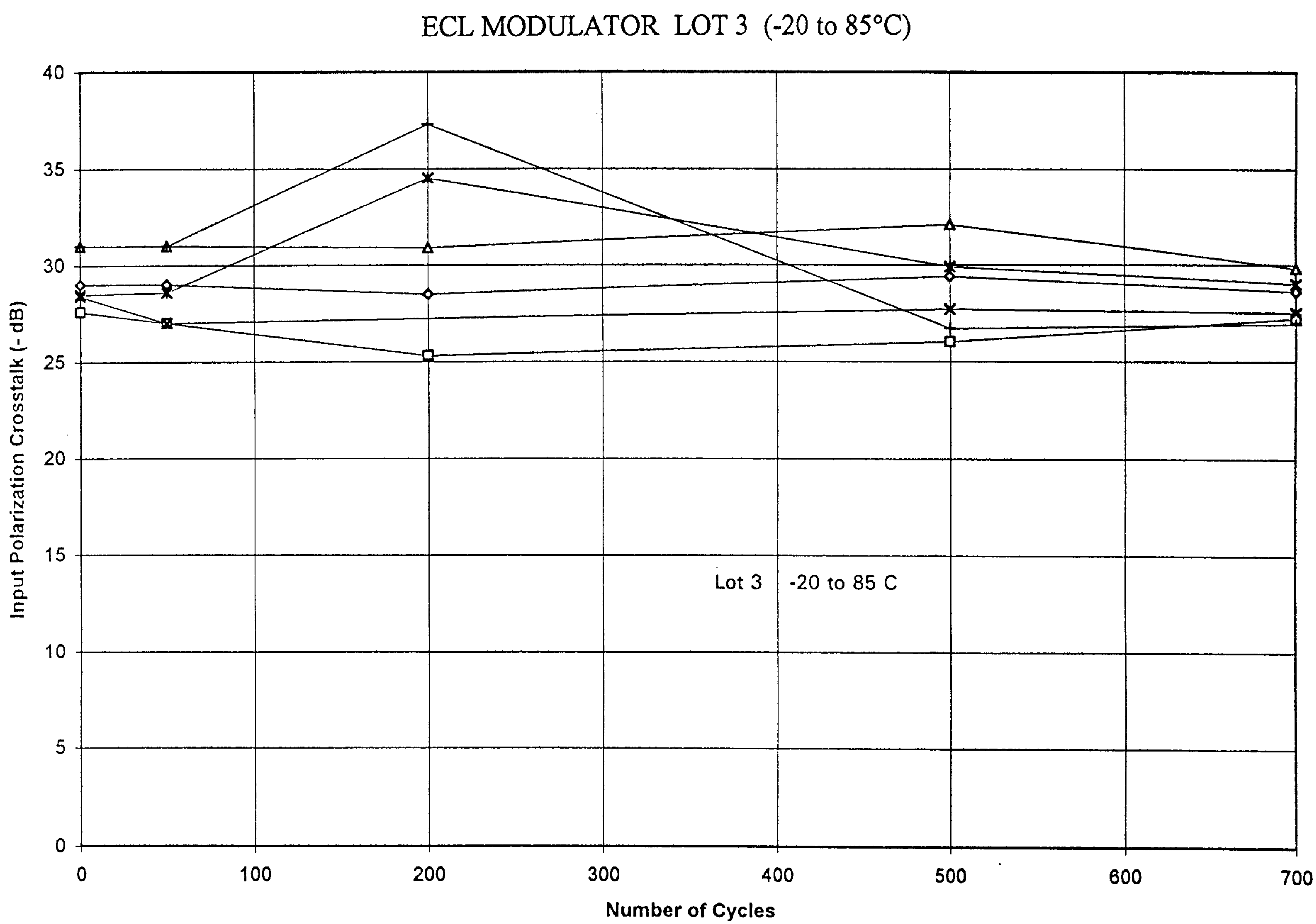


Appendix B.1

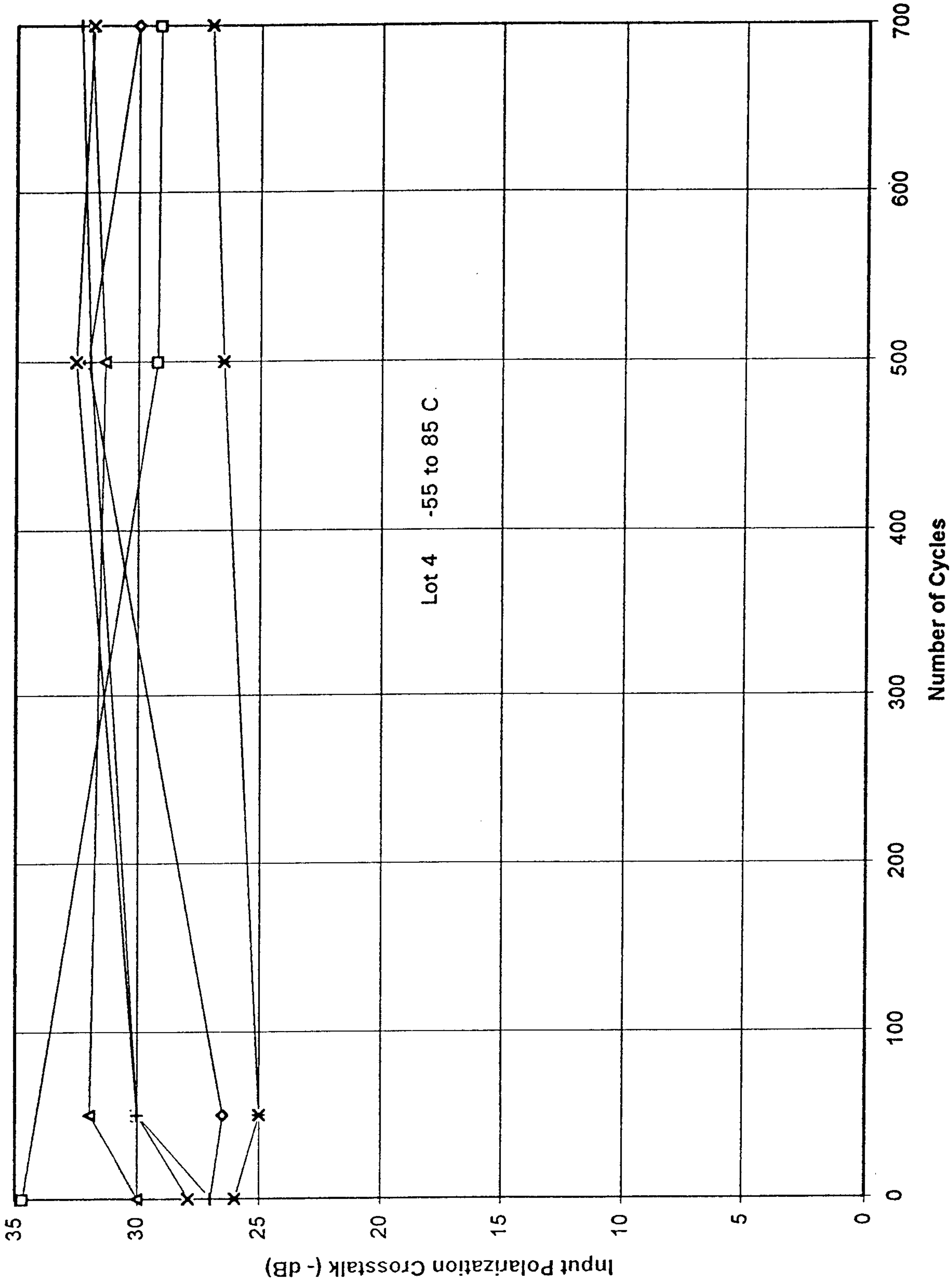
ECL MODULATOR LOT 2 (0 to 70°C)



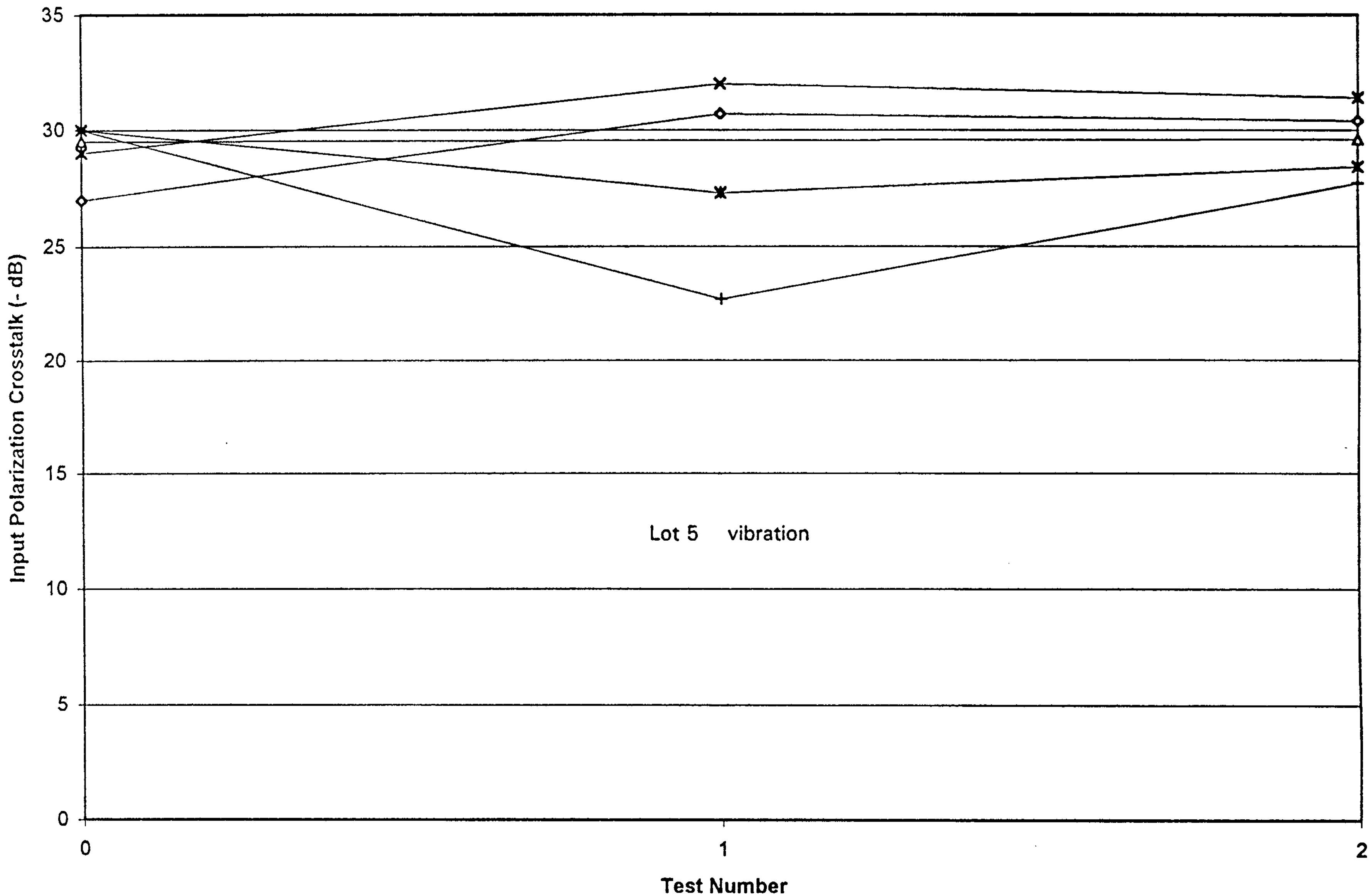
Appendix B.2


ECL MODULATOR LOT 3 (-20 to 85°C)
Input Polarization Crosstalk (- dB)
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
Number of Cycles
Lot 3 -20 to 85 C

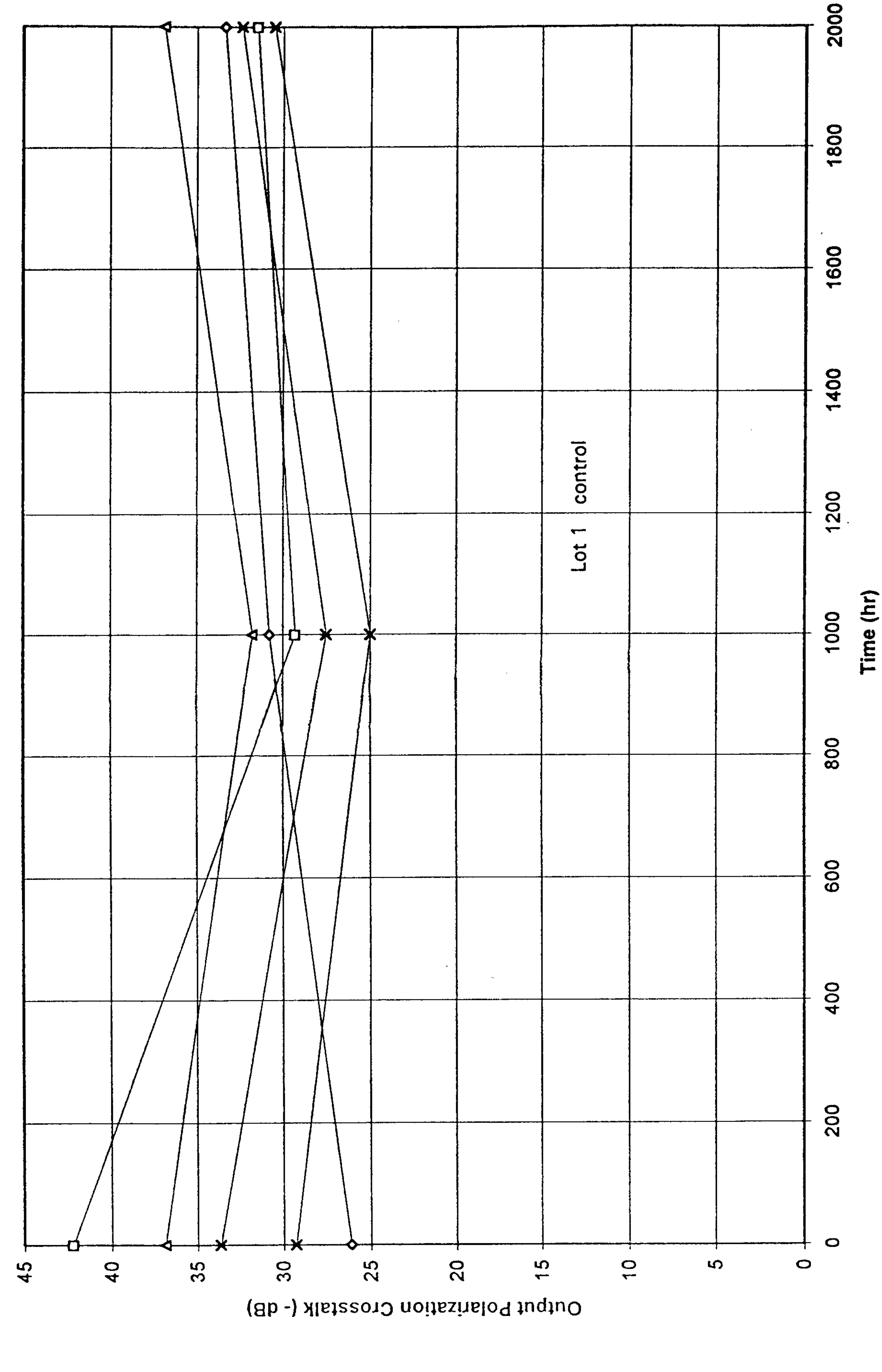
ECL MODULATOR LOT 4 (-55 to 85°C)



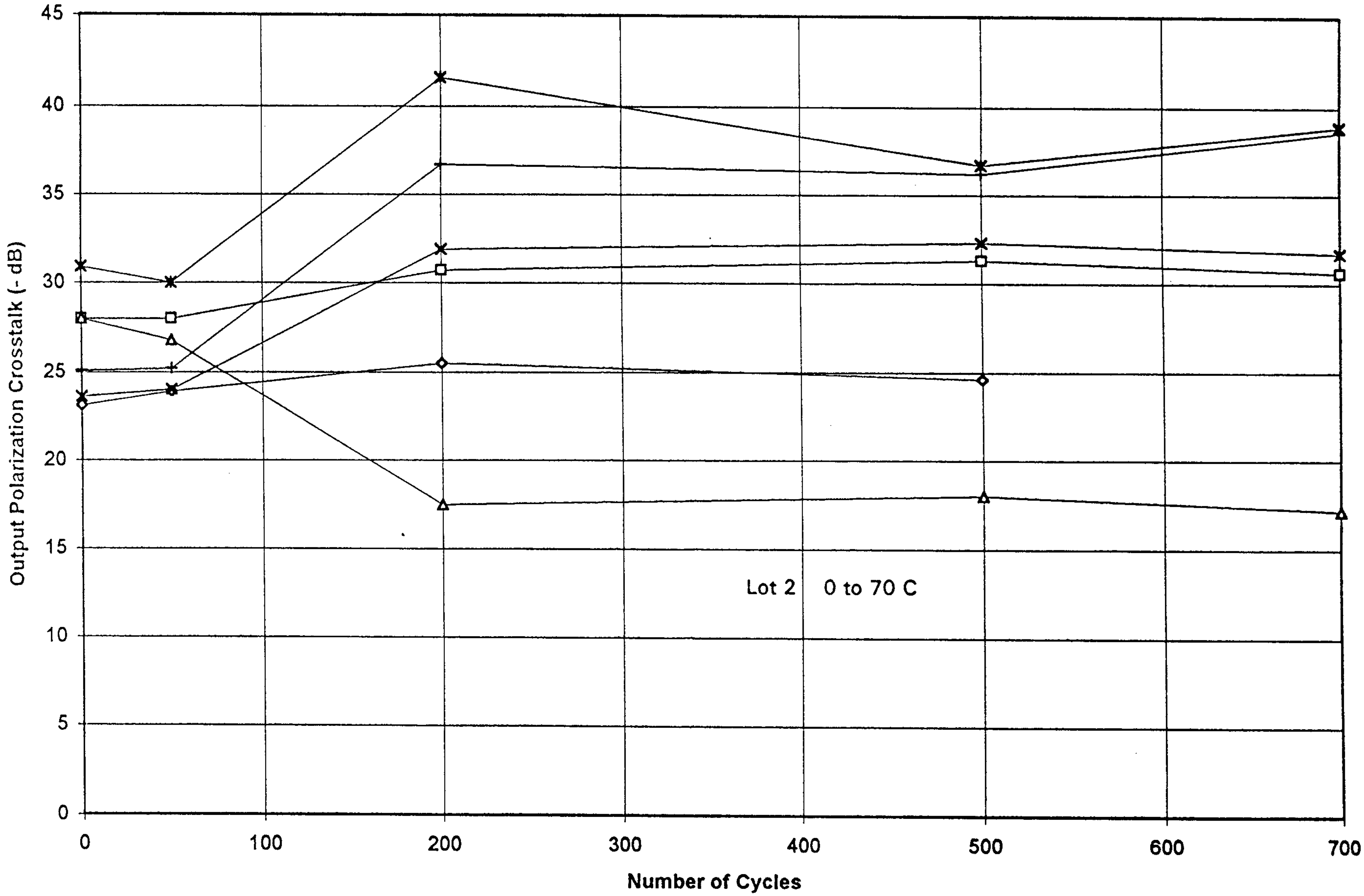
ECL MODULATOR LOT 5 (VIBRATION)

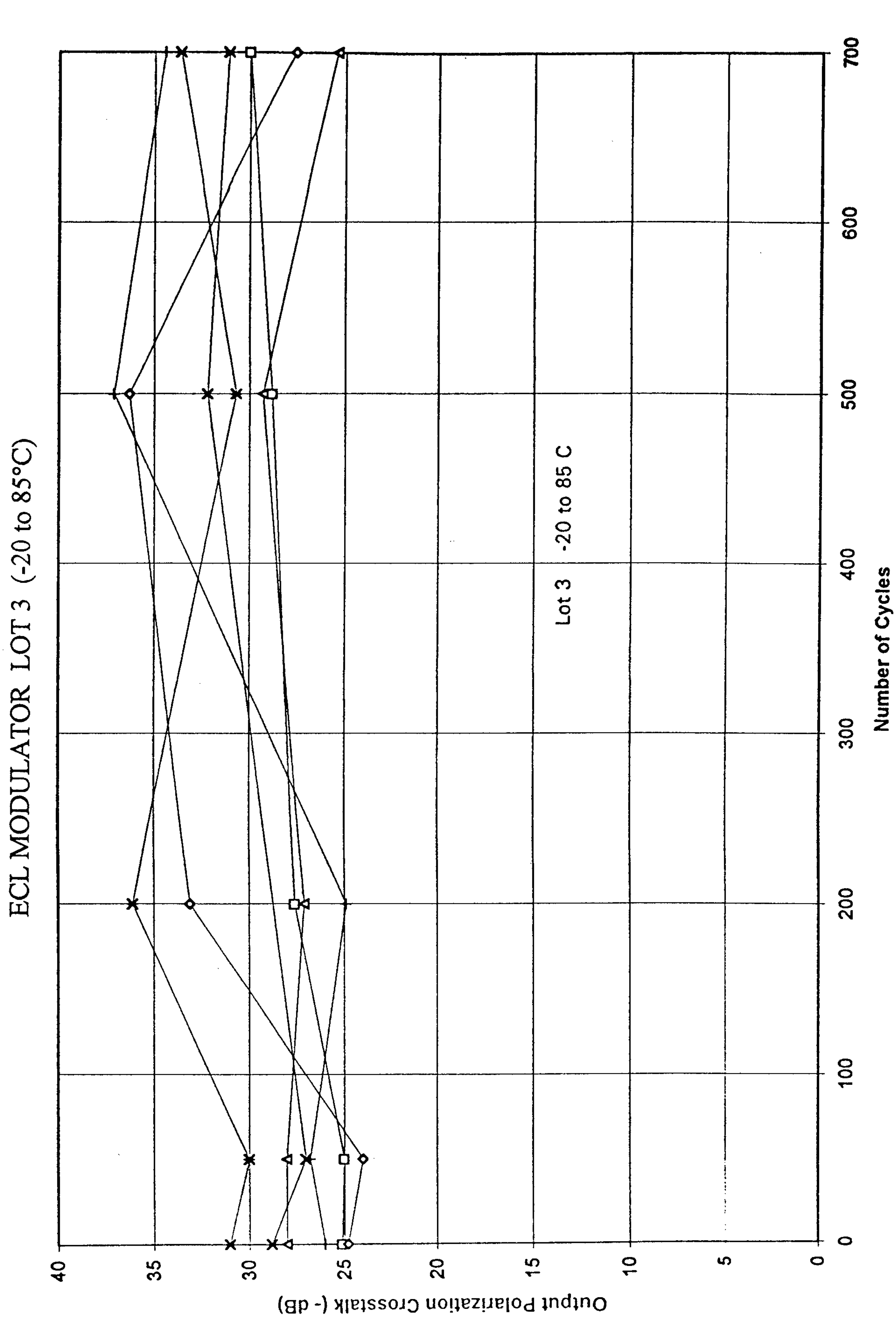


ECL MODULATOR LOT 1 (CONTROL)



