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CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 509918

TITLE

STEEL TRANSITION FRACTURE TOUGHNESS REFERENCE TEMPERTURE DETERMINATION

System Number:

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National Defence
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DREA CR 98/439
OCTOBER 1998

STEEL TRANSITION FRACTURE TOUGHNESS REFERENCE TEMPERATURE DETERMINATION

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CONTRACTOR REPORT

Prepared for

Defence
Research
Establishment
Atlantic

Centre de
Recherches pour la
Défense
Atlantique

Canada

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W7708-7-0705
Contract Number

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Abstract

Quantitative measurements of cracking resistance are needed to assess the risk of brittle fracture under service conditions in warships. This requires laboratory toughness testing at the minimum service temperature and at loading rates equivalent to hull impact events such as wave slamming and minor collisions. Material specifications for ship steels have traditionally relied on tensile strength and Charpy impact energy for quality assessments and as an indicator of structural performance. Unfortunately the data from Charpy tests cannot be used rigorously to describe the fracture of larger components or in structural calculations, and is thus not able to demonstrate adequate damage tolerance in the welded hull.

A technique has recently been standardized by ASTM for determining the fracture toughness of ferritic marine construction steels and welds in the brittle-ductile transition range. K_{Jc} toughness transition curves are generated statistically from the analysis of toughness data populations using a master curve concept. This report describes a preliminary series of tests to evaluate CSA G21 350WT steel plate using this approach, and has established that such a procedure will provide useful data for structural integrity analyses. This work is being extended to include rate effects, plate orientation, and the study of welds.

Résumé

Pour évaluer le risque de rupture fragile en conditions de service sur les navires de guerre, on utilise des mesures quantitatives de résistance aux fissures recueillies lors d'essais de ténacité effectués en laboratoire à la température de service minimale et à des taux de charge équivalents aux impacts sur la coque, comme le battement des vagues et les faibles collisions. Les spécifications pour les aciers entrant dans la fabrication des navires reposent habituellement sur des valeurs de résistance à la rupture et d'énergie d'impact Charpy pour définir les évaluations et pour servir d'indicateur de la performance structurale. Malheureusement, les données des essais Charpy ne sont pas suffisamment exactes pour décrire la rupture des éléments plus imposants ou pour servir aux calculs structuraux, et ne permettent donc pas de faire de démonstration convenable de la tolérance aux dommages d'une coque soudée.

Une technique a récemment été normalisée par l'ASTM pour déterminer la ténacité, dans la zone de transition fragile-ductile, des aciers ferritiques et des soudures entrant dans la fabrication des navires. Les courbes de transition K_{Jc} sur la ténacité sont produites à l'aide de statistiques prélevées à partir de l'analyse d'ensembles statistiques sur les données de ténacité en utilisant le concept de la courbe maîtresse. Le présent rapport décrit une série préliminaire d'essais qui ont servi grâce à cette approche à évaluer une plaque d'acier 350 WT satisfaisant aux exigences de la norme CSA G21. Le rapport démontre qu'une telle procédure peut fournir des données utiles pour l'analyse de l'intégrité structurale. La portée des travaux a été étendue pour inclure les effets de conditionnement, l'orientation des plaques et l'étude des soudures.

DREA CR 98/439

Steel Transition Fracture Toughness Reference Temperature Determination

D.A. Hull

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Executive Summary

The material specification for the CSA 350WT steel plate used in the Halifax class frigates is based primarily on tensile strength and Charpy impact energy. Ferritic steels such as CSA 350WT plate and weld fusion zone exhibit a ductile-brittle transition over a range of temperature, with lower and upper Charpy energy shelves where the material response is "brittle" or "ductile" respectively. There is a need for improved fracture control procedures for ships' hulls to provide guidance for both material selection and specification. In addition, improved inspection and damage assessment procedures are needed to reduce structural maintenance costs. Unfortunately the data generated from Charpy tests tends to be specific to that test, is thus only a qualitative indicator of toughness, and cannot be used rigorously to describe the fracture of larger components or in structural calculations.

There is thus a demand for alternative test procedures to demonstrate adequate damage tolerance in the welded steels used in hull construction. A first step in this process is the quantitative assessment of the resistance to crack initiation. The demonstration of a sufficiently high toughness would provide confidence that the discovery of cracks and their repair could be achieved without compromising the operation of the ship or risking catastrophic failure. It would also provide data for the determination of tolerable crack sizes and the specification of inspection intervals in critical locations under service conditions. This requires laboratory testing at the minimum service temperature and at loading rates equivalent to hull impact events such as wave slamming and minor collisions.

A fracture test method has recently been standardized by ASTM which employs a relatively simple "master curve" procedure to characterize toughness over the lower shelf to mid-transition range. For a wide range of ferritic steels the median toughness for cleavage crack initiation has a characteristic variation with temperature. A series of identical fracture toughness tests is carried out at a selected low temperature, and combined with the master curve analysis to provide statistical estimates of median toughness and upper and lower bound confidence intervals over the transition range. The procedure can also include the estimation of safety margin adjustments to the transition curve.

This report describes a first series of tests on 15 mm thick CSA 350WT plate. The results met all of the requirements of the test procedure for data validation, and thus could be used successfully to generate the desired toughness transition curve. Follow-up work is underway which will include studies of the effect of orientation and higher deformation rates, plus master curve derivation for a welded plate of the same grade of steel.

TABLE OF CONTENTS

	Page
1.0 Introduction	1
2.0 Fracture Toughness Test Procedure	1
3.0 Results	2
4.0 Conclusions	3

Tables 1-6, Figures 1-3

Appendix A - CSA 350WT Fracture Toughness Results

Appendix B - CSA 350WT Tensile Results

1.0 INTRODUCTION.

The Dockyard Laboratory Pacific (DL(P)) has a requirement to determine the fracture toughness of ferritic steels and welds in the ductile to brittle (cleavage) transition temperature range. A new ASTM procedure to determine a fracture toughness master curve of ferritic steels using fatigue pre-cracked specimens, weakest link statistics, and a reference temperature estimate has been developed. This master curve allows the fracture toughness over a range of temperatures to be calculated, and in principle, can be used to facilitate structural integrity analysis of cracked components operating in the material's transition range.

This report describes work undertaken on behalf of DL(P) to determine CSA 350WT plate fracture toughness in the transition range using the ASTM Test Method "Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range", (ASTM E1921-97). The objective was to determine whether this procedure, when applied to 350WT plate, would meet the validity requirements of the standard. A longer term objective of the overall program is to assess the utility of the data so generated for structural integrity analyses of both plates and welds. Engineering Material Research (EMR) carried out the fracture toughness measurements under research and development contract W7708-7-0705/001/XSA.

2.0 FRACTURE TOUGHNESS TEST PROCEDURE.

The 15 mm thick CSA 350WT plate from which the L-T oriented specimens were machined had the chemistry shown in Table 1. Room temperature yield strength was 450 MPa, and the Charpy V-notch energy was 120 Joules at -40°C. The NDT and Dynamic Tear transition temperatures were -40°C and -30°C respectively. The nominal dimensions of the L-T Single Edge notch Bend, SE(B), specimens supplied to EMR were 15 x 30 X 120 mm.

A 100 kN capacity servo-hydraulic load frame was used in this investigation. A personal computer was used to control the load frame and acquire data. A cold box with 100 mm thick insulation was installed in the load frame to allow tests to be conducted at temperatures as low as -100°C within $\pm$2°C The specimen temperature was monitored using two thermocouples mounted 5.0 mm on each side of the specimen starter notch. Liquid nitrogen cooled the interior of the cold box from behind a baffle. A temperature controller cycled a solenoid valve to control the flow of nitrogen from a cryogenic dewar. The specimens were evaluated in a stainless steel three point bend fixture. Applied load was monitored using the load cell attached to the load frame crosshead. Specimen crack mouth opening displacement (CMOD) and load line displacement (LLD) were measured using a clip gauge and extensometer respectively that had been calibrated in accordance with ASTM E83-96. The manufacturer's low temperature operating limit for both gauges was -100°C. In practice, all of the specimens were evaluated at -96°C which provided a small margin of safety for the gauges. The test temperature was selected on the basis of both the measured energy values from Charpy V-notch specimen tests, using the guidelines provided in ASTM E1921-96, and the results from a few trial tests. The basic requirements are that cleavage fracture occurs at the test temperature and the median K_{Jc} value be approximately 100 MPa$\sqrt{m}$. The ASTM E1921-97 procedure was followed throughout the test program.

Specimens were pre-cracked to a nominal crack length, a/W, of 0.5 and then side-grooved 10% of the thickness on each side. The SEB specimens were cooled to -96°C and then dwelled at temperature for 10 to 20 minutes prior to evaluation. Fracture toughness tests were made using displacement control at a rate of 0.05 mm/s. This typically resulted in an elastic loading rate of 4 MPa$\sqrt{m}$/s. The fracture load was usually reached after approximately 30 seconds. Plots of load versus LLD were generated to permit J-integral calculation using the expressions provided in the standard. For each specimen a K_{Jc} values was calculated from the J value at the onset of cleavage. Although the procedure only requires six replicate tests, in this work, 10 such tests were carried out. The larger the number of tests, the narrower would be the tolerance bounds on the calculated master curve. Following completion of the test, the broken halves of the specimen were warmed to approximately 50°C to remove condensation from the fracture surfaces and were then air cooled.

Crack lengths were measured with an optical travelling microscope using the nine point average procedure of ASTM E1921-97. In order to provide tensile data at test temperature needed for data analysis, four tensile specimens were machined from two CSA 350WT steel blanks supplied by DL(P). The specimen geometry met the subsize requirements of ASTM E8-98 for a cylindrical specimen with threaded ends. These specimens were evaluated at -96°C in the 100 kN load frame and the yield strength (0.2% offset), ultimate tensile strength and the elastic modulus were each determined.

3.0 RESULTS.

Detailed results from the individual tensile and fracture tests are provided in Appendices A and B, and summarized in Tables 2 and 3. The fracture load at which cleavage failure occurred varied from 15.7 to 21.7 MPa, and the corresponding range of K_{Jc} was 79 to 161 MPa√m. The mean and median values were 110 and 90 MPa√m respectively, the latter being reasonably close to the desired median. ASTM E1921-97 uses a combination of crack length, K_{Jc} capacity, and cleavage criterion to determine if the K_{Jc} results are valid. The nine crack length measurements must not differ by more than 7% or 0.5 mm, whichever is larger, from the average. Inspection of the specimen crack length measurements in Appendix A revealed this criterion was not violated.

The ASTM standard also requires that cleavage occur prior to reaching K_{Jc}(limit). The KJc(limit) for the SE(B) specimen used in this study was determined to be 237 MPa√m. Inspection of the fracture surface revealed the presence of cleavage on all specimens, and all specimens failed abruptly below the estimated specimen limit load. Consequently all of the KJc results in Table 3 were valid and there was no requirement to exclude or censor any of the data. The 10 K_{Jc} values determined at -96°C were ranked in increasing order and converted to a KJc equivalence for a 25 mm (1T) thickness in Table 4. ASTM E1921-97 uses a three parameter Weibull distribution to describe the fracture toughness cumulative probability for failure. The Weibull minimum value and the exponent, i.e., distribution shape parameter, are assumed to be 20 MPa√m and 4.0 respectively. Only the Weibull distribution's scale parameter, Ko, is to be determined.