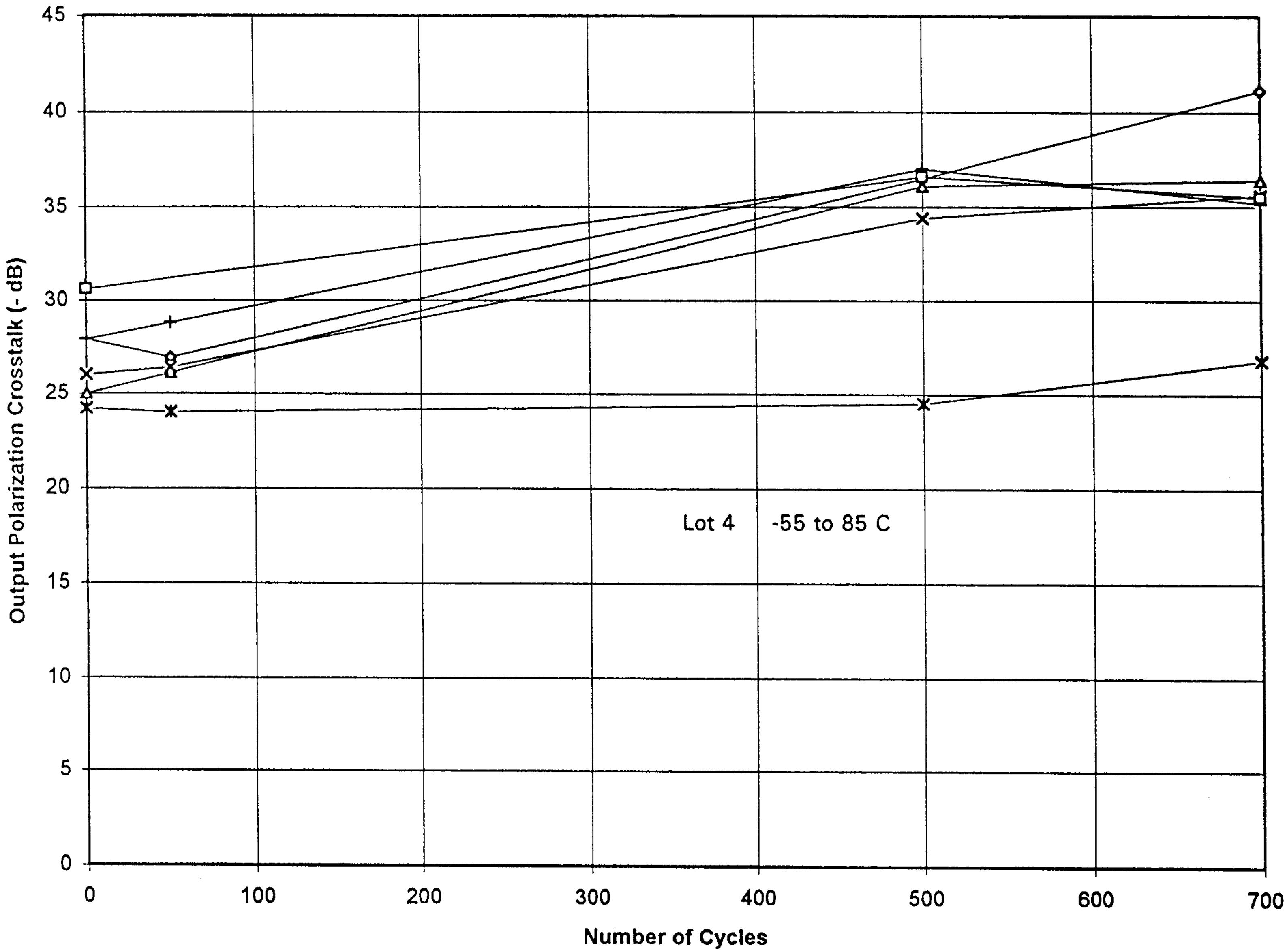
ECL MODULATOR LOT 2 (0 to 70°C)



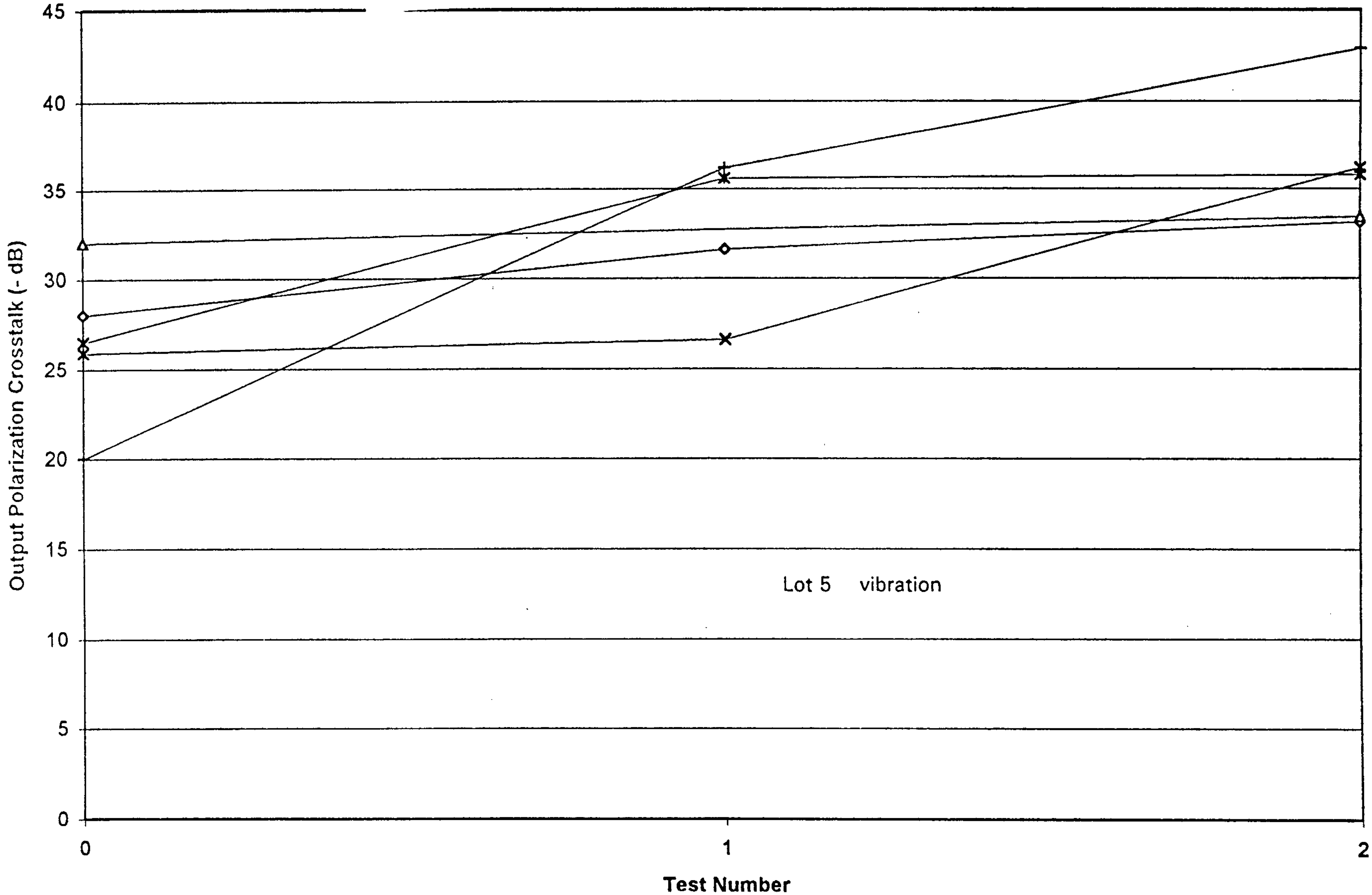


ECL MODULATOR LOT 3 (-20 to 85°C)
Lot 3 -20 to 85 C
Output Polarization Crosstalk (- dB)
Number of Cycles
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
700

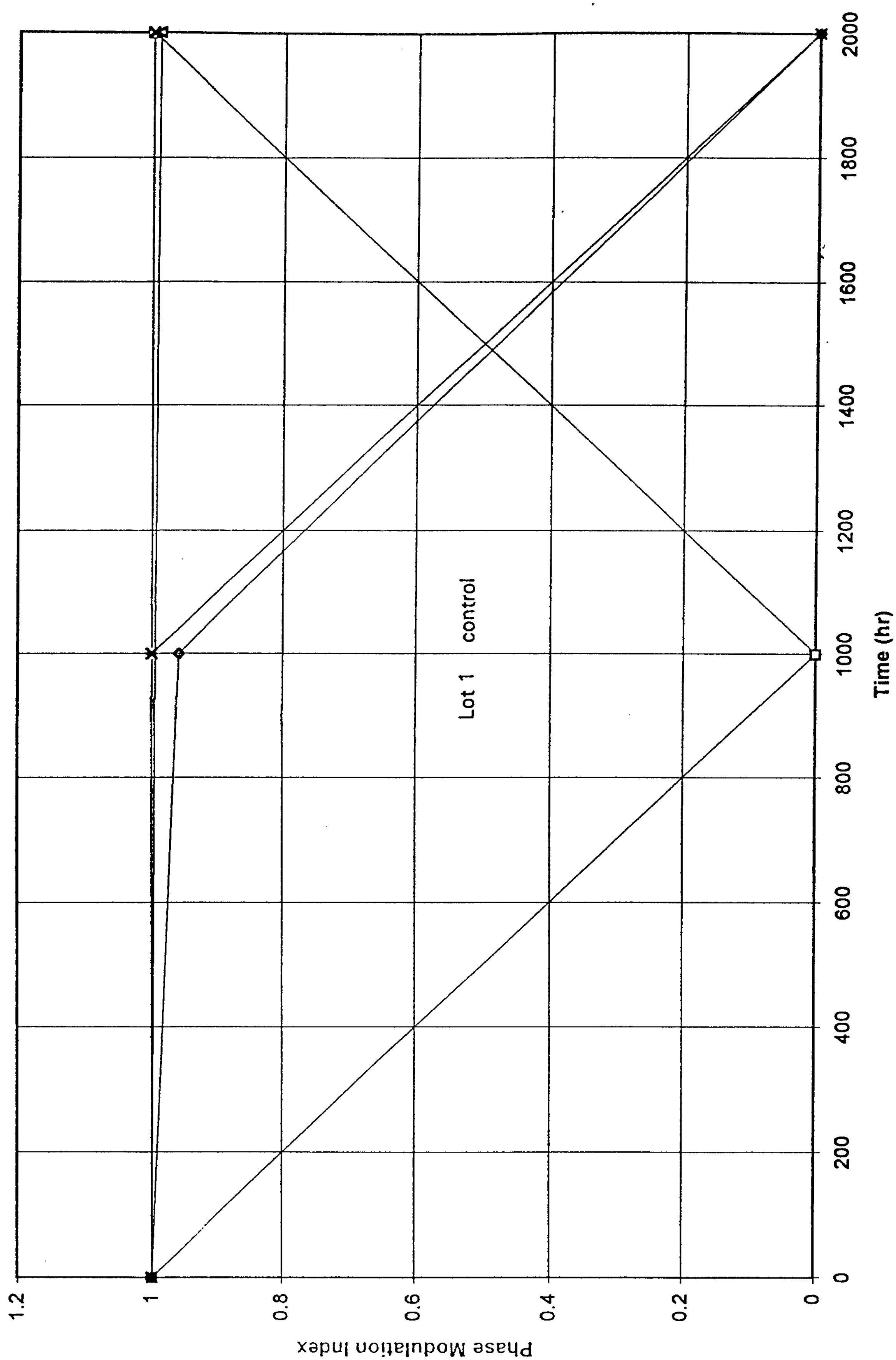
ECL MODULATOR LOT 4 (-55 to 85°C)



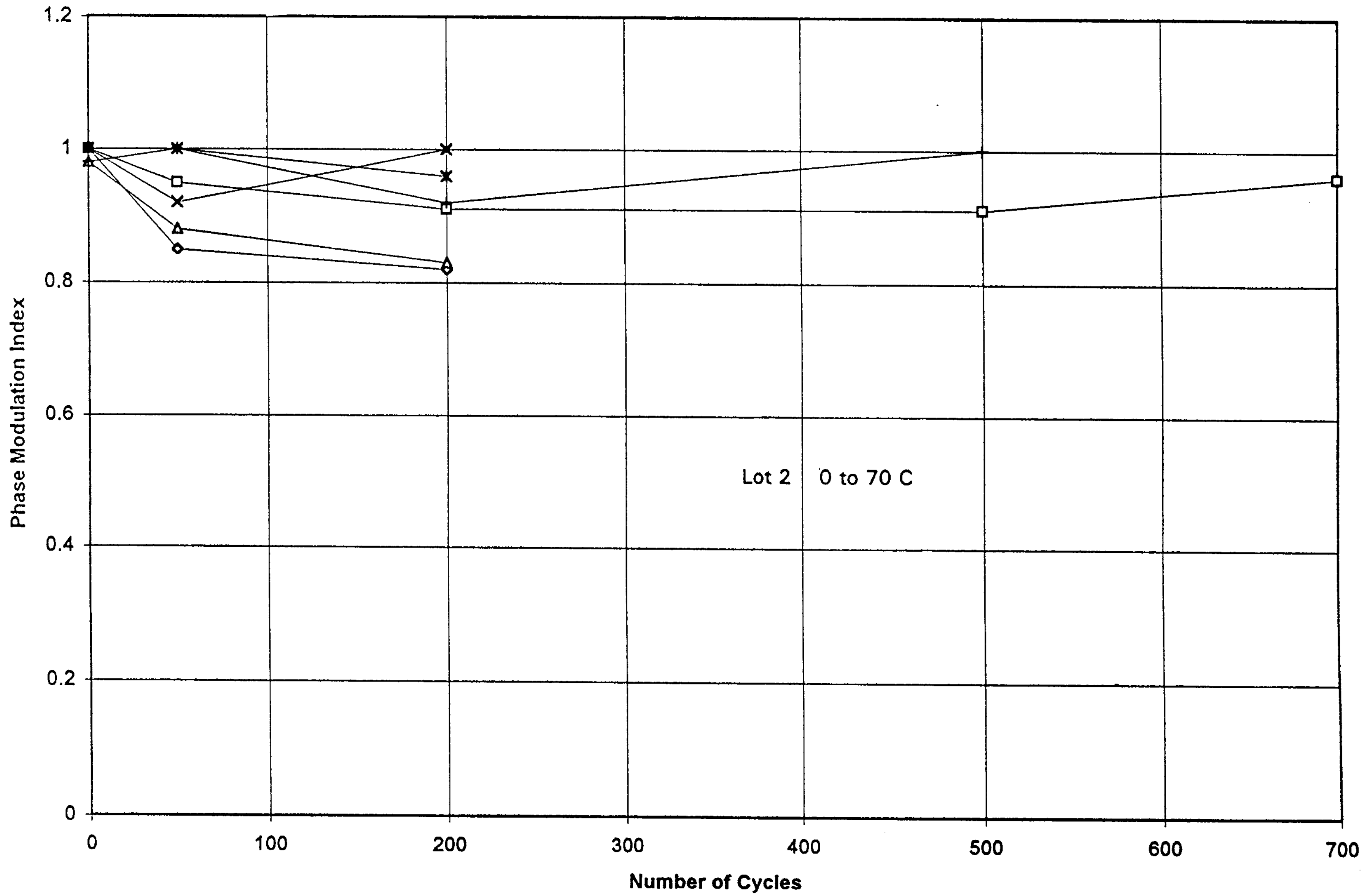
ECL MODULATOR LOT 5 (VIBRATION)



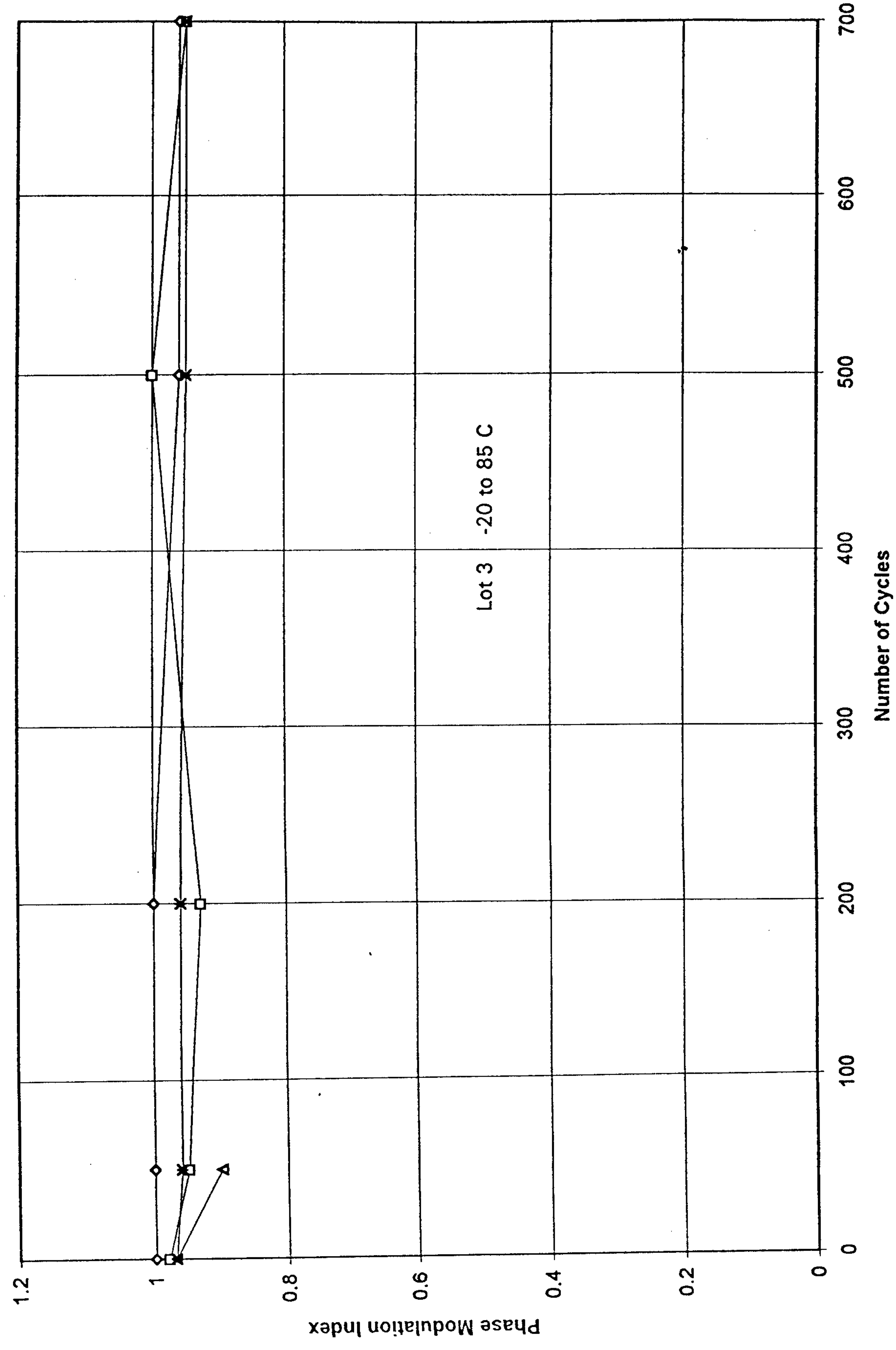
ECL MODULATOR LOT 1 (CONTROL)



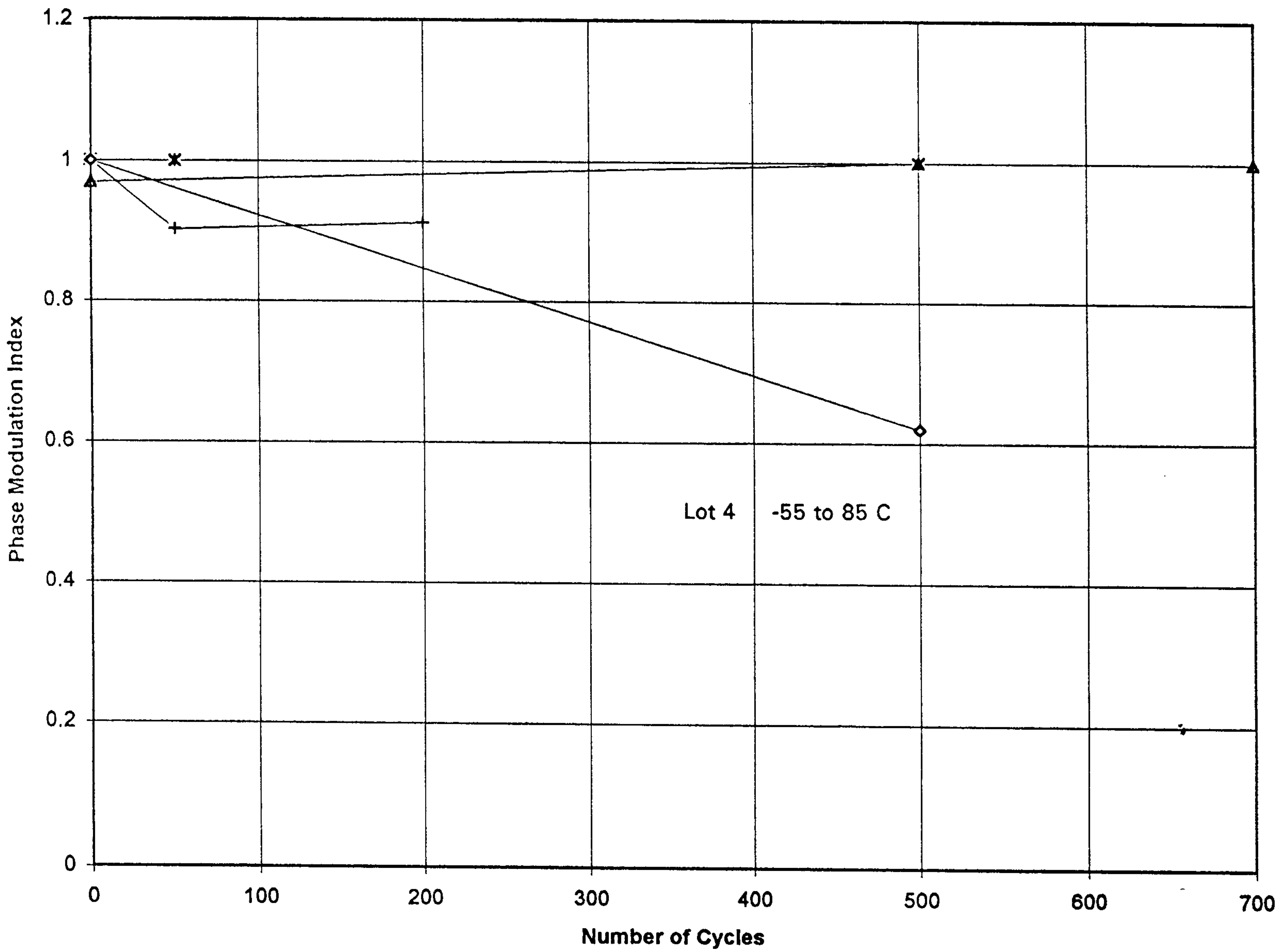
ECL MODULATOR LOT 2 (0 to 70°C)



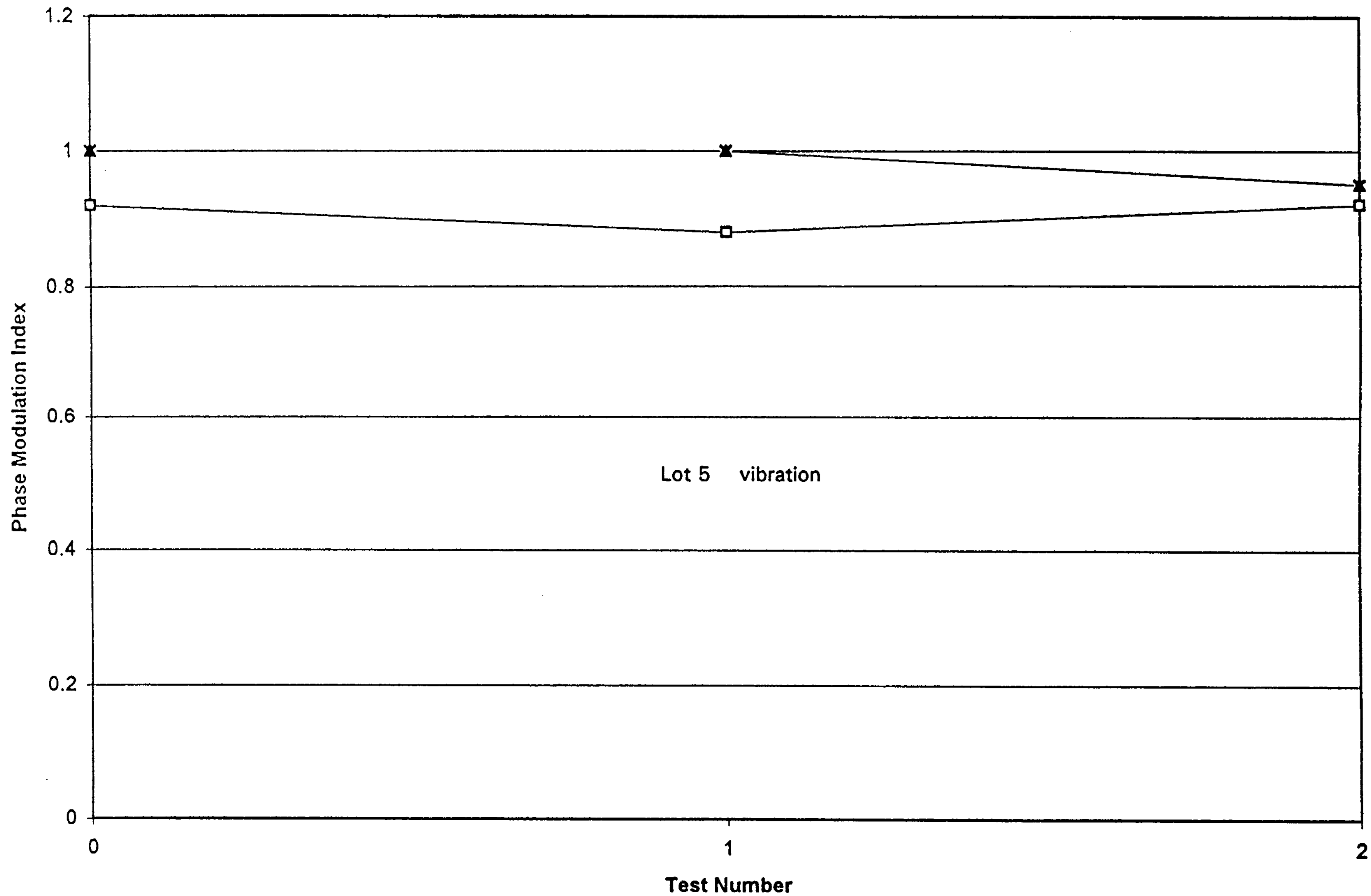
ECL MODULATOR LOT 3 (-20 to 85°C)



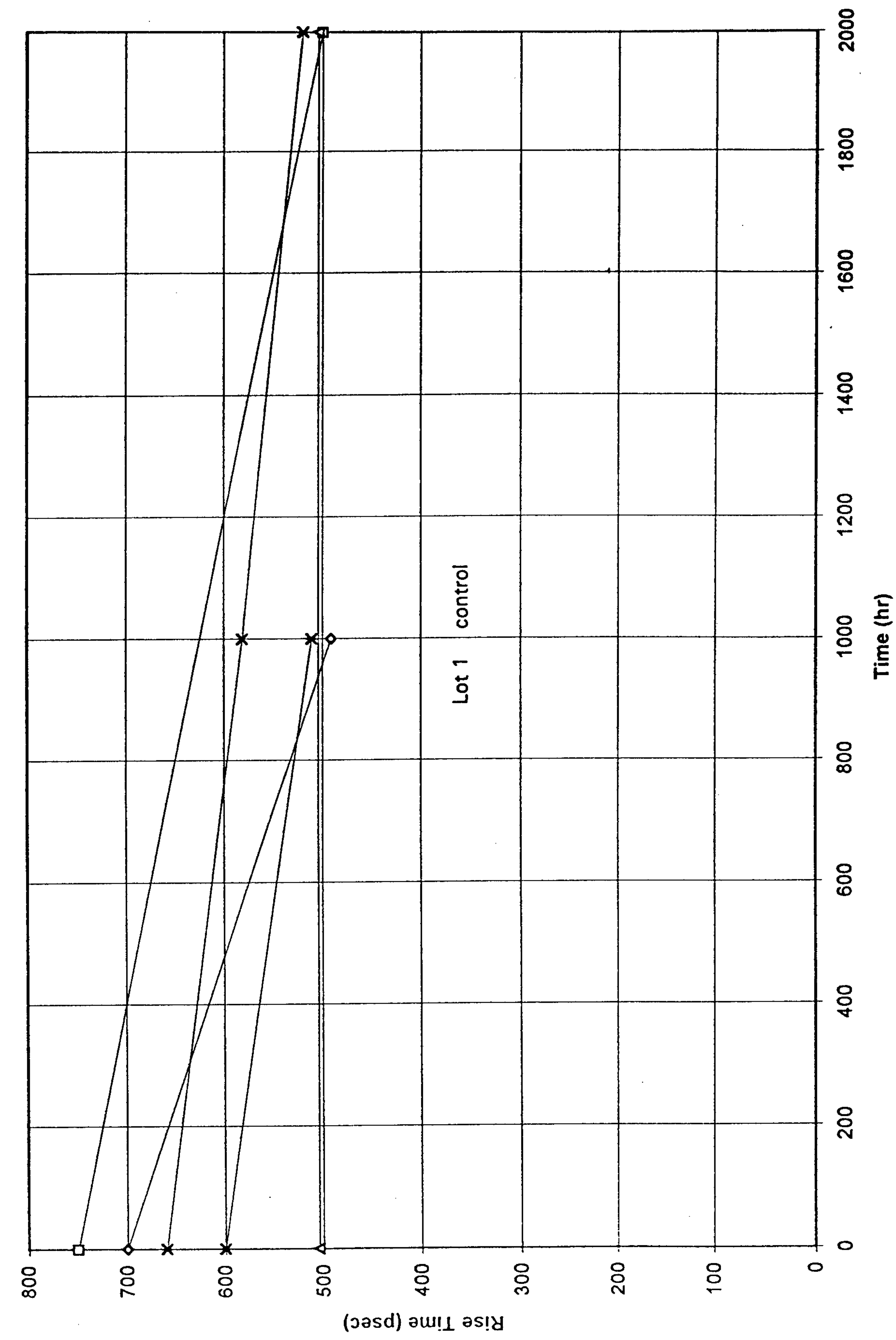
ECL MODULATOR LOT 4 (-55 to 85°C)



ECL MODULATOR LOT 5 (VIBRATION)

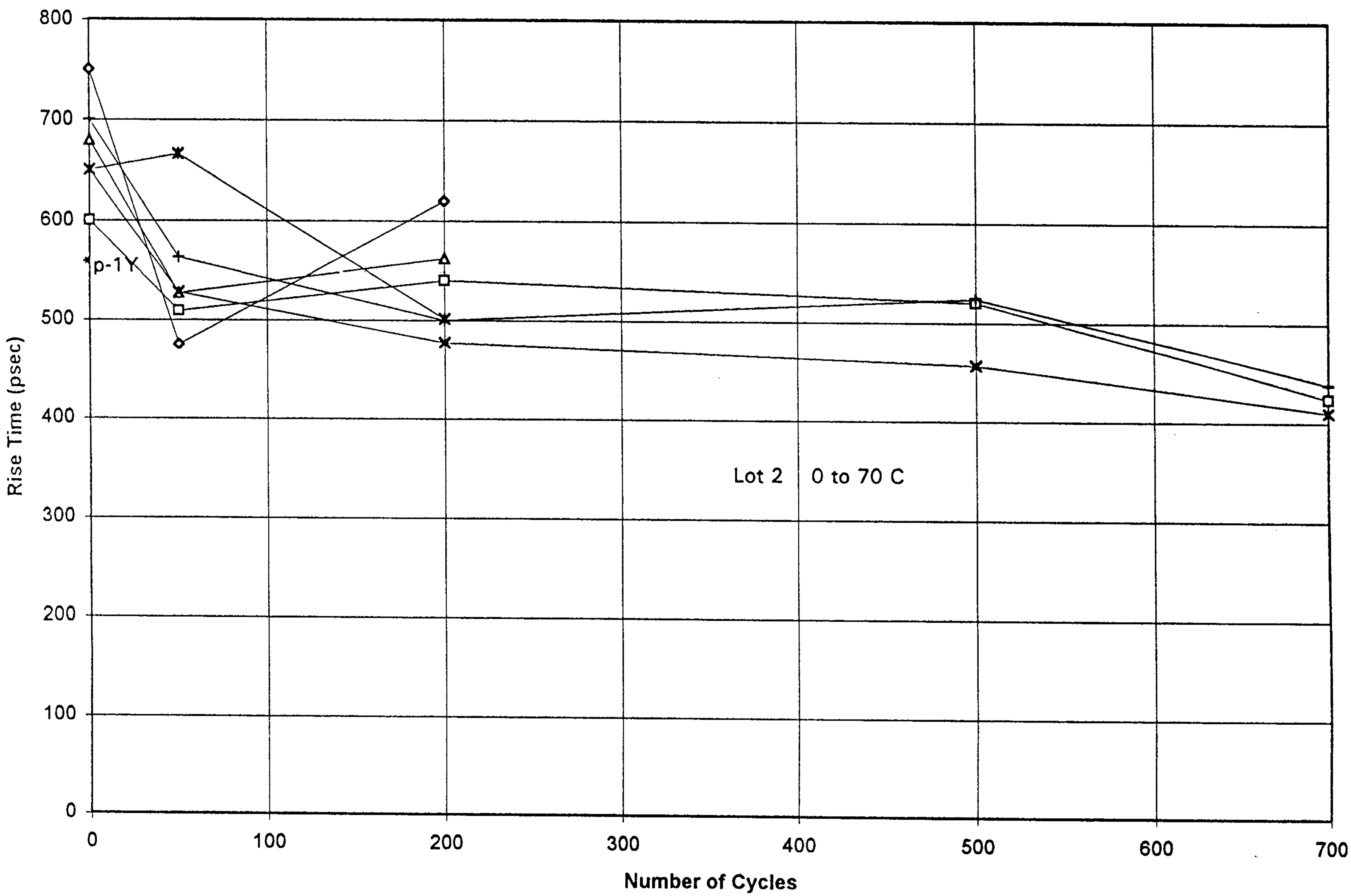


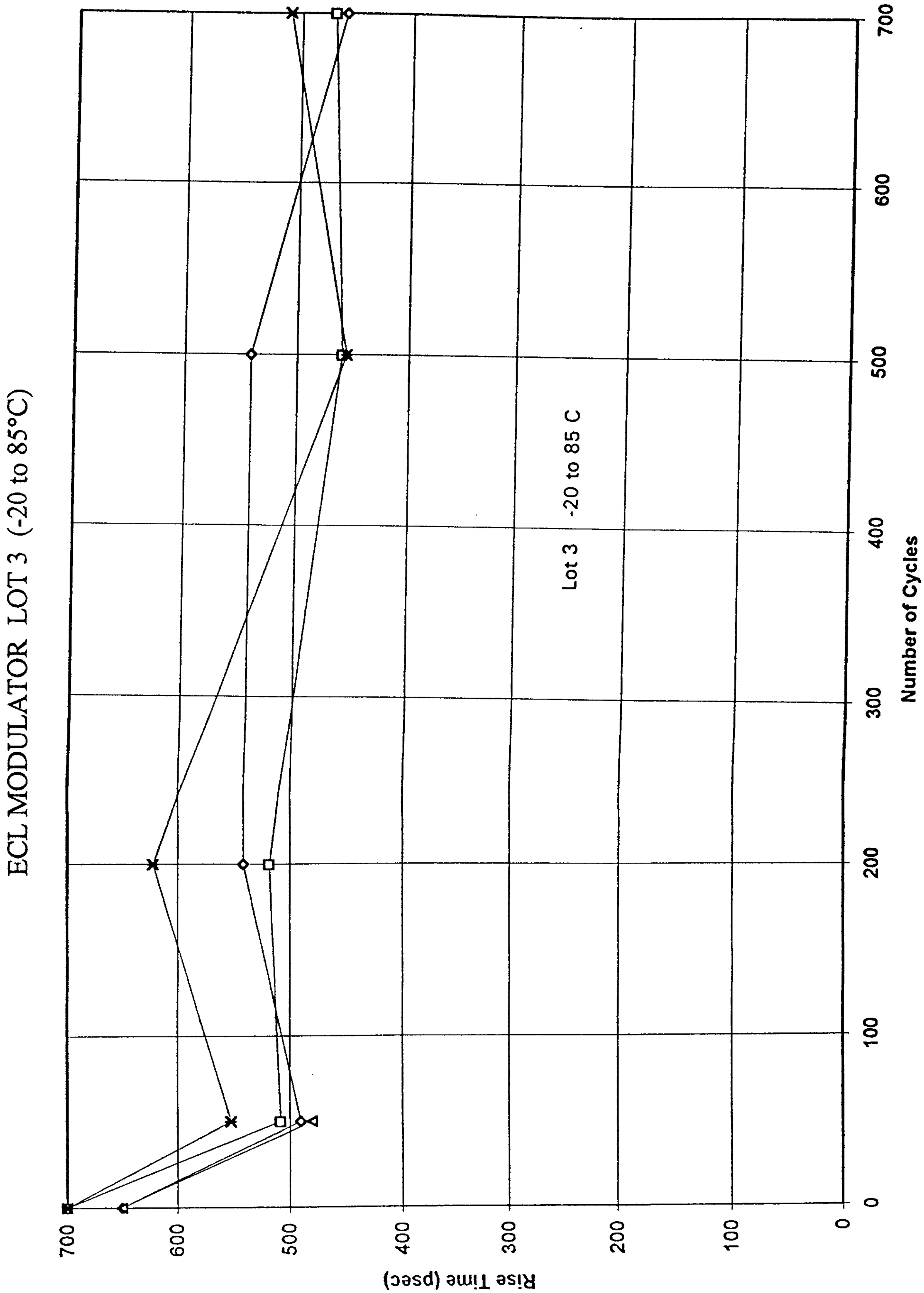
ECL MODULATOR LOT 1 (CONTROL)



Appendix E.1

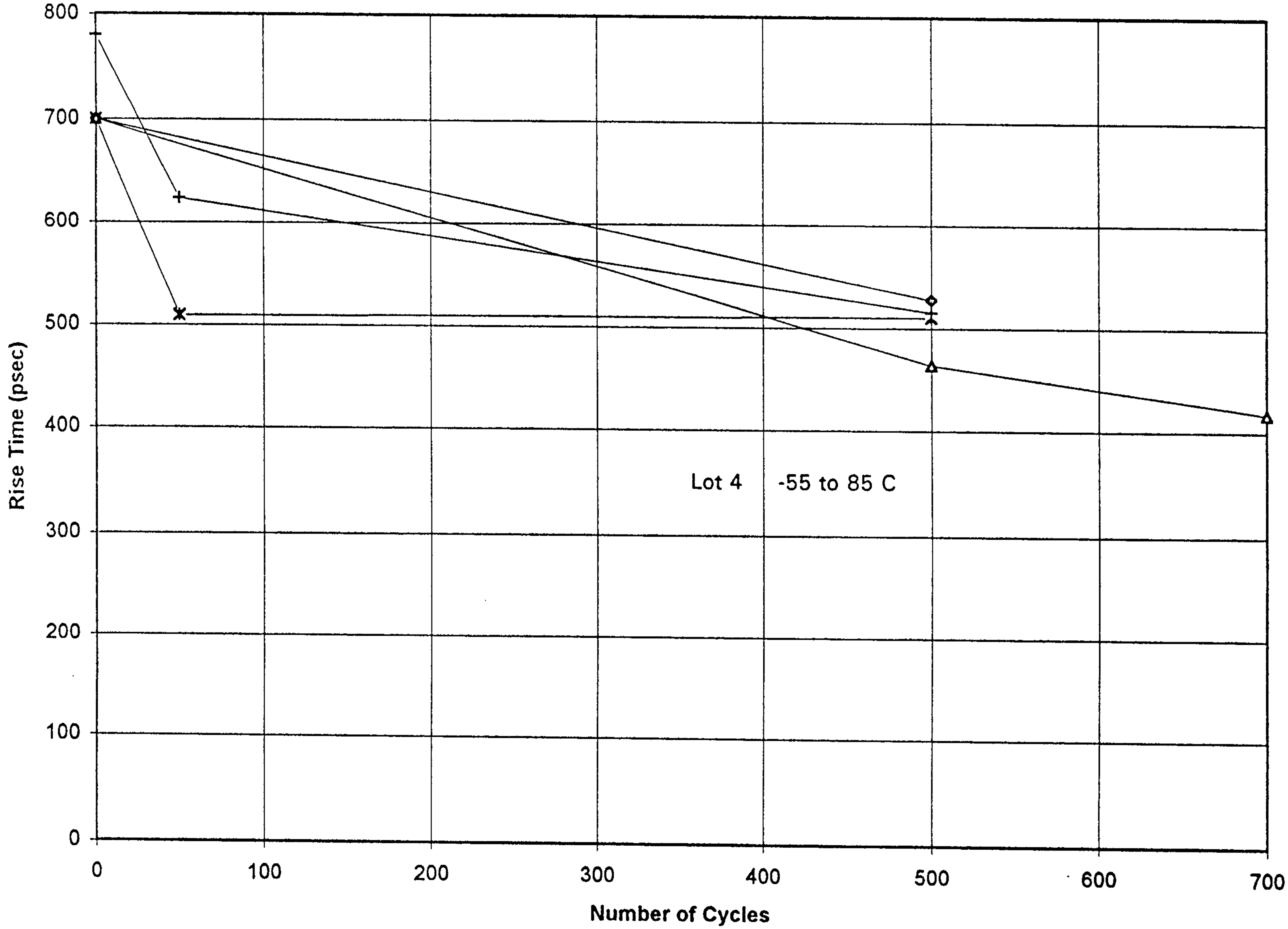
ECL MODULATOR LOT 2 (0 to 70°C)