ASTM E1921-97 recommends the scale parameter may be determined using the maximum likelihood method or determined graphically from a Weibull plot of the fracture toughness results. Both of these methods were employed with the 350WT plate results. It is noted in passing that an alternate method of determing the Weibull distribution would be to select initial values for each of the Weibull parameters and iterate using linear regression and the correlation coefficient to determine the "goodness of fit" of the provisional Weibull distribution to the experiment results.

The maximum likelihood method gave a reference temperature of -100°C. The corresponding master curve and confidence band equations are presented in Table 5. Figure 1 shows a Weibull plot of the K_{Jc} results with a regression line fitted to these results. This regression line has the form:

$$Y = 4X + Y_0$$

where $Y_0 = -4 \ln(K_0 - 20)$. The scale parameter was determined graphically as the x coordinate of the intersection between the regression line and the x axis. The reference temperature using the Weibull plot was -90°C and the master curve and confidence bands are presented in Table 6. There is thus a difference of 10°C between the reference temperatures calculated by the two methods. The master curves and tolerance bands determined using the maximum likelihood method and Weibull plot are presented in Figures 2 and 3 respectively. The graphs were plotted to -40°C which is the approximate temperature where the median curve reaches the K_{Jc} capacity of the specimen. Upper and lower tolerance bands were determined at 95% and 5% levels of significance. A margin adjusted lower band (LB) accounts for the uncertainty associated with the determination of T_0 using a limited number of specimens. Comparison of the two plots shows that the master curve determined from the Weibull plot is the more conservative of the two master curves. For example, at -50°C, the predicted maximum likelihood and Weibull K_{JC} values are 210 and 179 MPa√m respectively.

4.0 CONCLUSIONS.

A master curve that describes CSA350 WT fracture toughness in the transition range was determined using the method of ASTM E1921-97 and 10 valid test results were obtained at -96°C. The test program was successful in meeting the requirements of the procedure. It is clear in this orientation at least, and at the loading rate employed, that this plate is very tough, and has a satisfactorily low reference temperature and master curve. There is a need to assess the significance of these results with reference to the structural performance of this material in a welded ship, but this is beyond the scope of this contract. Further testing is needed on both the plate in the less tough L-T orientation, and also on the corresponding weld used in frigate construction and repair. The procedure as written places limits on the loading rate to be used and also does not cover testing of a weld heat effected zone, and it would be of interest to determine whether these restrictions are necessary when applied to this steel. In addition, it is suggested that the assumption that the Weibull distribution scale and minimum parameters are fixed, needs further study by exploring alternate methods of fitting the Weibull distribution to the experimental results.

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Ti	Al
0.16	1.38	0.009	0.005	0.28	0.019	0.21	0.018	0.009	0.07	0.002	0.009	0.036

Table 1.
CSA 350WT Plate Chemical Composition.

S/N	YS(0.2% offset) [MPa]	UTS [MPa]	E [MPa]
E350-T1	616	703	1.9E5
E350-T2	601	694	1.8E5
E350-T3	649	718	2.0E5
E350-T4	647	713	2.1E5
Average	628	707	2.0E5

Table 2.
Tensile Specimen Results.

S/N	Temp [°C]	Pmax [kN]	LLDmax [mm]	a/W	K_{Jc} [MPa√m]	Fracture Surface Appearance
E350-2	-80	19.9	0.4	0.52	121	flat
E350-3	-96	21.7	0.6	0.52	161	flat/int. shear
E350-4	-96	18.5	0.3	0.52	92	flat
E350-5	-96	19.7	0.5	0.55	129	flat
E350-6	-96	20.4	0.7	0.53	153	flat
E350-7	-96	15.7	0.3	0.53	79	flat
E350-8	-96	17.1	0.3	0.54	90	flat
E350-9	-96	13.4	0.2	0.53	68	flat
E350-10	-96	18.6	0.6	0.55	155	flat
E350-11	-96	16.3	0.4	0.53	82	flat
E350-13	-96	16.8	0.4	0.54	89	flat

K_{Jc} Average(-96°C results) = 109.8 MPa√m

Table 3.
SE(B) Specimen Results.

Rank (i)	S/N	K_{Jc} [MPa√m]	K_{Jc} (1T Thickness) [MPa√m]
1	E350-9	68	62
2	E350-7	79	72
3	E350-11	82	74
4	E350-13	89	81
5	E350-8	90	81
6	E350-4	92	83
7	E350-5	129	116
8	E350-6	153	137
9	E350-10	155	138
10	E350-3	161	144

Table 4.
Ranked K_{Jc} Results Converted to K_{Jc} (1T)

Scale Parameter K_0 [MPa√m] = 114

Median K_{Jc} [MPa√m] = 106

Reference Temperature T_0 [°C] = -100

Master Curve: K_{Jc} (median) = 30 + 70 exp[0.019(T + 100)]

Upper Confidence Band: K_{Jc} (95%) = 34.6 + 102.2 exp[0.019 (T + 100)]

Lower Confidence Band: K_{Jc} (5%) = 25.4 + 37.8 exp[0.019 (T +100)]

Margin Adjusted Lower Bound Curve: K_{Jc} (LB) = 25.4 + 37.8 exp[0.019(T + 89)]

Table 5.
Master Curve Analysis Results Using Ko Determined By The Maximum Likelihood Method.

From Figure 1: Ln(K_0-20) = 4.375

Scale Parameter K_0 [MPa√m] = 99

Median K_{Jc} [MPa√m] = 92

Reference Temperature T_0 [°C] = -90

Master Curve: K_{Jc} (median) = 30 + 70 exp[0.019(T + 90)]

Upper Confidence Band: K_{Jc} (95%) = 34.6 + 102.2 exp[0.019 (T + 90)]

Lower Confidence Band: K_{Jc} (5%) = 25.4 + 37.8 exp[0.019 (T + 90)]

Margin Adjusted Lower Bound Curve: K_{Jc} (LB) = 25.4 + 37.8 exp[0.019(T + 79)]

Table 6.
Master Curve Analysis Results Using K_0 Determined From The Weibull Plot.

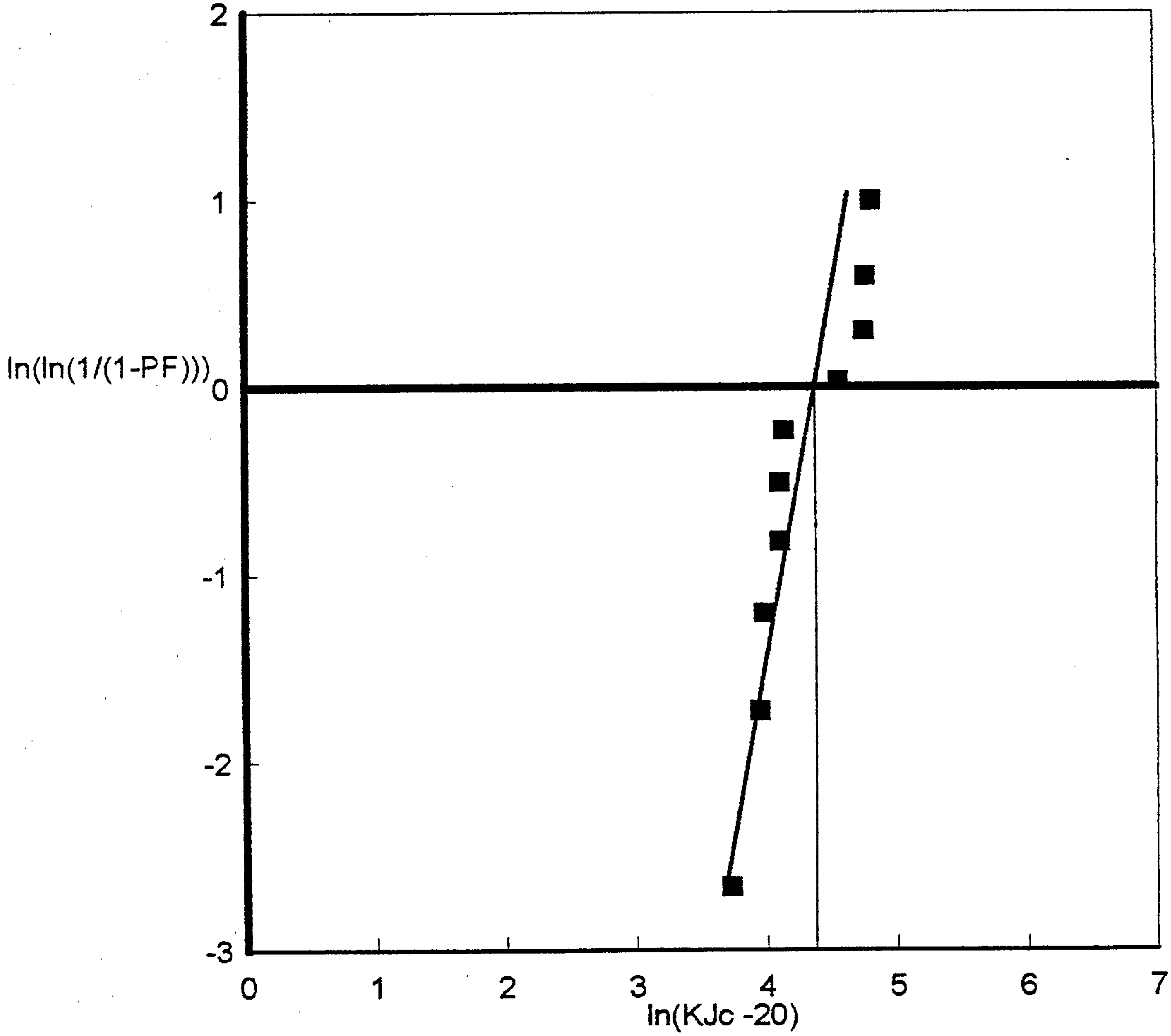

FIGURE 1.
WEIBULL PLOT OF KJc RESULTS AT -96C.