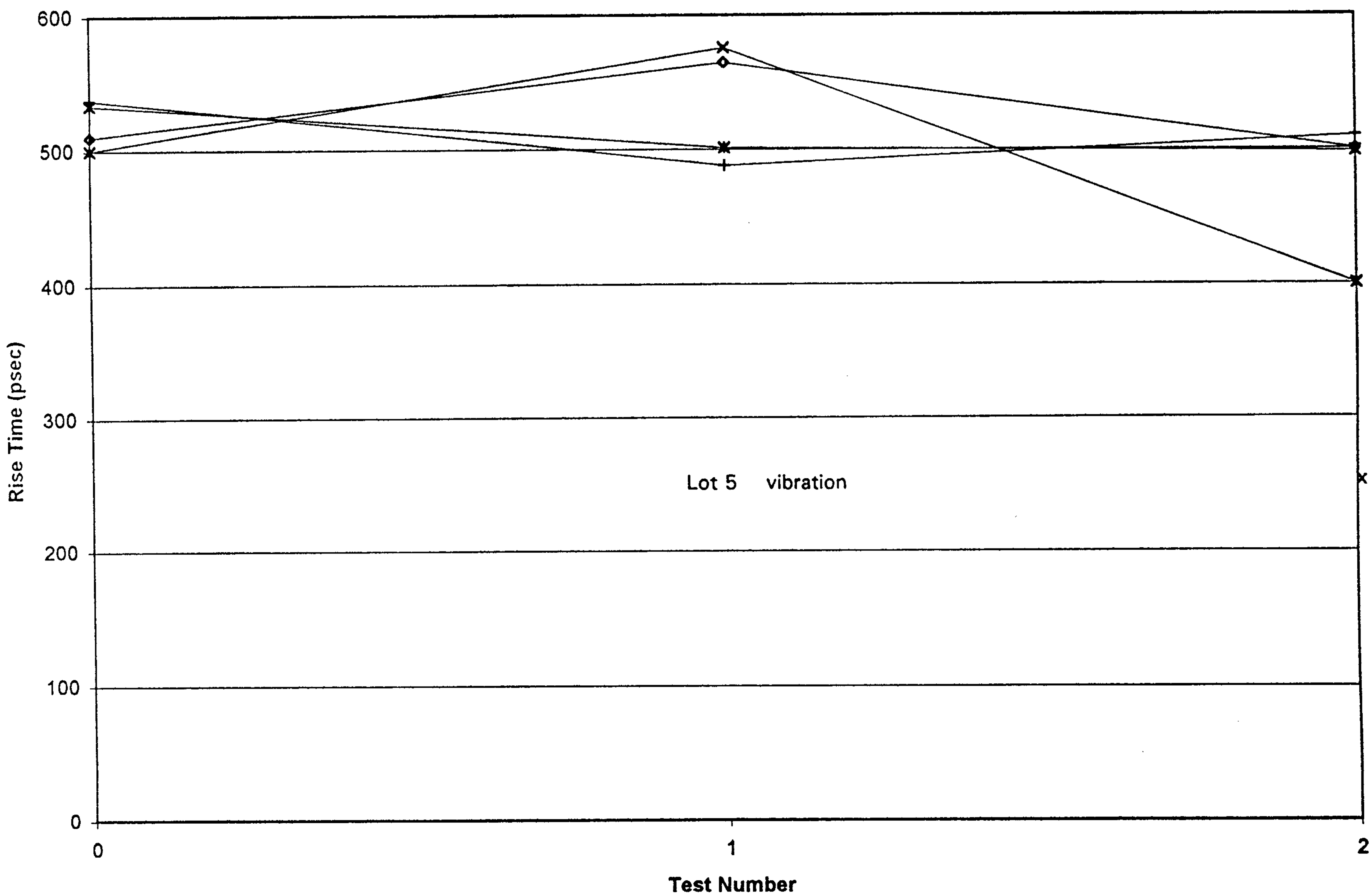


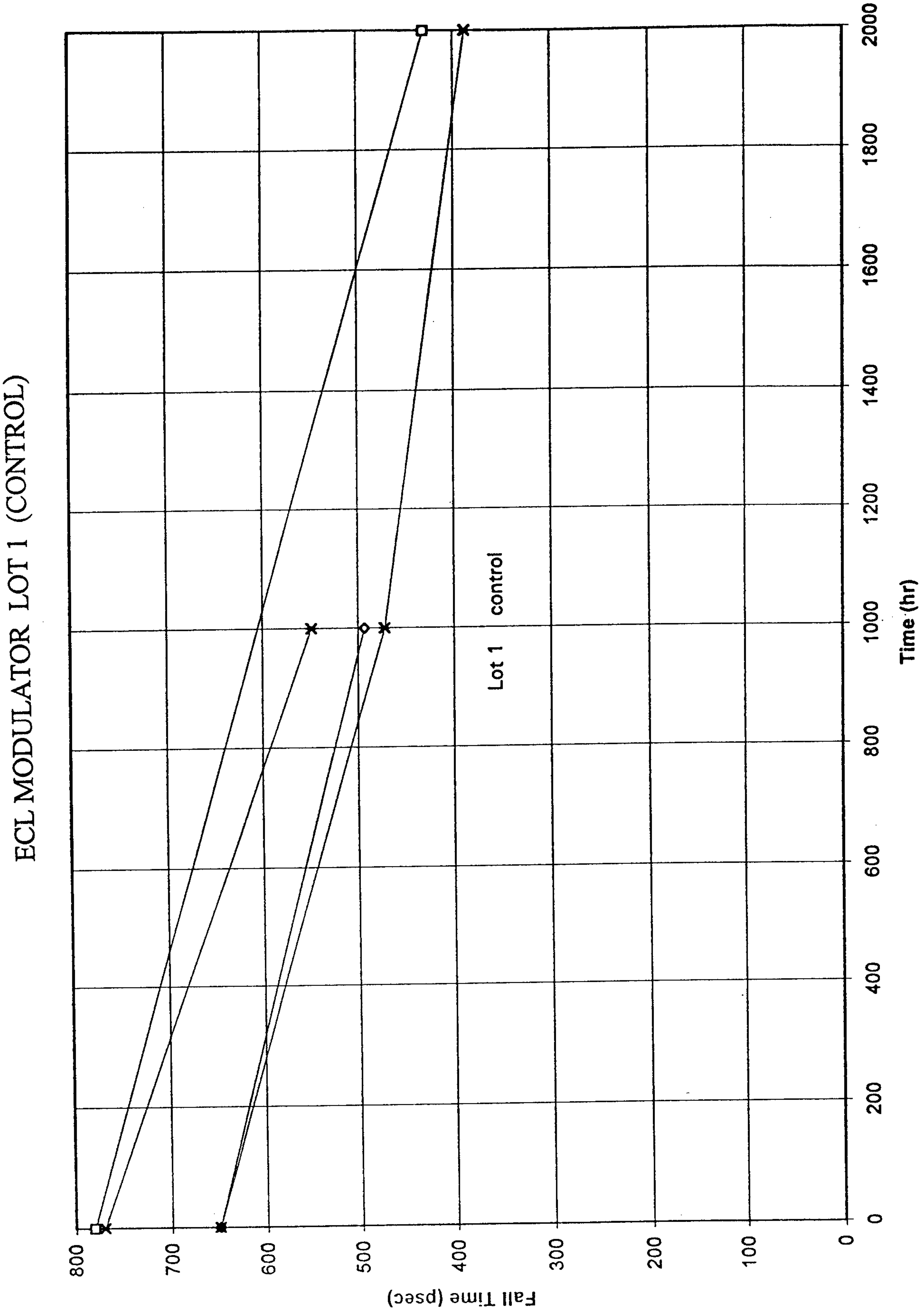
ECL MODULATOR LOT 3 (-20 to 85°C)
Lot 3 -20 to 85 C
Rise Time (psec)
700
600
500
400
300
200
100
0
Number of Cycles
0
100
200
300
400
500
600
700

ECL MODULATOR LOT 4 (-55 to 85°C)



ECL MODULATOR LOT 5 (VIBRATION)

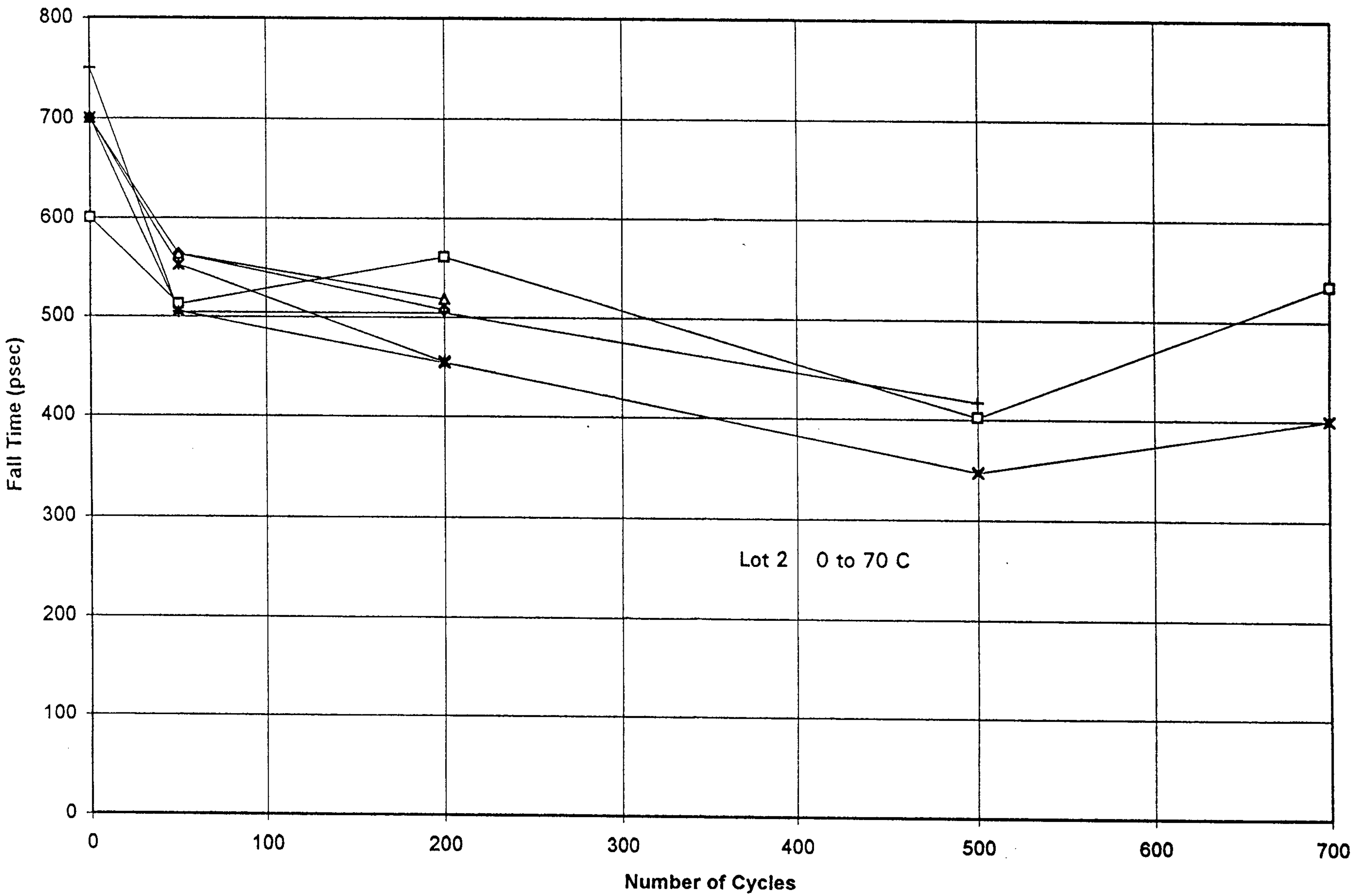




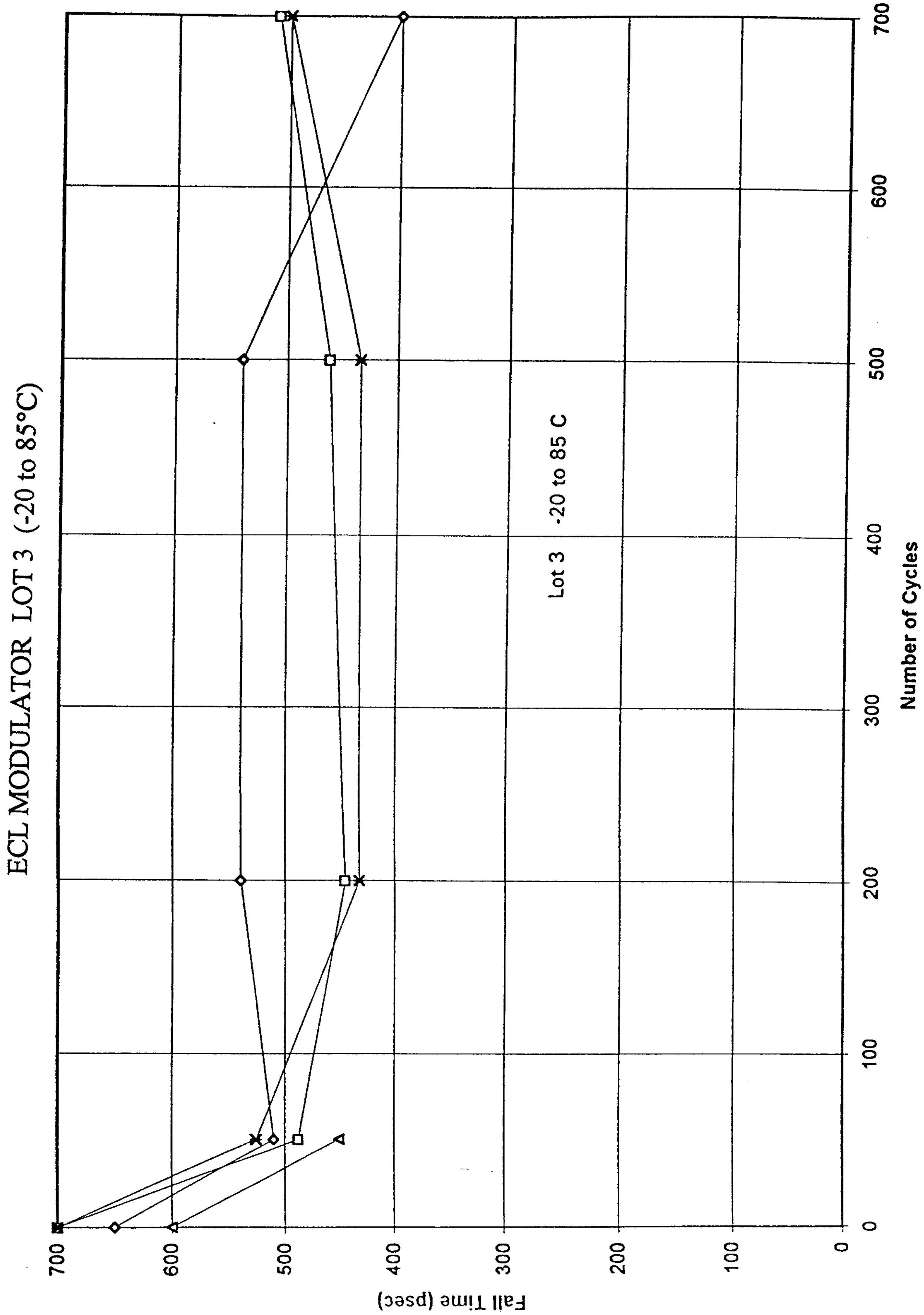
ECL MODULATOR LOT 1 (CONTROL)
Fall Time (psec)
800
700
600
500
400
300
200
100
0
Time (hr)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Lot 1 control

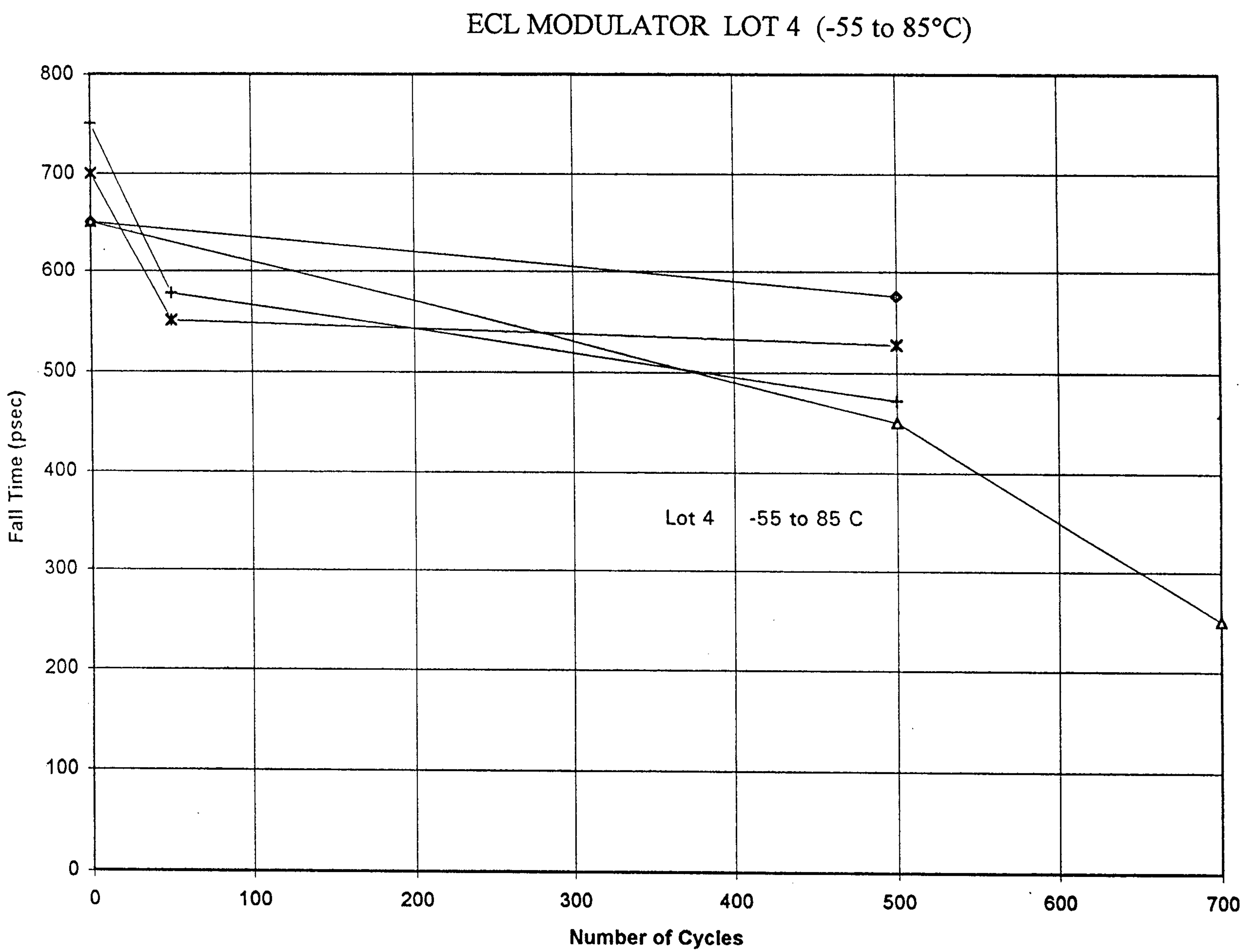
Appendix F.1

ECL MODULATOR LOT 2 (0 to 70°C)



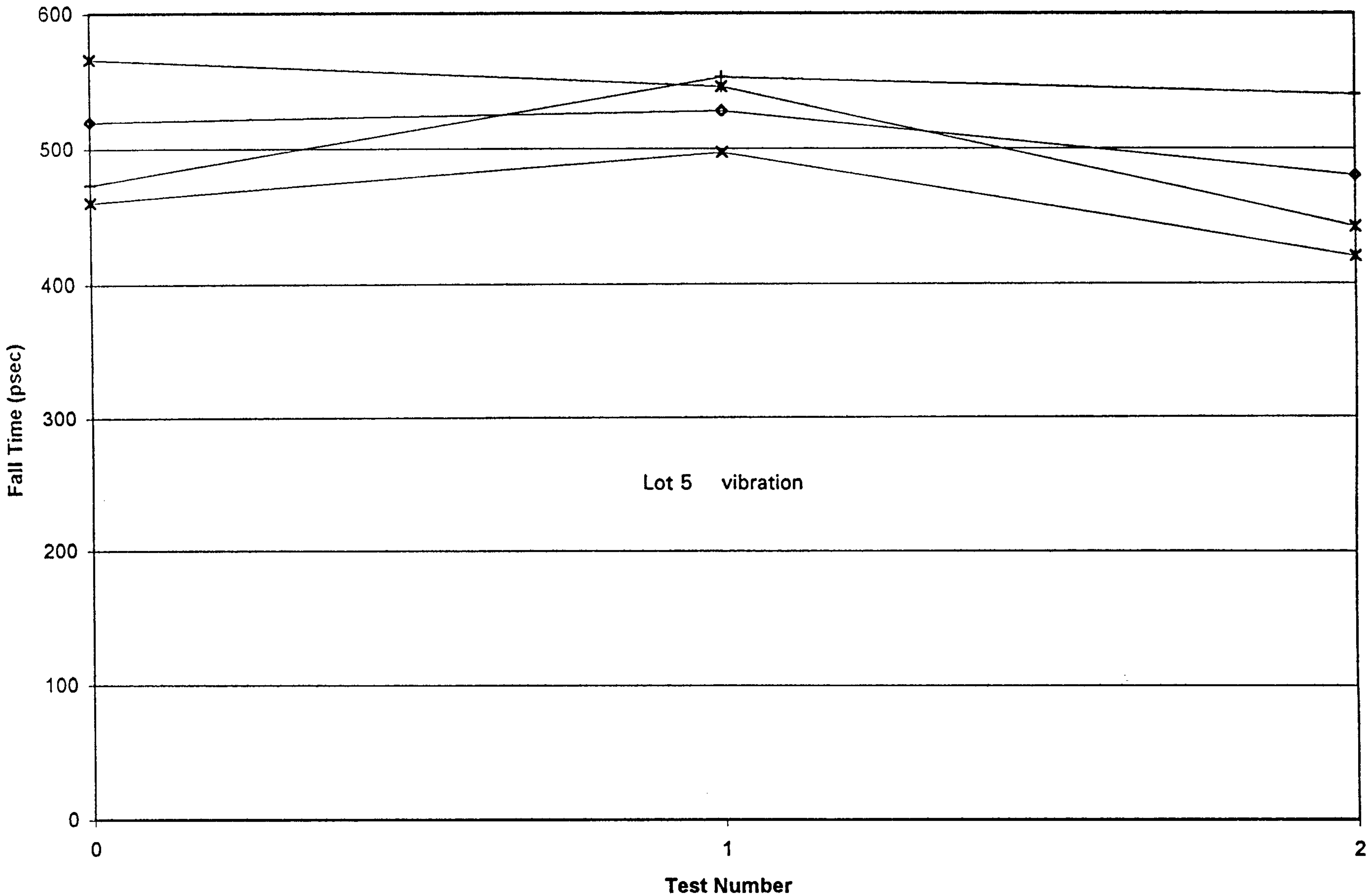
Appendix F.2


ECL MODULATOR LOT 3 (-20 to 85°C)
Lot 3 -20 to 85 C
Fall Time (psec)
700
600
500
400
300
200
100
0
Number of Cycles
0
100
200
300
400
500
600
700

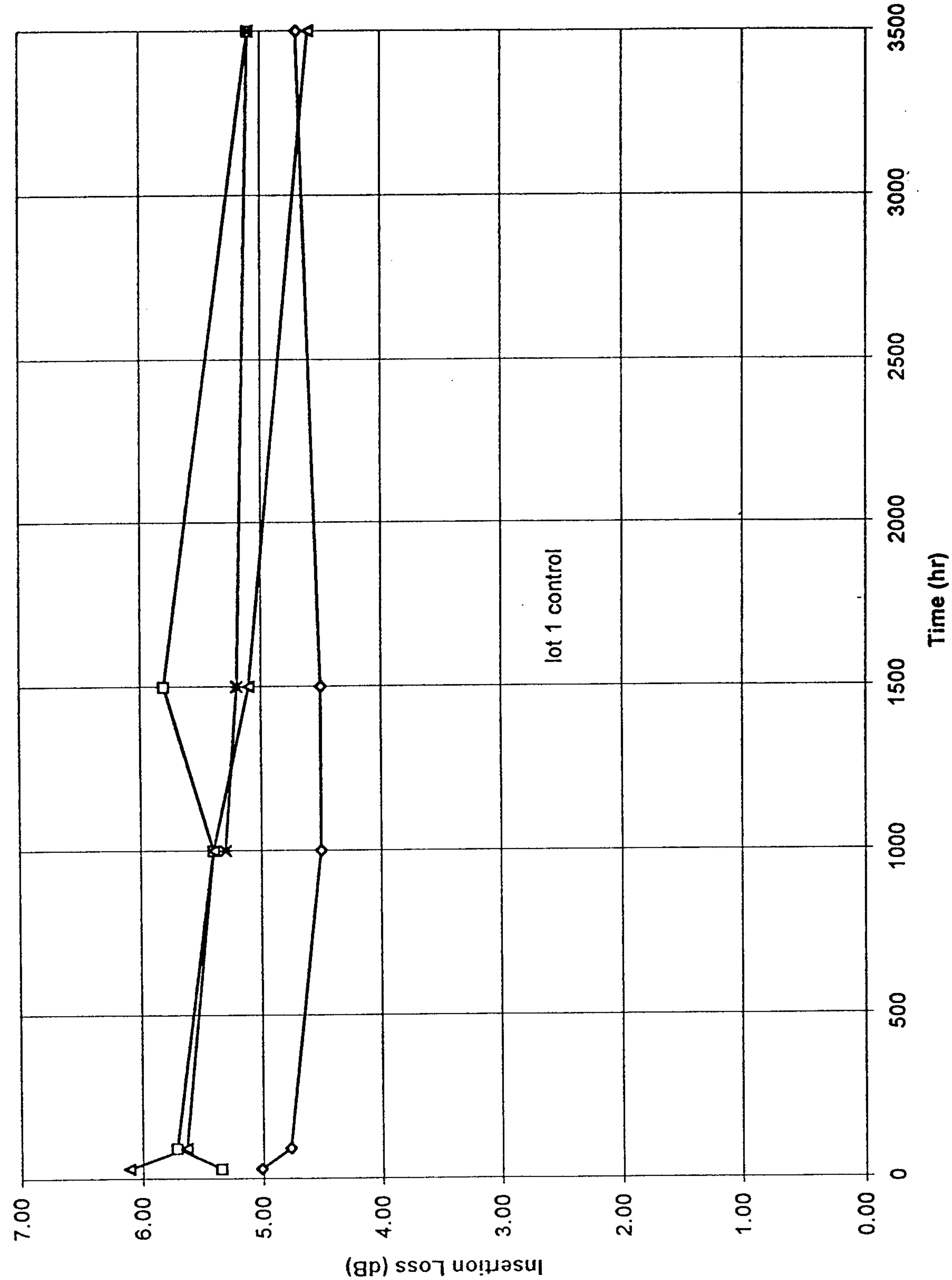


ECL MODULATOR LOT 4 (-55 to 85°C)
Fall Time (psec)
800
700
600
500
400
300
200
100
0
Lot 4 -55 to 85 C
0
100
200
300
400
500
600
700
Number of Cycles

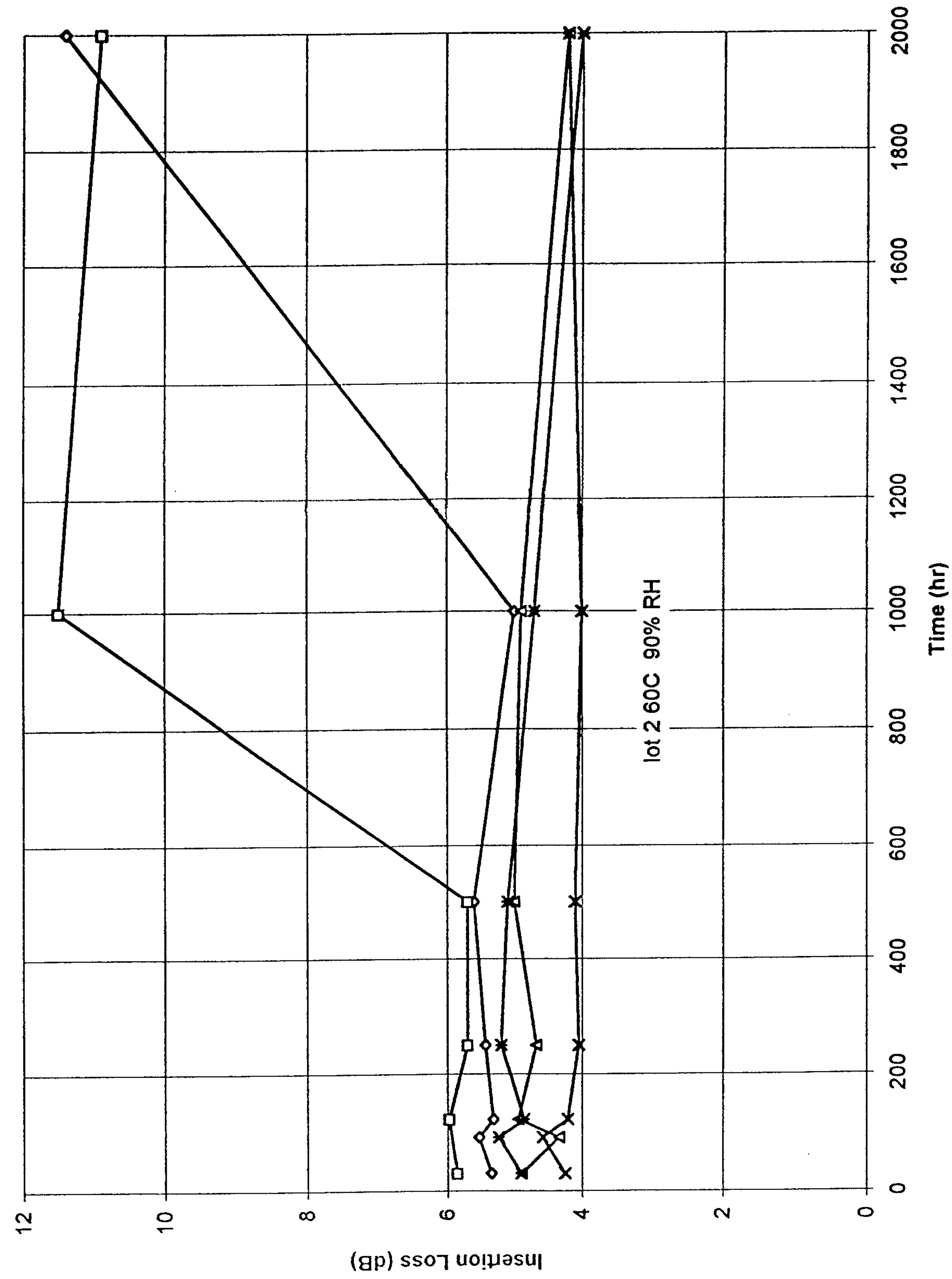
ECL MODULATOR LOT 5 (VIBRATION)



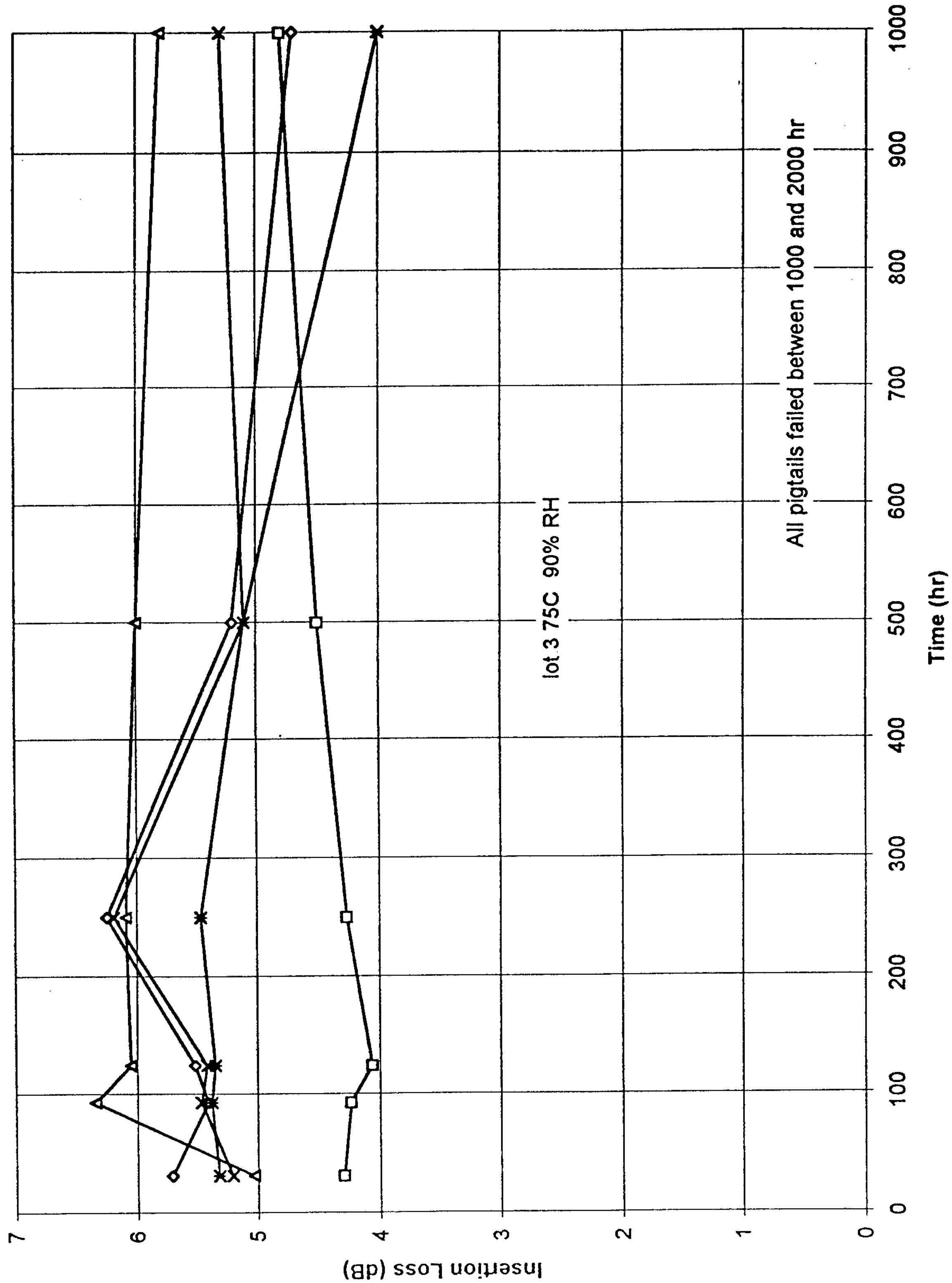
BCM MODULATOR LOT 1 (CONTROL)

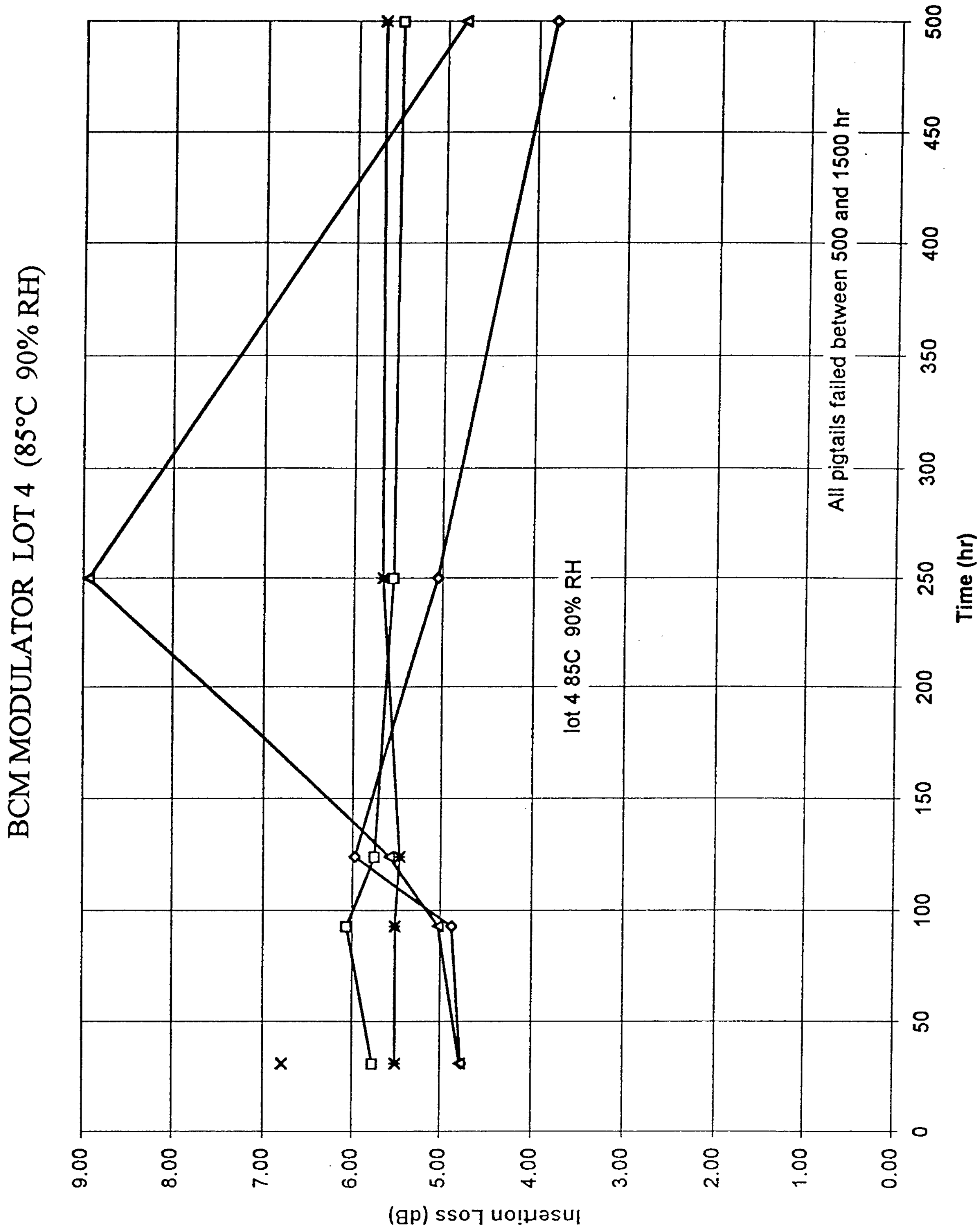


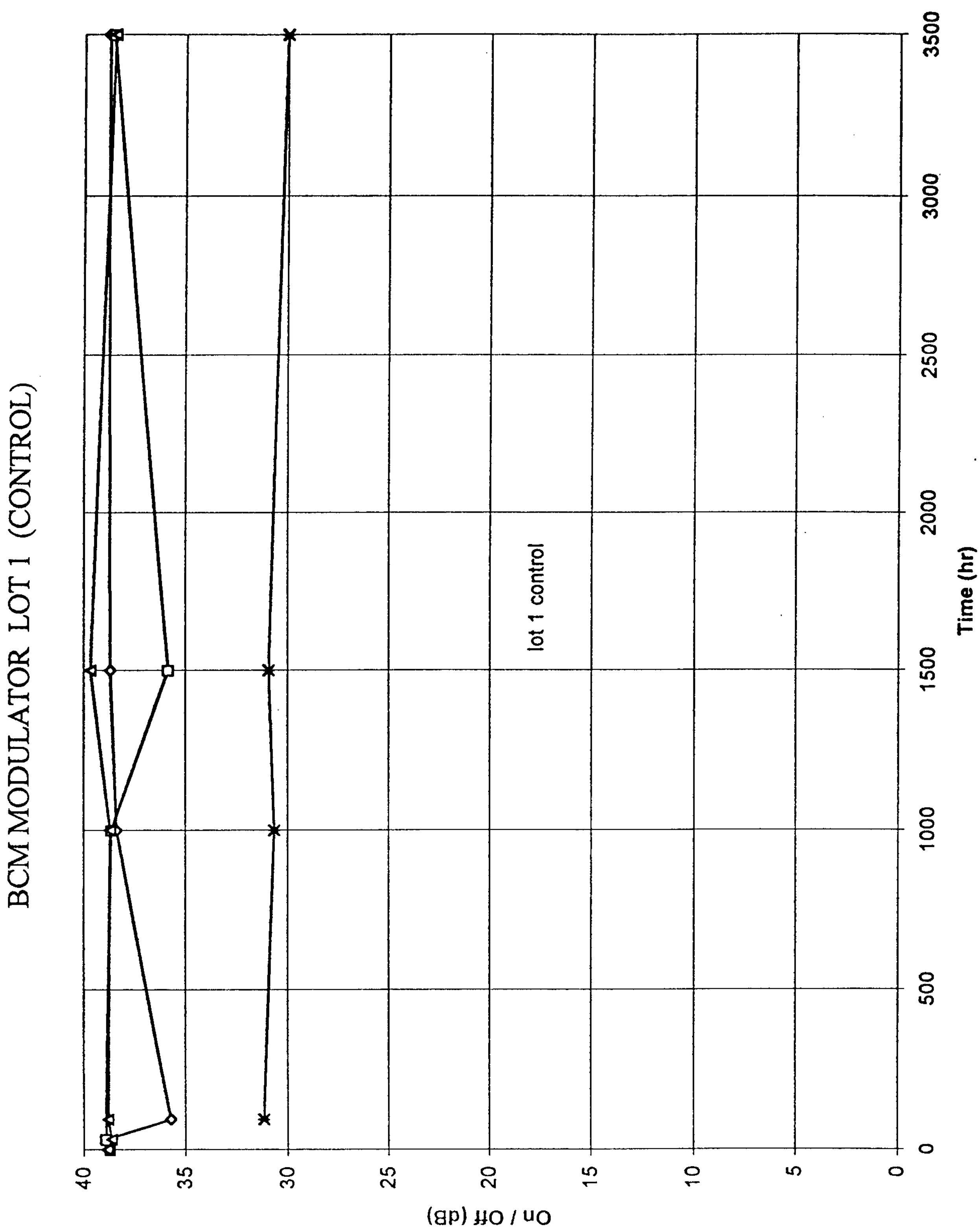
BCM MODULATOR LOT 2 (60°C 90% RH)

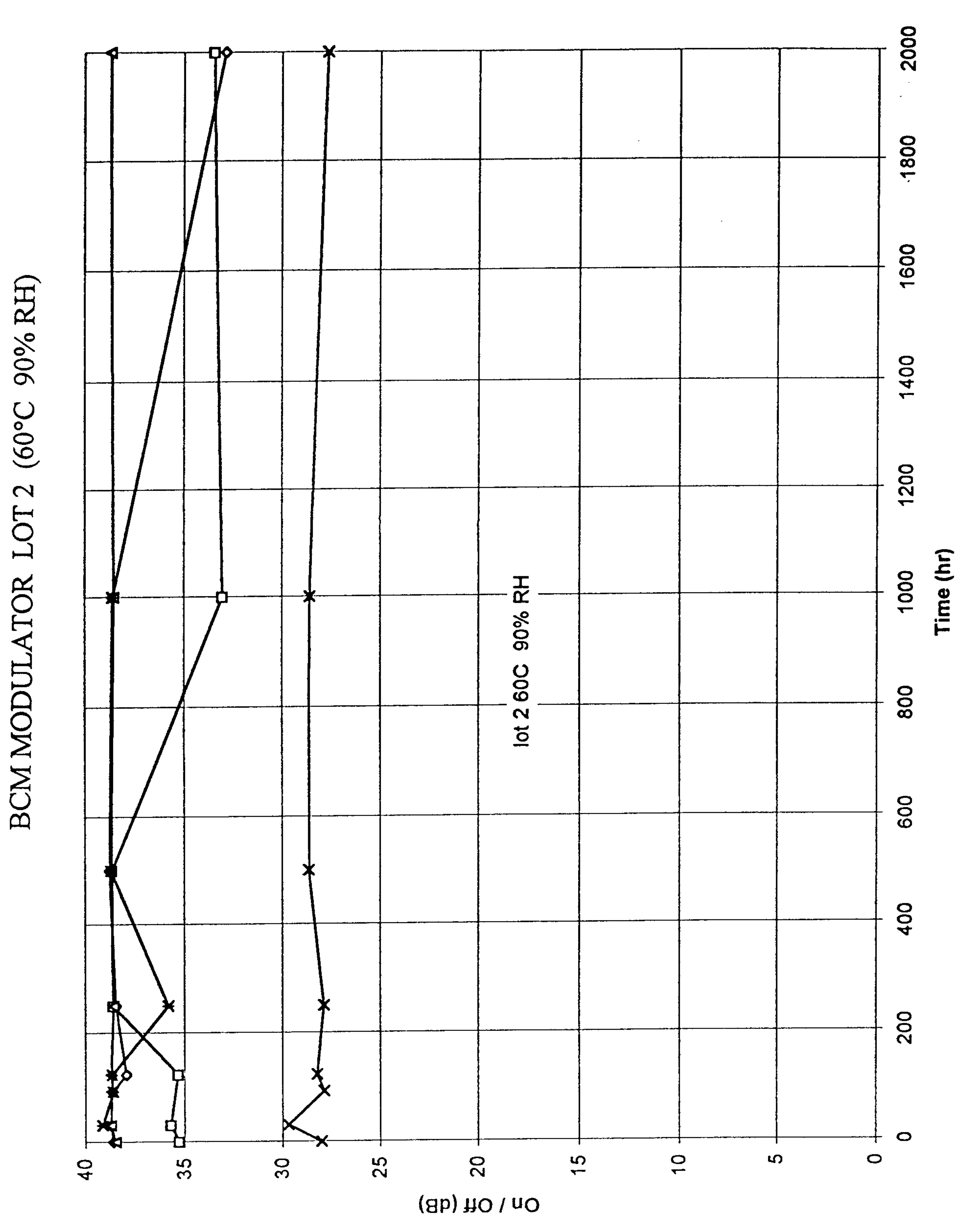


BCM MODULATOR LOT 3 (75°C 90% RH)

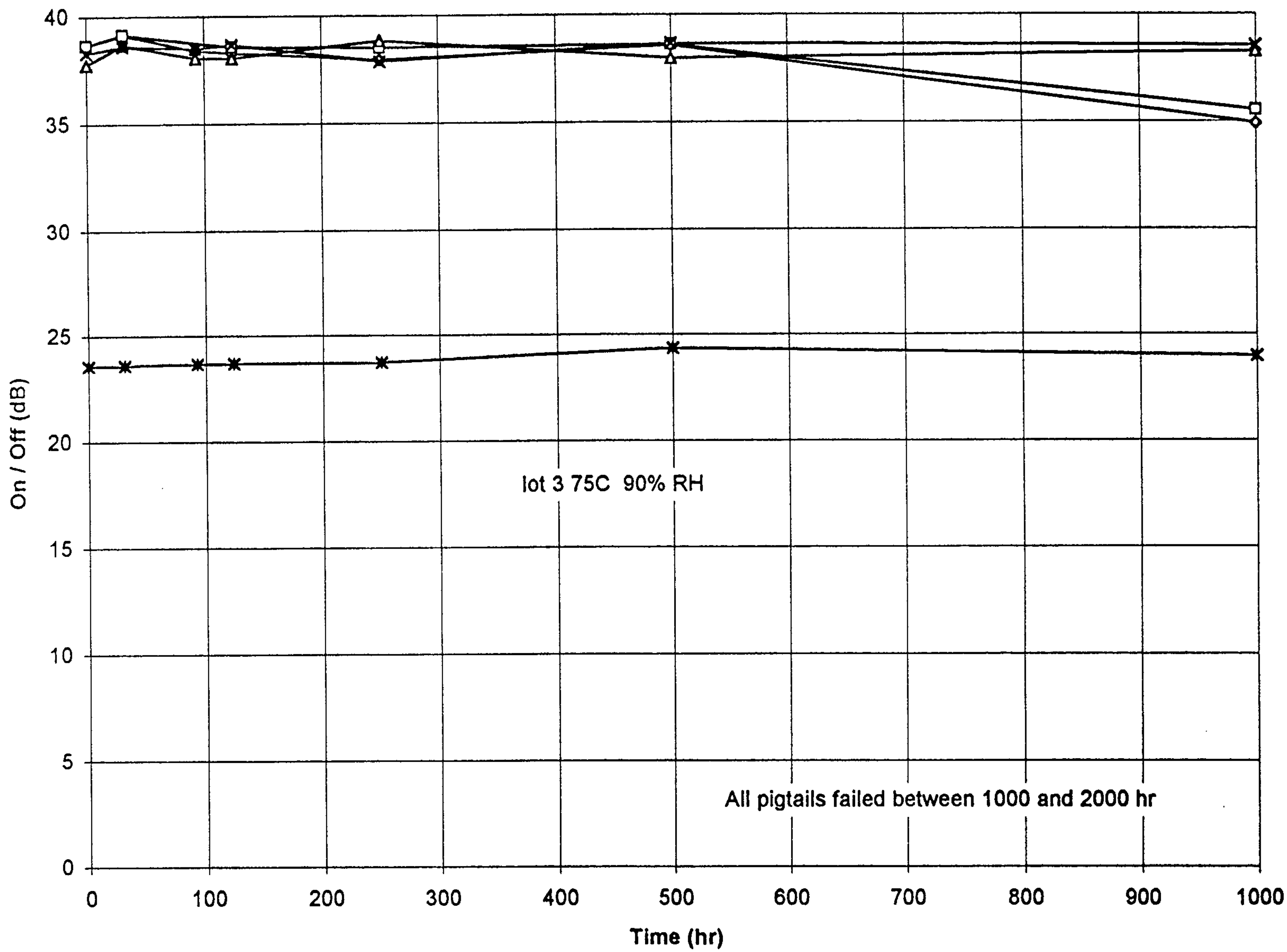



BCM MODULATOR LOT 4 (85°C 90% RH)
Insertion Loss (dB)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
50
100
150
200
250
300
350
400
450
500
Time (hr)
lot 4 85C 90% RH
All pigtails failed between 500 and 1500 hr