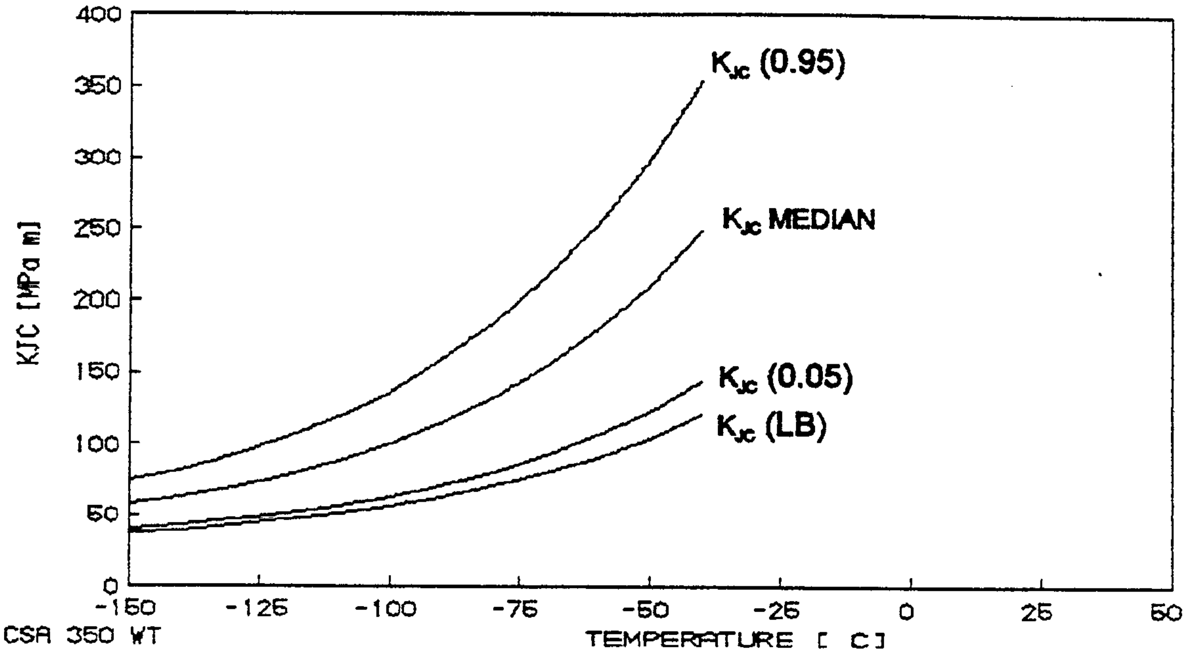

FIGURE 2.
CSA 350WT Master Curve Using The K_0 Determined By The Maximum Likelihood Method.

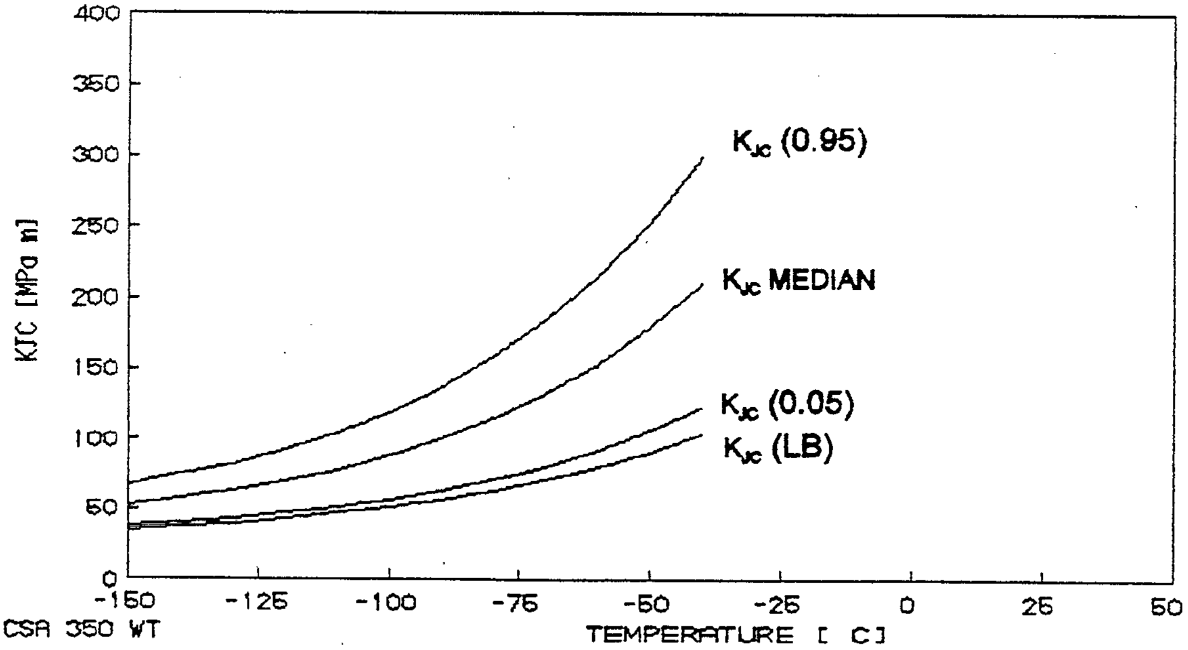

FIGURE 3.
CSA 350WT Master Curve Determined Using The K_0 From The Weibull Plot.

APPENDIX A.
CSA 350WT FRACTURE TOUGHNESS RESULTS.

Table of Contents.

Table No.	Name
A1.	Specimen E350-2 Results.
A2.	Specimen E350-3 Results.
A3.	Specimen E350-4 Results.
A4.	Specimen E350-5 Results.
A5.	Specimen E350-6 Results.
A6.	Specimen E350-7 Results.
A7.	Specimen E350-8 Results.
A8.	Specimen E350-9 Results.
A9.	Specimen E350-10 Results.
A10.	Specimen E350-11 Results.
A11.	Specimen E350-13 Results.

Figure No.	Name
A1.	Specimen E350-2 Load Vs. LLD Plot At -80°C.
A2.	Specimen E350-3 Load Vs. LLD Plot At -96°C.
A3.	Specimen E350-4 Load Vs. LLD Plot At -96°C.
A4.	Specimen E350-5 Load Vs. LLD Plot At -96°C.
A5.	Specimen E350-6 Load Vs. LLD Plot At -96°C.
A6.	Specimen E350-7 Load Vs. LLD Plot At -96°C.
A7.	Specimen E350-8 Load Vs. LLD Plot At -96°C.
A8.	Specimen E350-9 Load Vs. LLD Plot At -96°C.
A9.	Specimen E350-10 Load Vs. LLD Plot At -96°C.
A10.	Specimen E350-11 Load Vs. LLD Plot At -96°C.
A11.	Specimen E350-13 Load Vs. LLD Plot At -96°C.