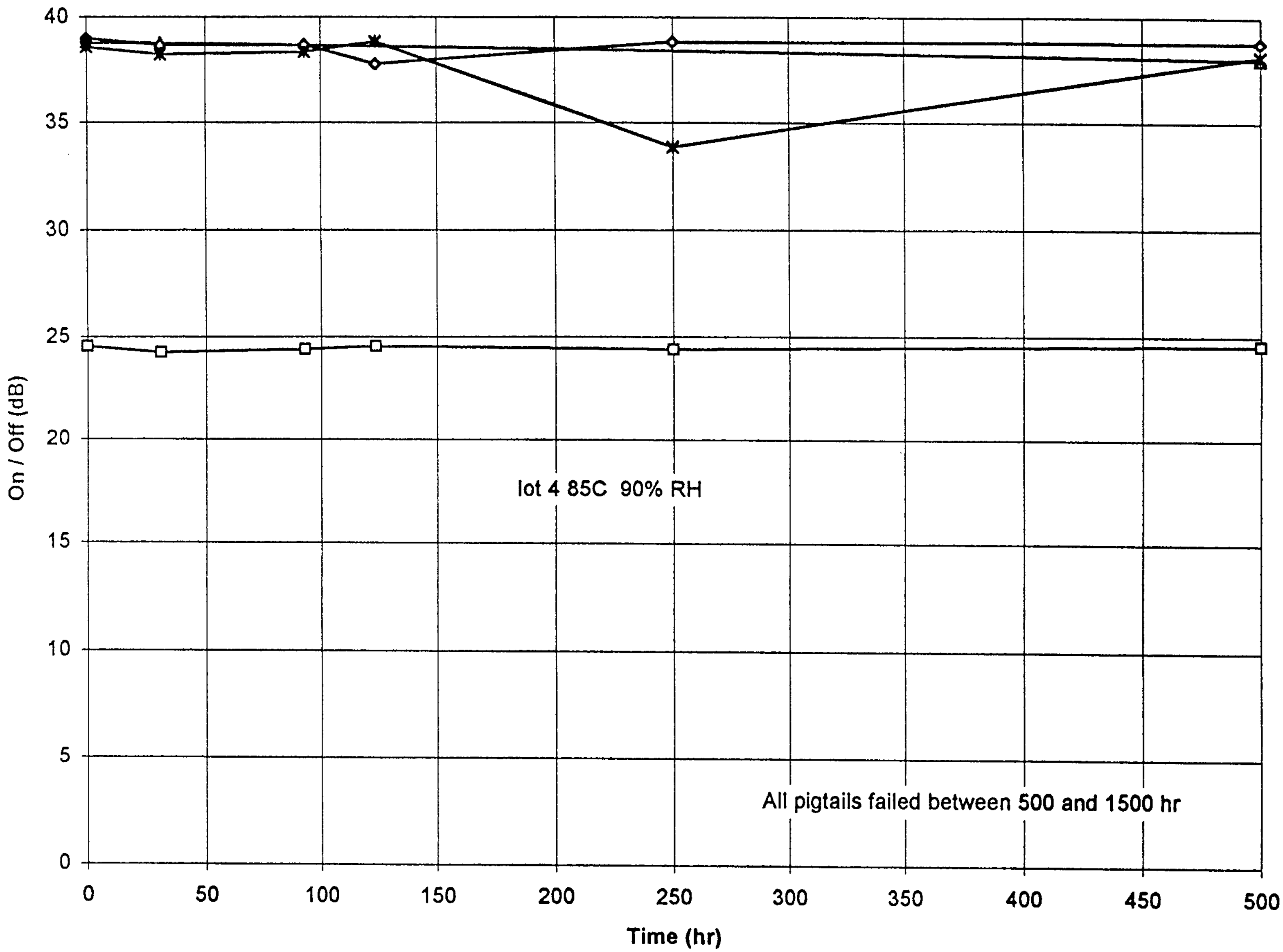

BCM MODULATOR LOT 1 (CONTROL)
lot 1 control
On / Off (dB)
Time (hr)
40
35
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500

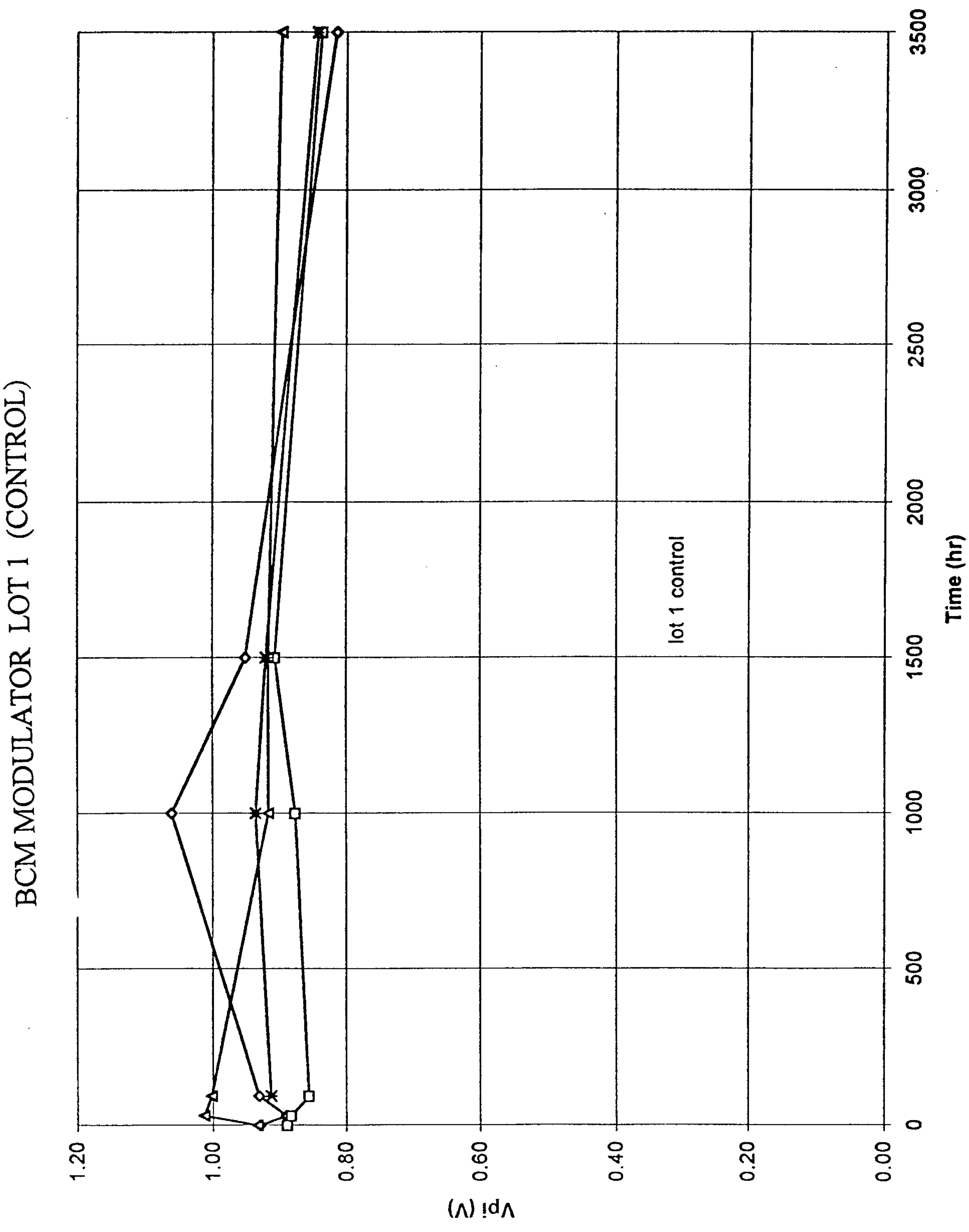

BCM MODULATOR LOT 2 (60°C 90% RH)
On / Off (dB)
0
5
10
15
20
25
30
35
40
Time (hr)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
lot 2 60C 90% RH

BCM MODULATOR LOT 3 (75°C 90% RH)



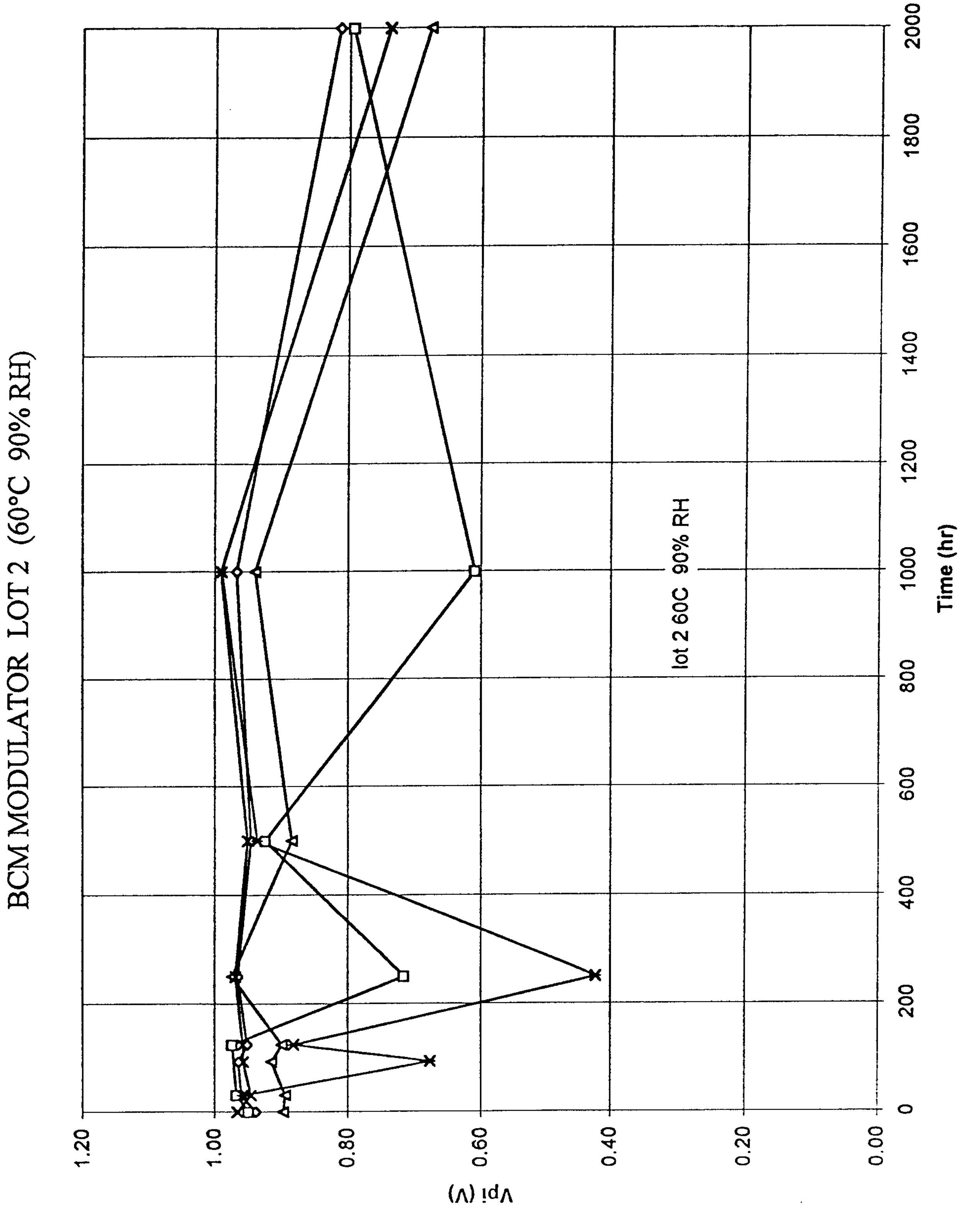
BCM MODULATOR LOT 4 (85°C 90% RH)



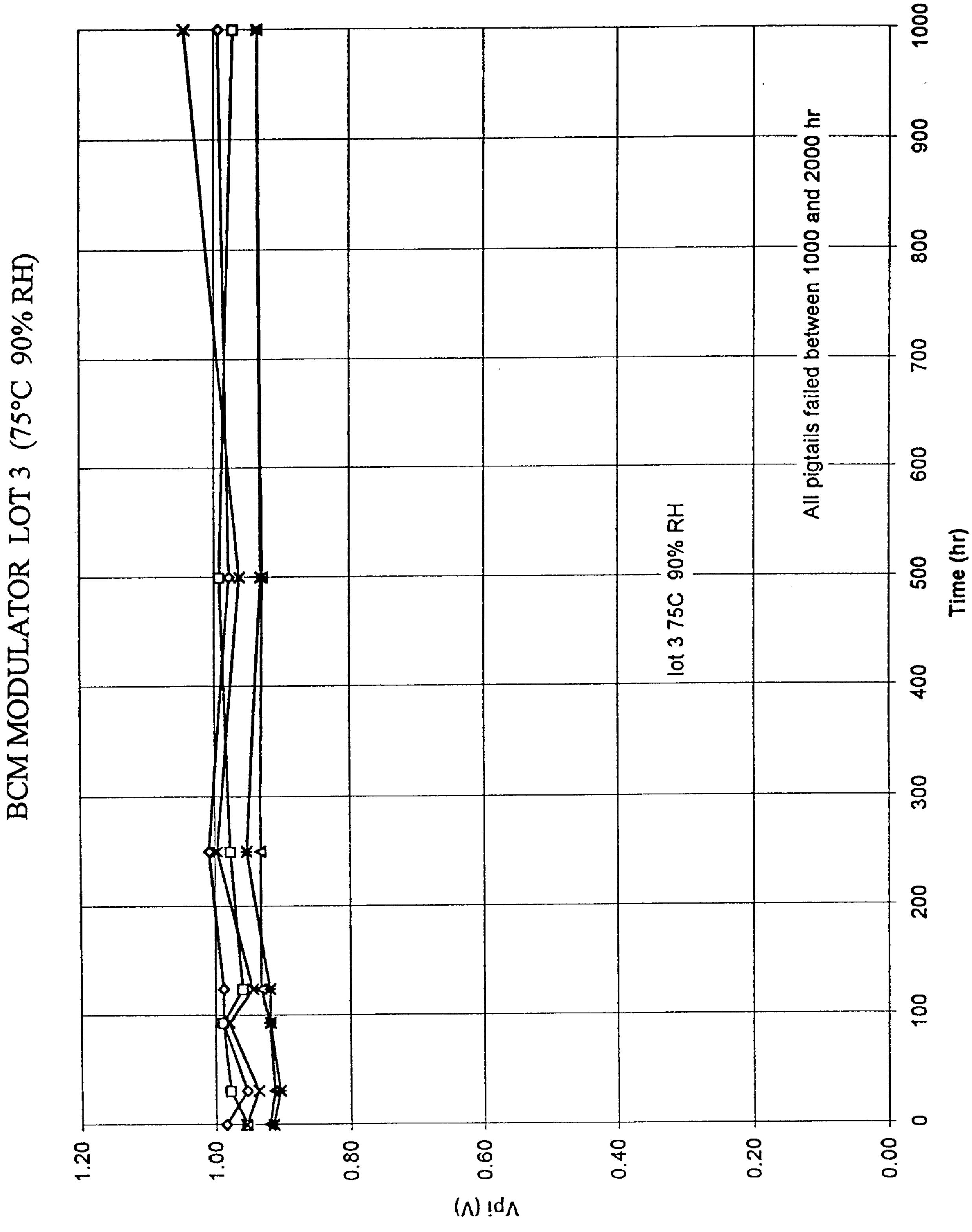


BCM MODULATOR LOT 1 (CONTROL)
Vpi (V)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
500
1000
1500
2000
2500
3000
3500
Time (hr)
lot 1 control

Appendix I.1

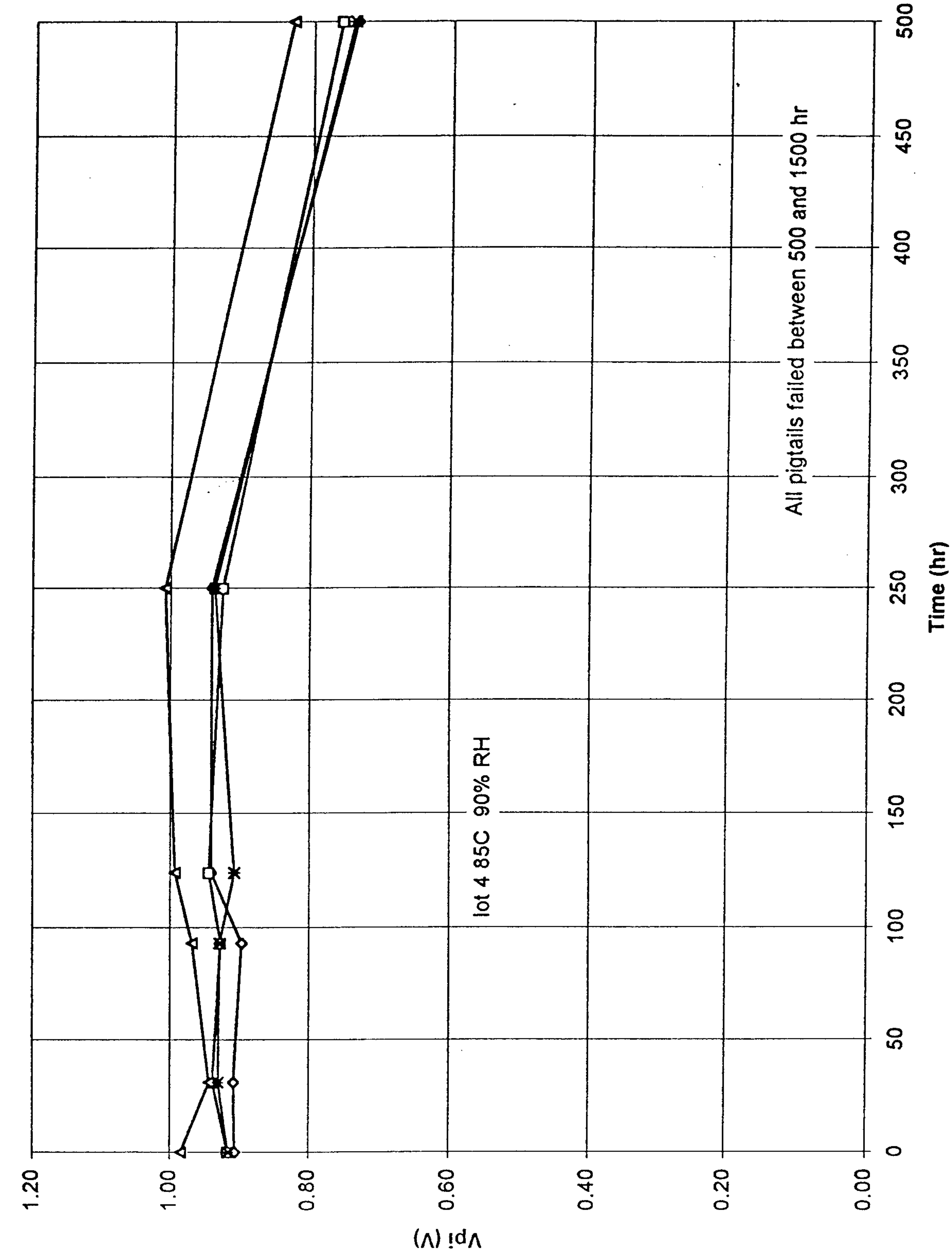

BCM MODULATOR LOT 2 (60°C 90% RH)
Vpi (V)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Time (hr)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
lot 2 60C 90% RH

Appendix I.2

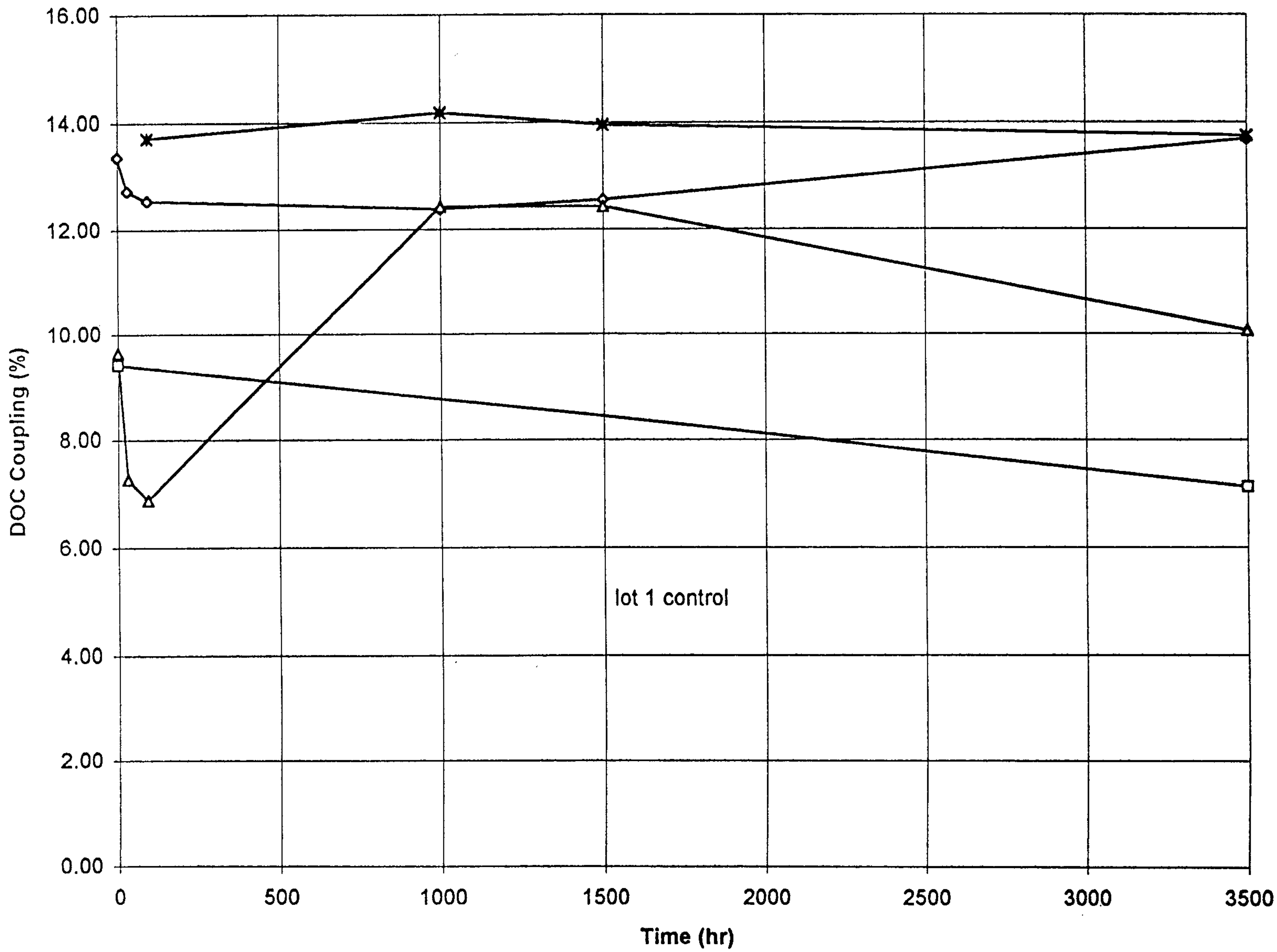


BCM MODULATOR LOT 3 (75°C 90% RH)
lot 3 75C 90% RH
All pigtails failed between 1000 and 2000 hr
Vpi (V)
Time (hr)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
100
200
300
400
500
600
700
800
900
1000

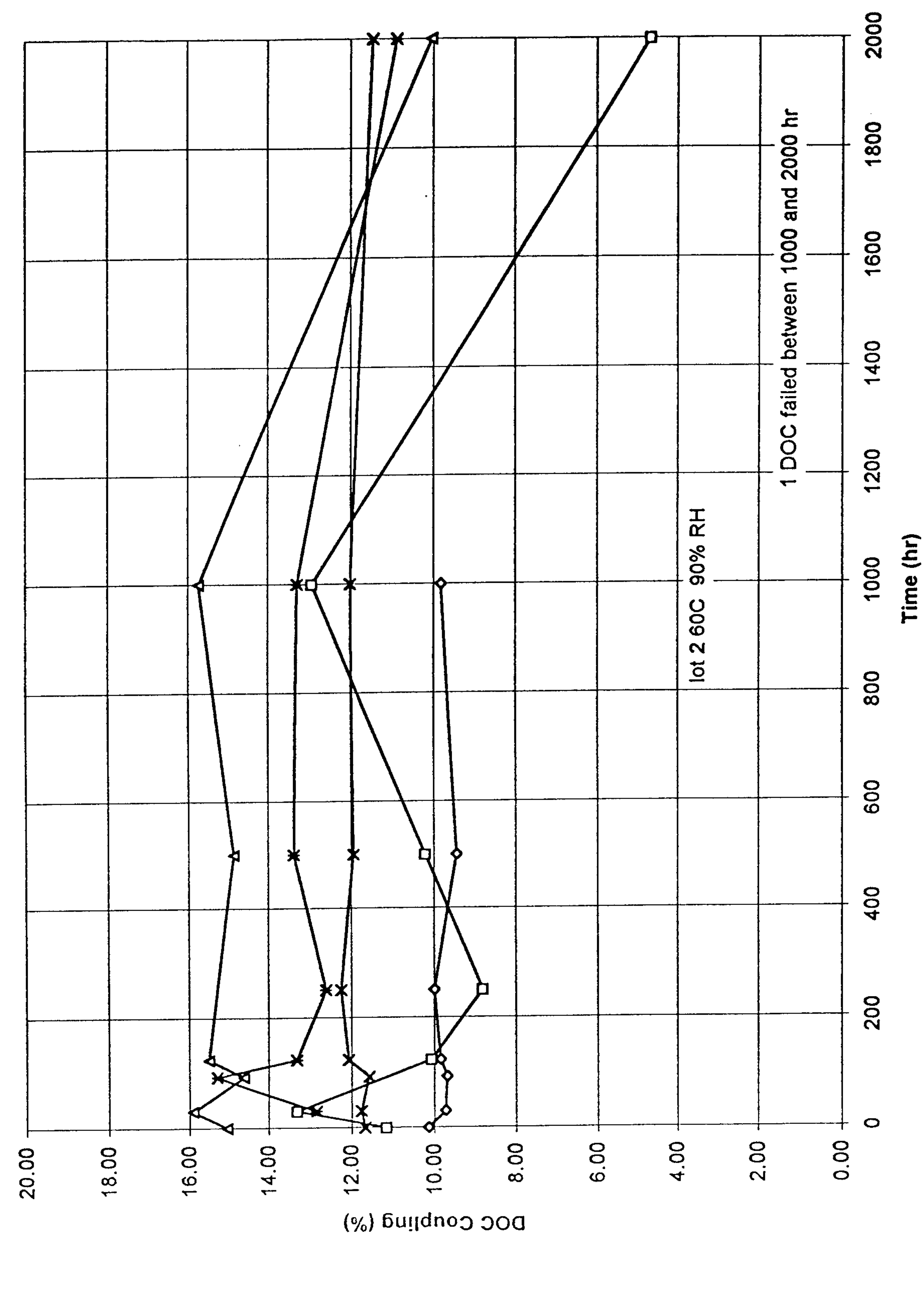
BCM MODULATOR LOT 4 (85°C 90% RH)

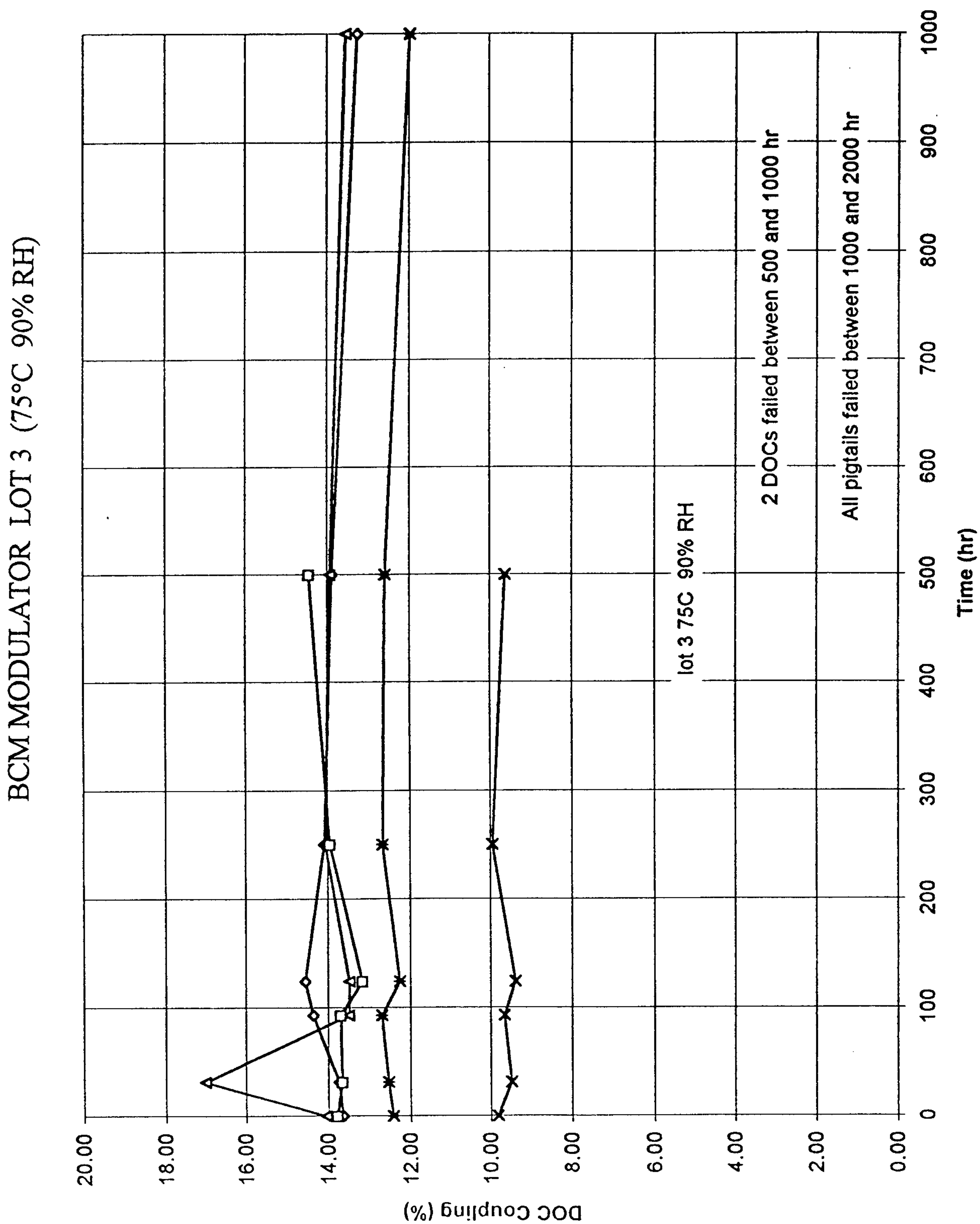


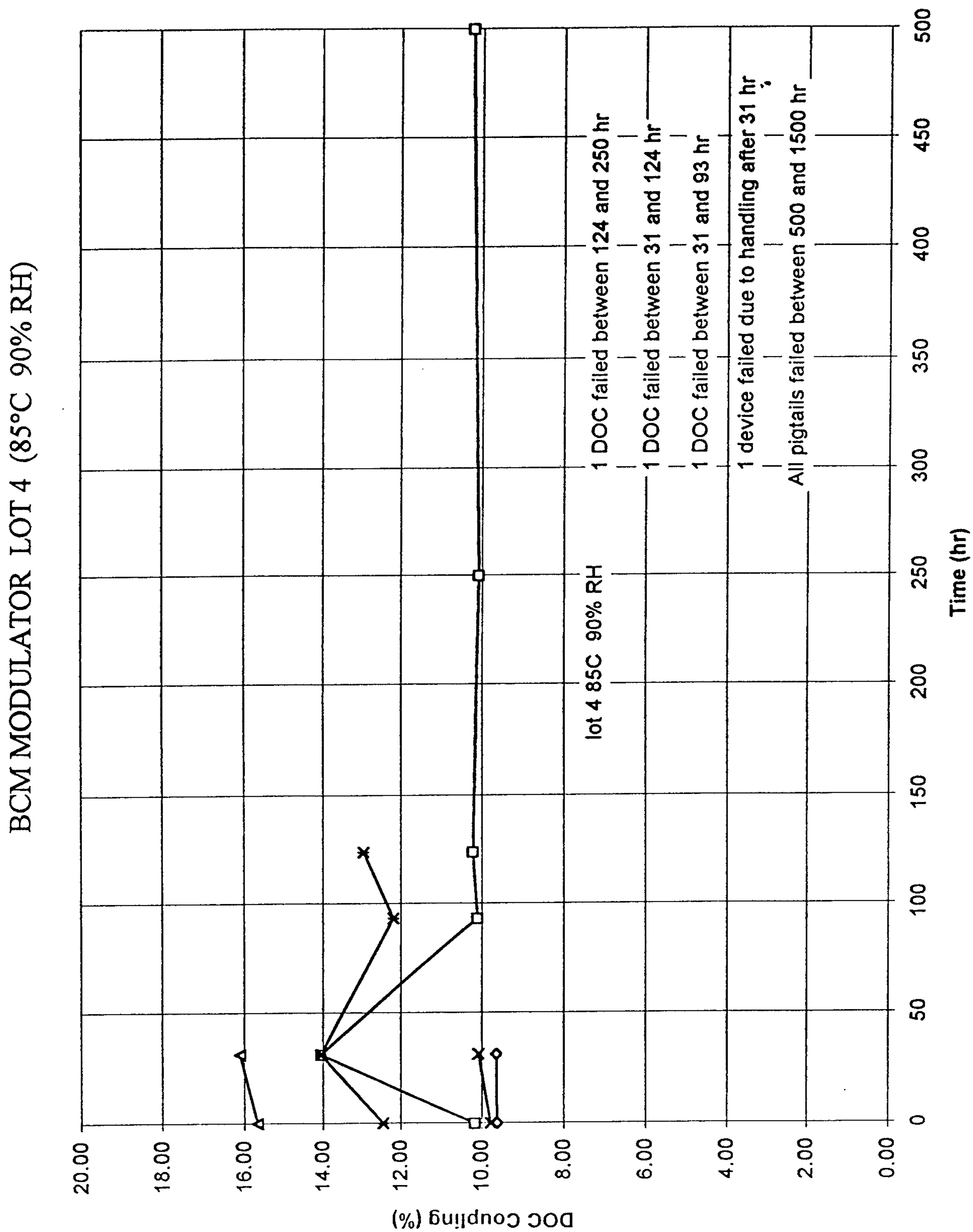
BCM MODULATOR LOT 1 (CONTROL)

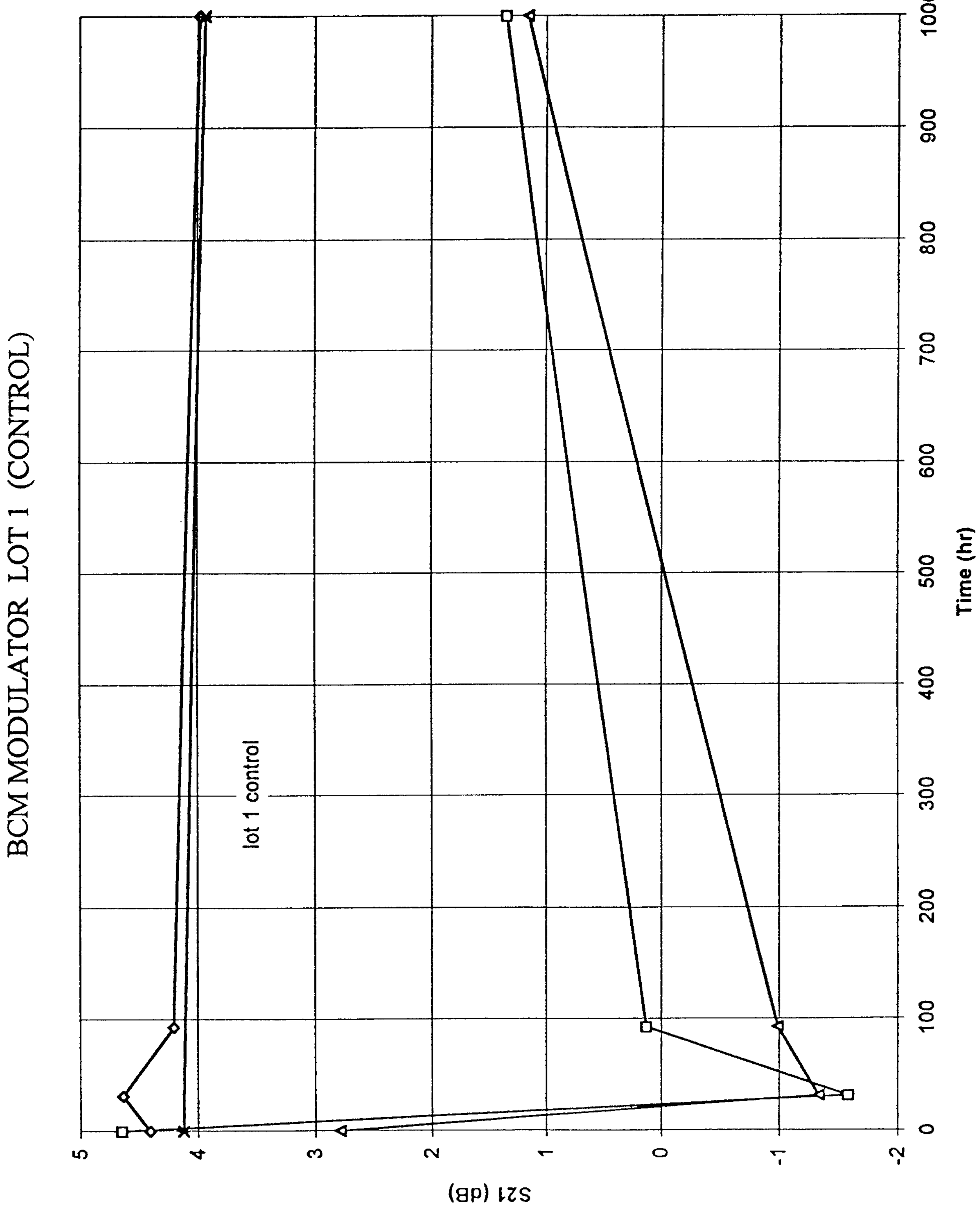


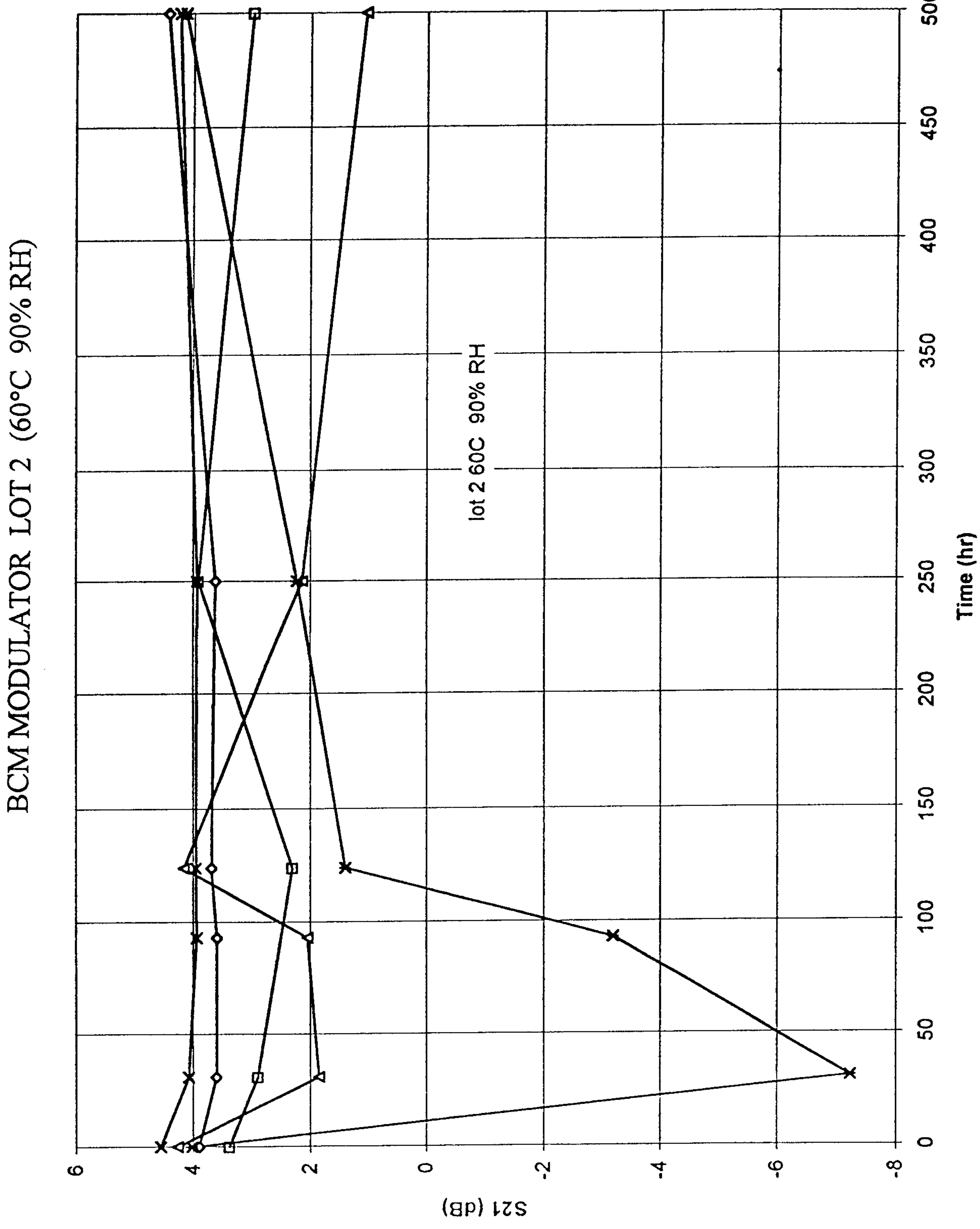
BCM MODULATOR LOT 2 (60°C 90% RH)




BCM MODULATOR LOT 3 (75°C 90% RH)
DOC Coupling (%)
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Time (hr)
0
100
200
300
400
500
600
700
800
900
1000
lot 3 75C 90% RH
2 DOCs failed between 500 and 1000 hr
All pigtails failed between 1000 and 2000 hr