SPECIMEN NO:	E350-2
TEMPERATURE:	-80 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-09

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.94	14.96	11.98	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.23	15.47	15.54	15.59	15.59	15.66	15.66	15.57	15.42	15.55	±0.11

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.52	19.86	97.3	47.4	25.5	72.9	120.7

Table A1.
Specimen E350-2 Results.

SPECIMEN NO:	E350-3
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-09

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
30.03	14.97	11.87	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.38	15.65	15.80	15.91	15.88	15.85	15.83	15.71	15.48	15.76	±0.16

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_p [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.52	21.69	108.3	58.6	71.4	130.0	161.3

Table A2.
Specimen E350-3 Results.

SPECIMEN NO:	E350-4
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-09

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
30.00	15.11	11.78	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.40	15.60	15.75	15.79	15.77	15.73	15.69	15.62	15.39	15.67	±0.13

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.52	18.49	91.6	41.9	0	41.9	91.6

Table A3.
Specimen E350-4 Results.

SPECIMEN NO:	E350-5
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-09

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.45	15.03	11.91	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.84	16.06	16.18	16.23	16.21	16.18	16.07	15.95	15.67	16.08	±0.16

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.55	19.66	108.1	62.5	20.1	82.6	128.5

Table A4.
Specimen E350-5 Results.

SPECIMEN NO:	E350-6
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-10

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
30.13	14.96	11.78	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.59	15.85	15.95	16.02	16.03	16.06	16.06	15.96	15.79	15.95	±0.13

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.53	20.42	103.4	53.5	62.8	116.3	152.5

Table A5.
Specimen E350-6 Results.

SPECIMEN NO:	E350-7
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-10

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
30.10	14.99	11.83	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.60	15.84	15.99	16.08	16.09	16.06	15.98	15.85	15.60	15.94	±0.17

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.53	15.7	79.4	31.6	0	31.6	79.4

Table A6.
Specimen E350-7 Results.

SPECIMEN NO:	E350-8
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-11

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.83	14.97	11.80	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.71	15.95	16.06	16.15	16.16	16.14	16.11	15.97	15.76	16.03	±0.15

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.54	17.1	89.9	40.4	0	40.4	89.9

Table A7.
Specimen E350-8 Results.

SPECIMEN NO:	E350-9
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-12

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
30.00	15.00	11.79	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.67	15.85	15.95	15.97	15.94	15.88	15.76	15.62	15.36	15.81	±0.16

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.53	13.4	67.7	22.9	0	22.9	67.7

Table A8.
Specimen E350-9 Results.

SPECIMEN NO:	E350-10
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-07-12

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.92	14.96	11.81	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
16.15	16.48	16.61	16.69	16.67	16.66	16.66	16.54	16.30	16.57	±0.16

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.55	18.6	103.2	53.2	66.2	119.4	154.5

Table A9.
Specimen E350-10 Results.

SPECIMEN NO:	E350-11
TEMPERATURE:	-96 °C
MATERIAL:	CSA G21 350 WT
SPECIMEN GEOMETRY:	SE(B) (120 X 30 X 15 mm)
DATE OF EVALUATION:	98-08-03

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.95	15.00	11.85	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.71	15.95	16.07	16.15	16.16	16.11	16.03	15.88	15.75	16.01	±0.15

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa√m]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa√m]
0.53	16.3	82.0	31.4	0	31.4	82.0

Table A10.
Specimen E350-11 Results.

SPECIMEN NO: E350-13

TEMPERATURE: -96 °C

MATERIAL: CSA G21 350 WT

SPECIMEN GEOMETRY: SE(B) (120 X 30 X 15 mm)

DATE OF EVALUATION: 98-08-03

MEASUREMENT RESULTS:

YIELD STRENGTH (0.2% offset): 628 [MPa]

W [mm]	B [mm]	BN [mm]	S [mm]	a_0 [mm]
29.87	15.01	11.73	120.2	12.0

PRE-CRACK LENGTH (9 POINT) [mm]:

a1	a2	a3	a4	a5	a6	a7	a8	a9	AVG*	ST.DEV.
15.76	16.03	16.15	16.22	16.25	16.27	16.21	16.10	15.84	16.13	±0.16

*As per ASTM E1921-97 Section 8.8.1

SUMMARY:

a/W	PM [kN]	K_e [MPa$\sqrt{m}$]	J_e [kJ/m2]	J_P [kJ/m2]	J_C [kJ/m2]	K_{JC} [MPa$\sqrt{m}$]
0.54	16.8	89.4	39.9	0	39.9	89.4

Table A11.
Specimen E350-13 Results.

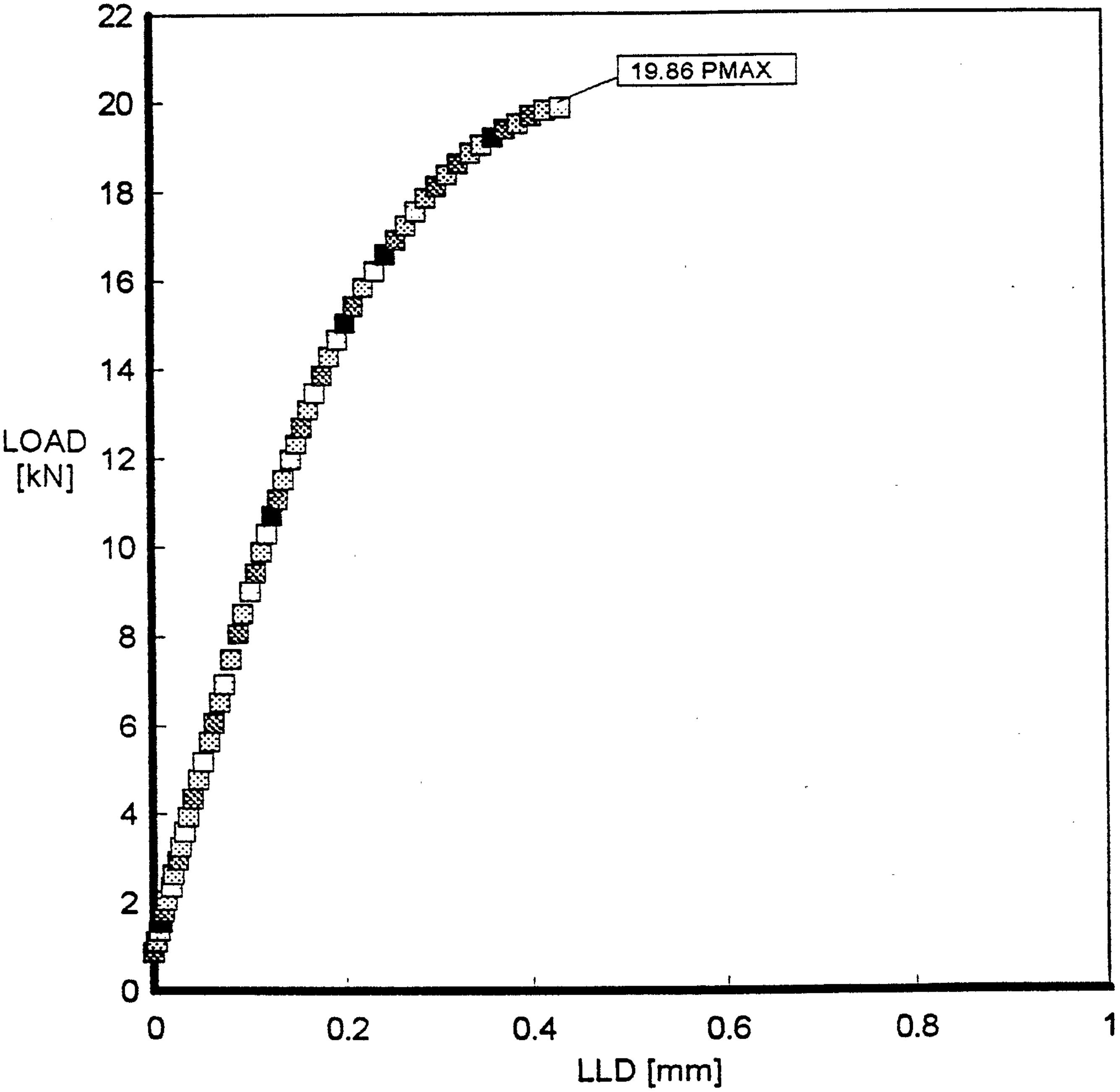

FIGURE A1.
SPECIMEN 350-2 LOAD VS. LLD PLOT AT -80C.