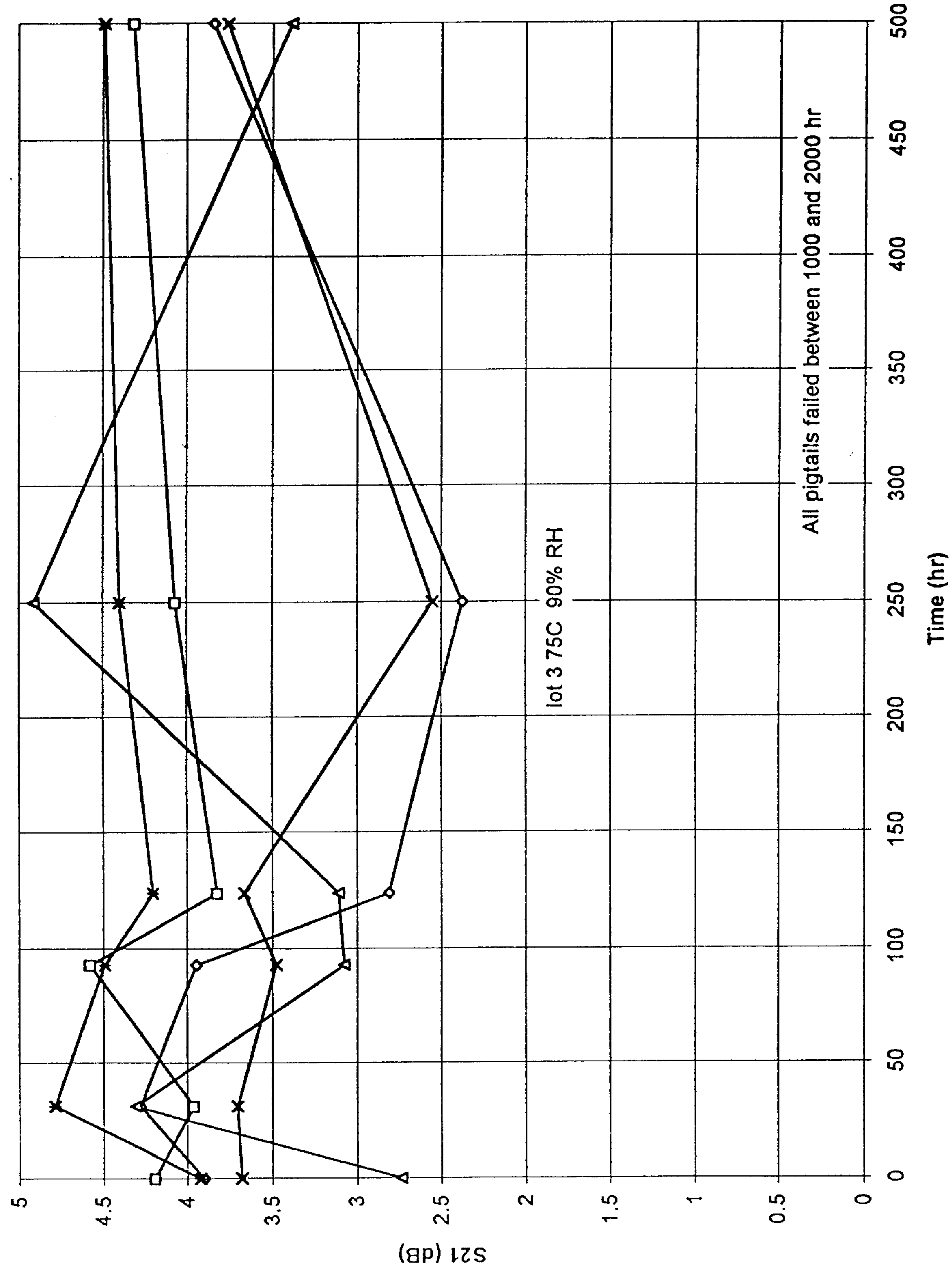

BCM MODULATOR LOT 4 (85°C 90% RH)
DOC Coupling (%)
Time (hr)
lot 4 85C 90% RH
1 DOC failed between 124 and 250 hr
1 DOC failed between 31 and 124 hr
1 DOC failed between 31 and 93 hr
1 device failed due to handling after 31 hr
All pigtails failed between 500 and 1500 hr
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
50
100
150
200
250
300
350
400
450
500


BCM MODULATOR LOT 1 (CONTROL)
lot 1 control
S21 (dB)
5
4
3
2
1
0
-1
-2
Time (hr)
0
100
200
300
400
500
600
700
800
900
1000

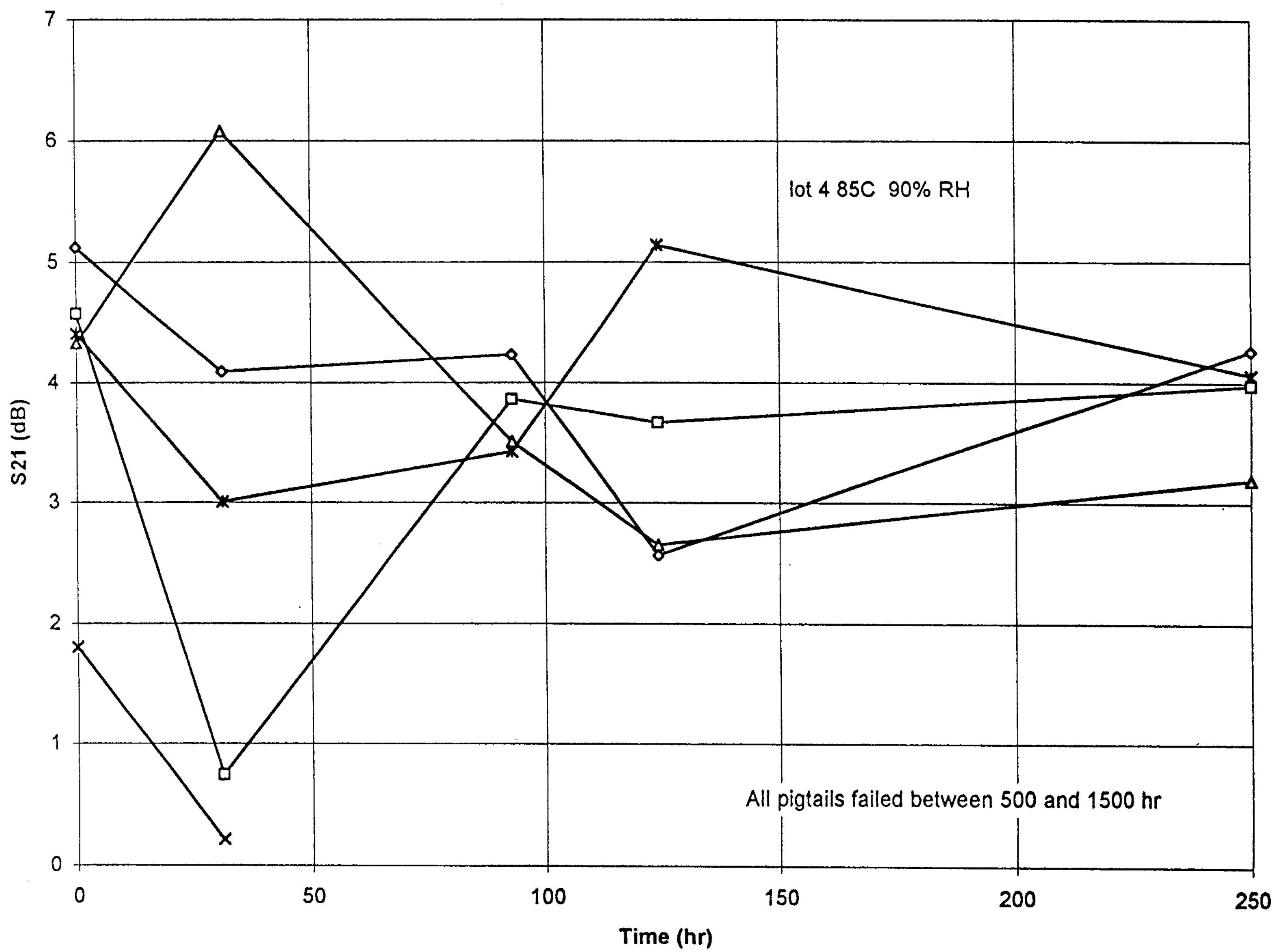


BCM MODULATOR LOT 2 (60°C 90% RH)
lot 2 60C 90% RH
S21 (dB)
6
4
2
0
-2
-4
-6
-8
Time (hr)
0
50
100
150
200
250
300
350
400
450
500

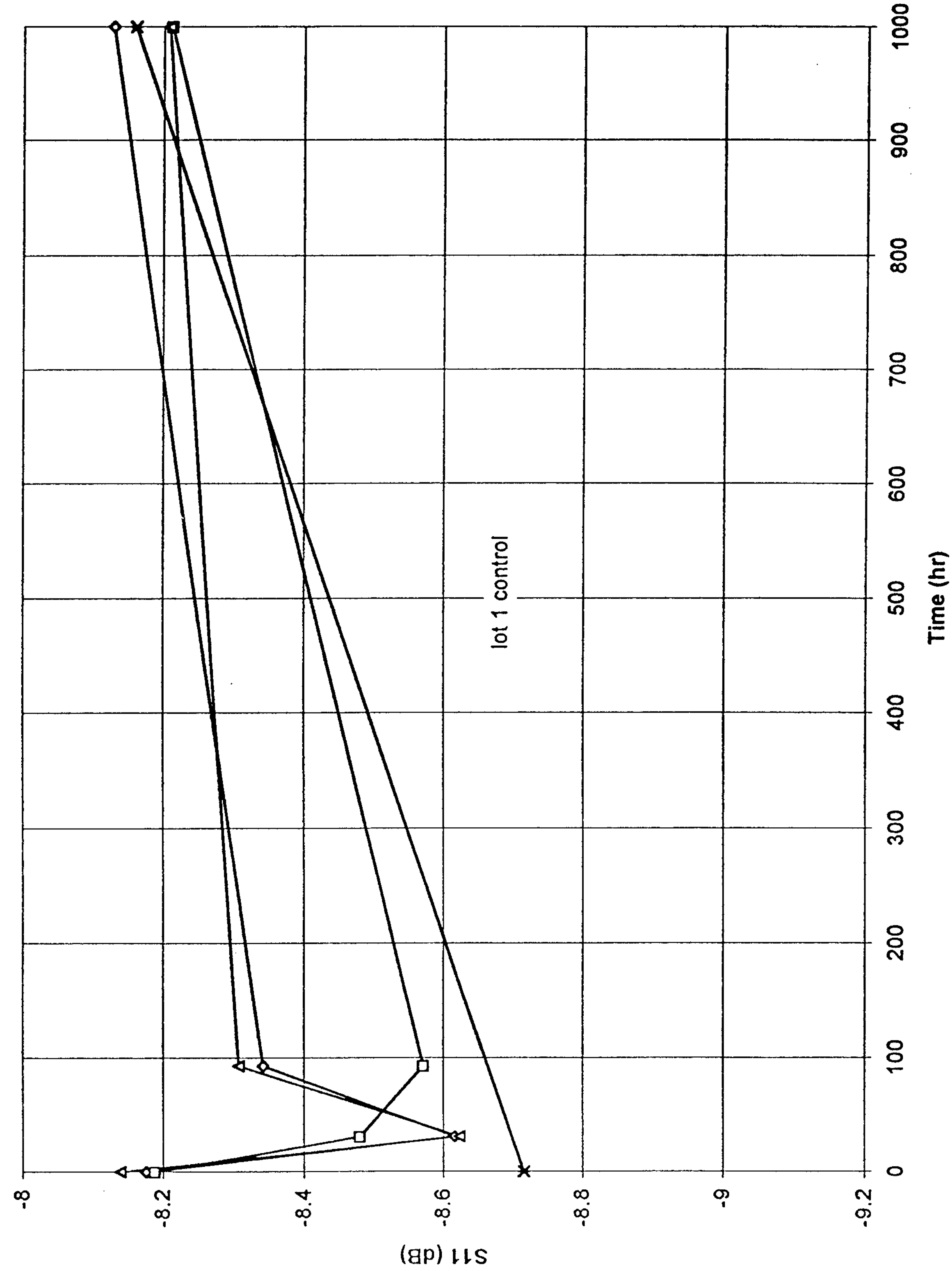
BCM MODULATOR LOT 3 (75°C 90% RH)

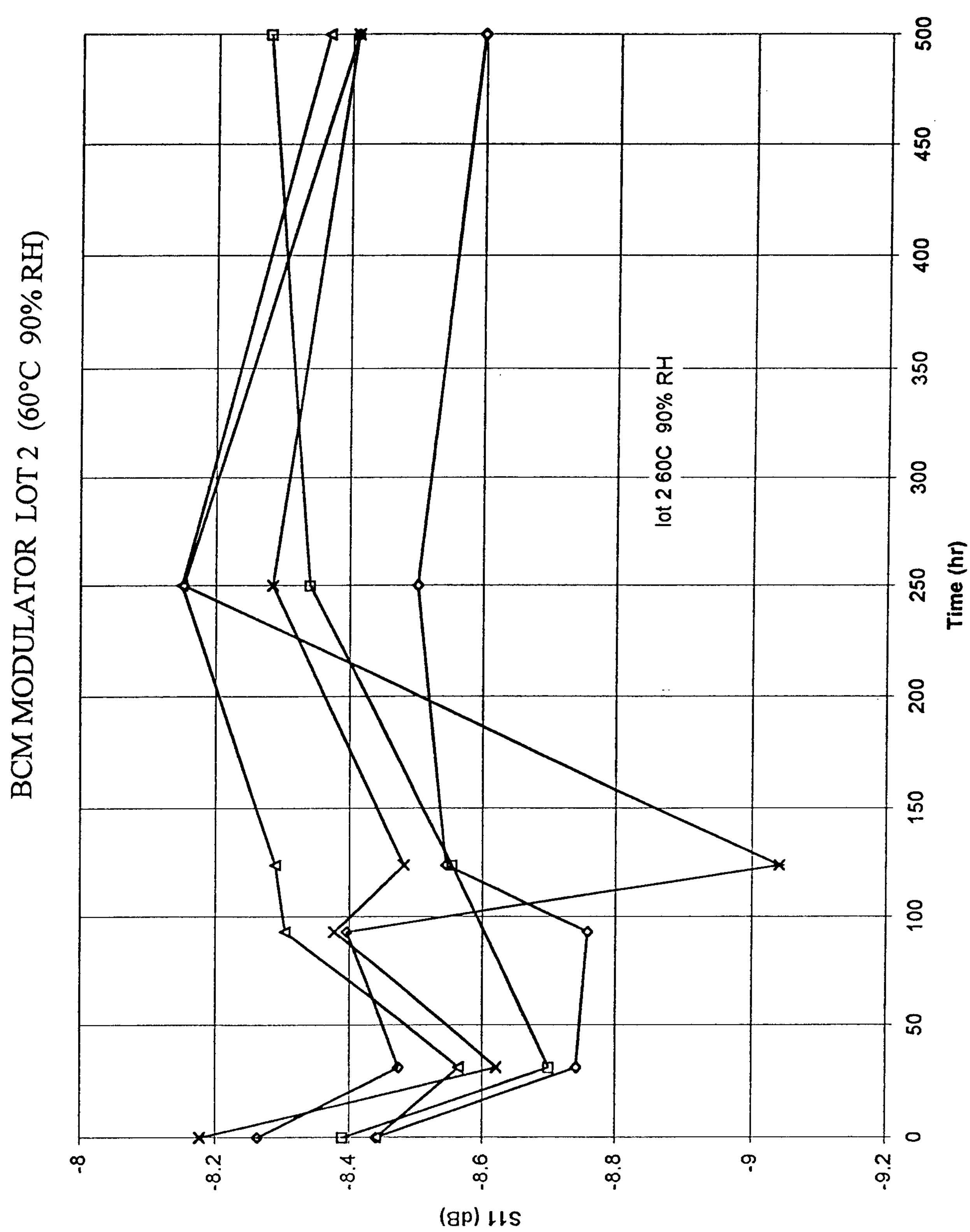


BCM MODULATOR LOT 4 (85°C 90% RH)



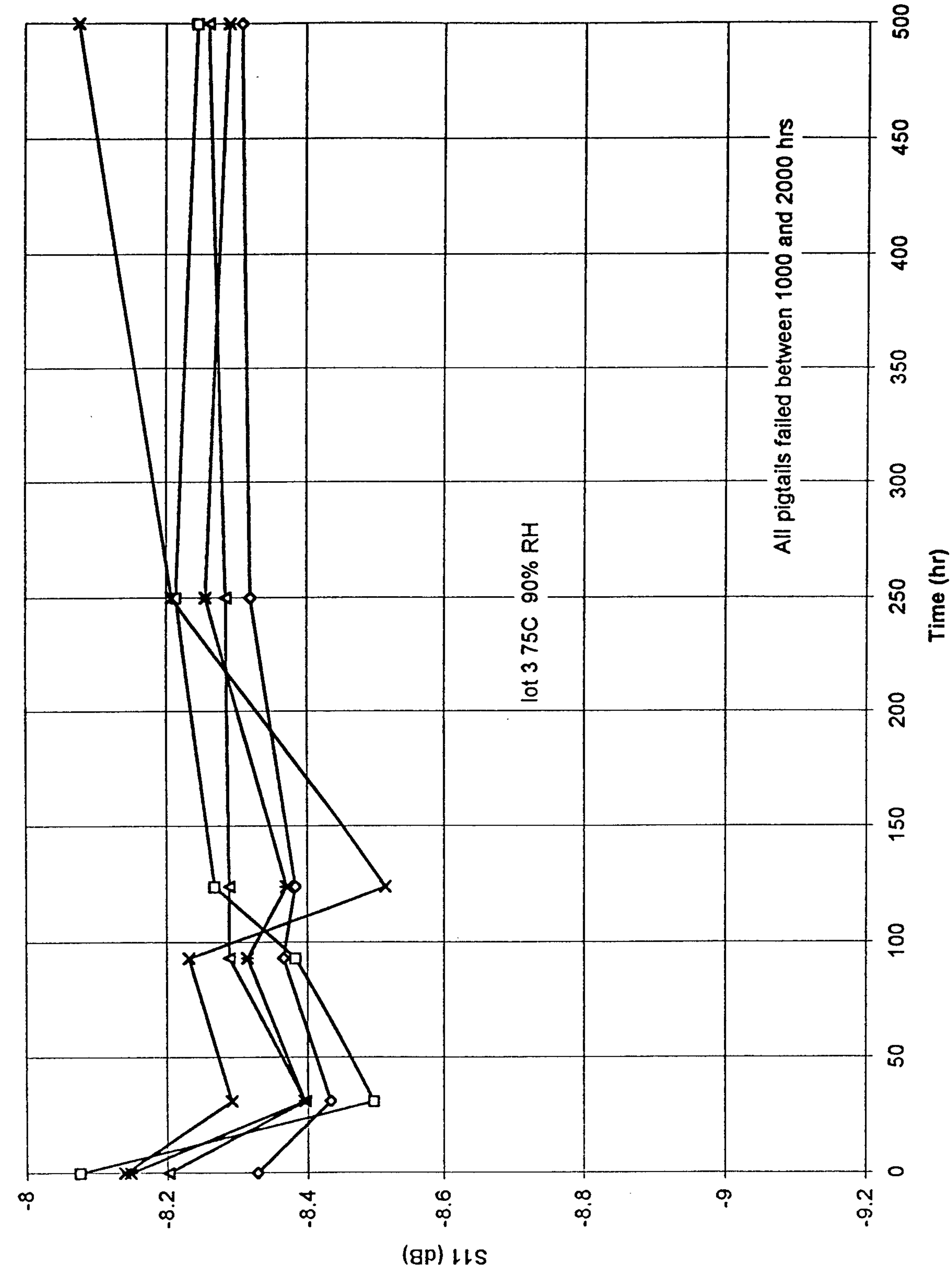
BCM MODULATOR LOT 1 (CONTROL)

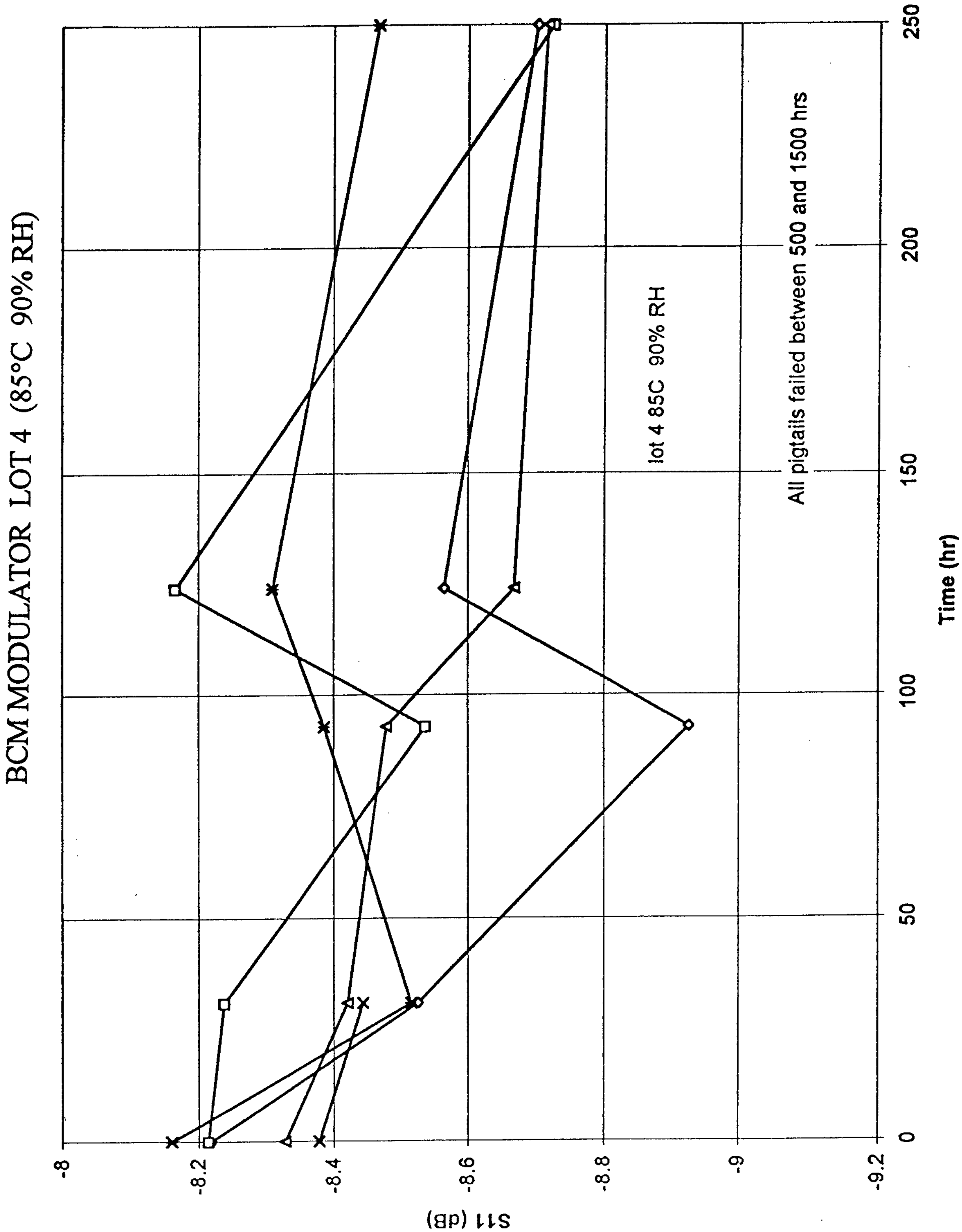




BCM MODULATOR LOT 2 (60°C 90% RH)
lot 2 60C 90% RH
S11 (dB)
Time (hr)
-8
-8.2
-8.4
-8.6
-8.8
-9
-9.2
0
50
100
150
200
250
300
350
400
450
500

BCM MODULATOR LOT 3 (75°C 90% RH)





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MISSION

OF

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Mission. The mission of Rome Laboratory is to advance the science and technologies of command, control, communications and intelligence and to transition them into systems to meet customer needs. To achieve this, Rome Lab:

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d. Promotes transfer of technology to the private sector;

e. Maintains leading edge technological expertise in the areas of surveillance, communications, command and control, intelligence, reliability science, electro-magnetic technology, photonics, signal processing, and computational science.

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