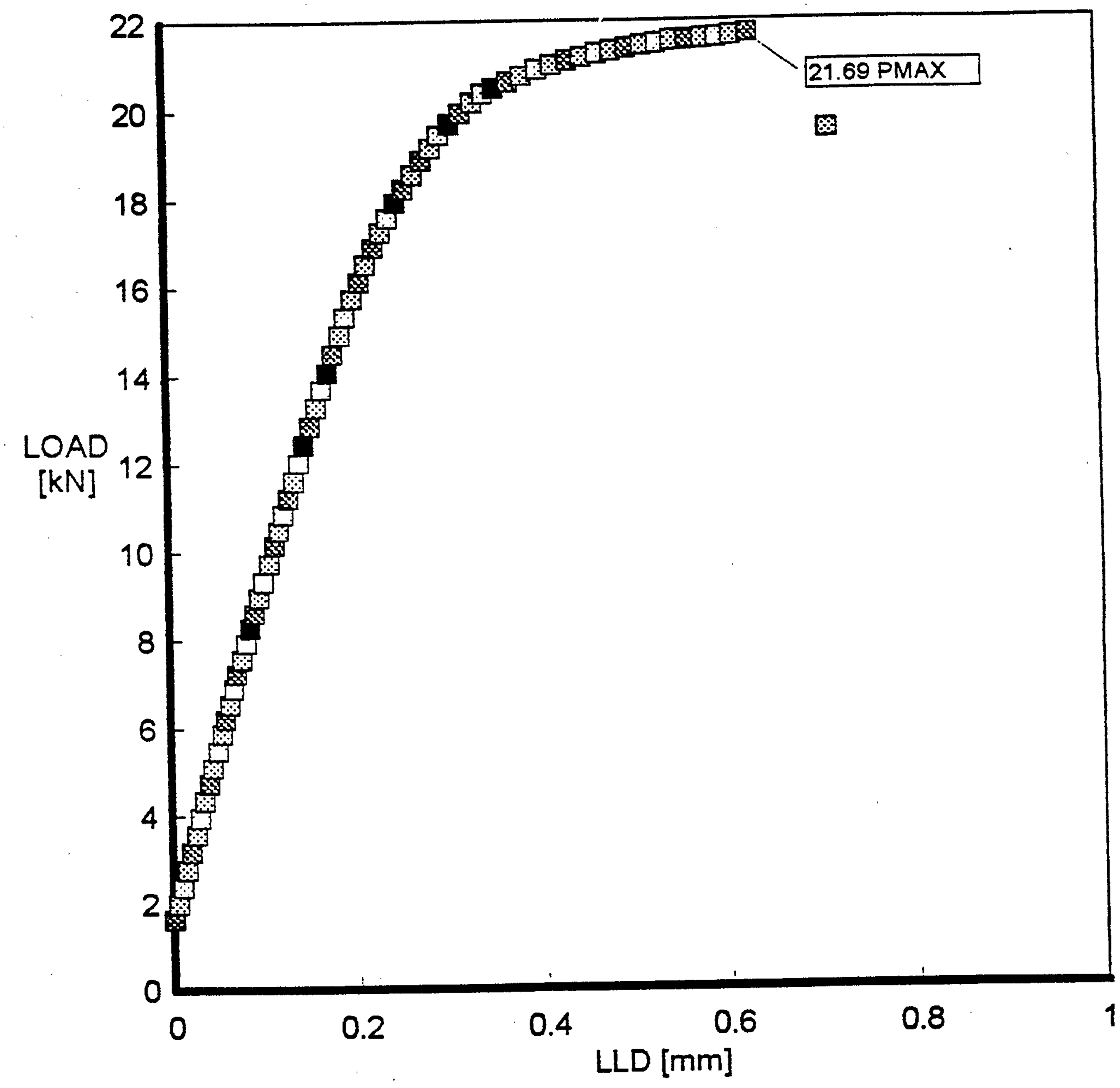

FIGURE A2.
SPECIMEN 350-3 LOAD VS. LLD PLOT AT -96C.

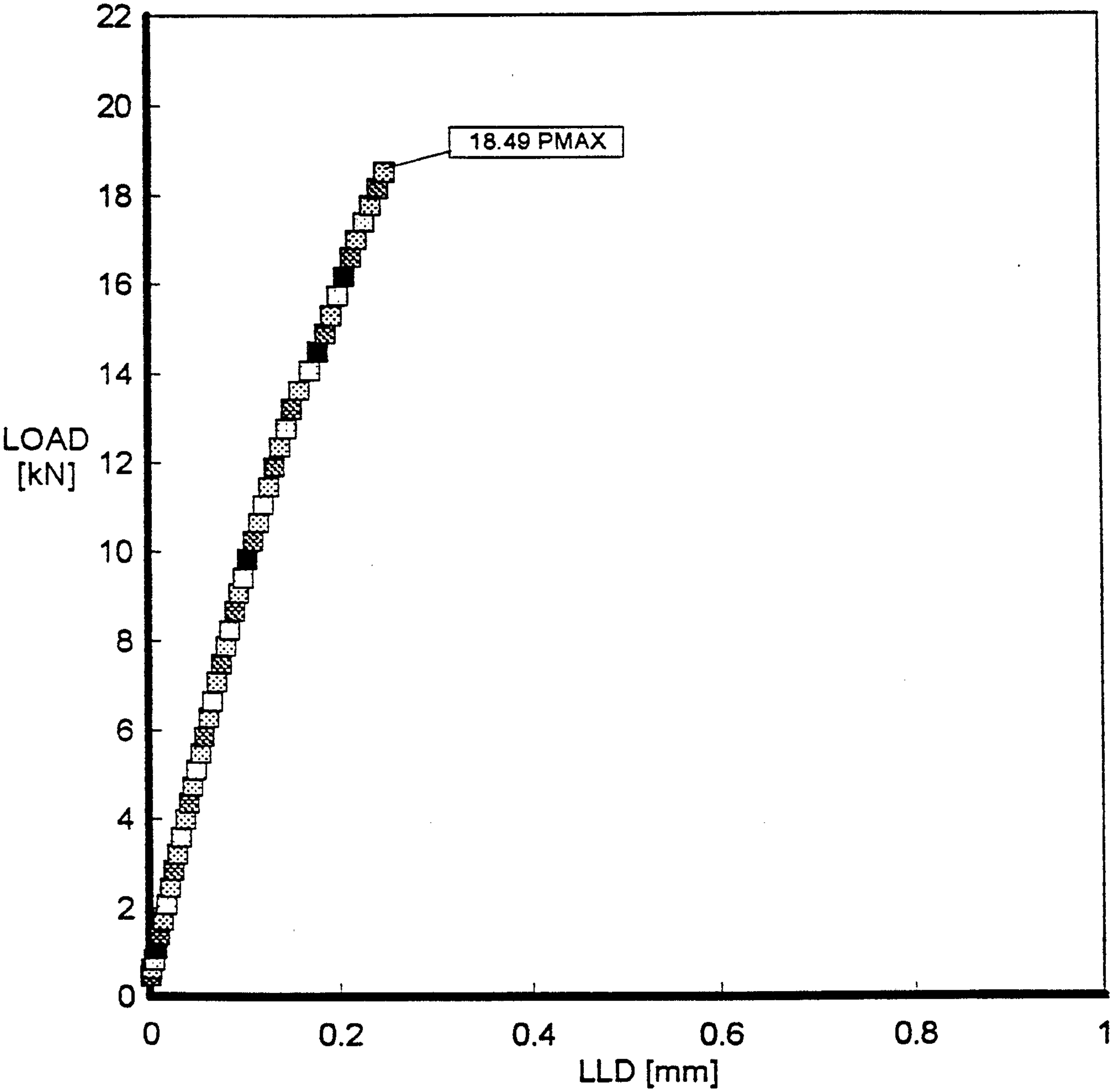

FIGURE A3.
SPECIMEN 350-4 LOAD VS. LLD PLOT AT -96C.

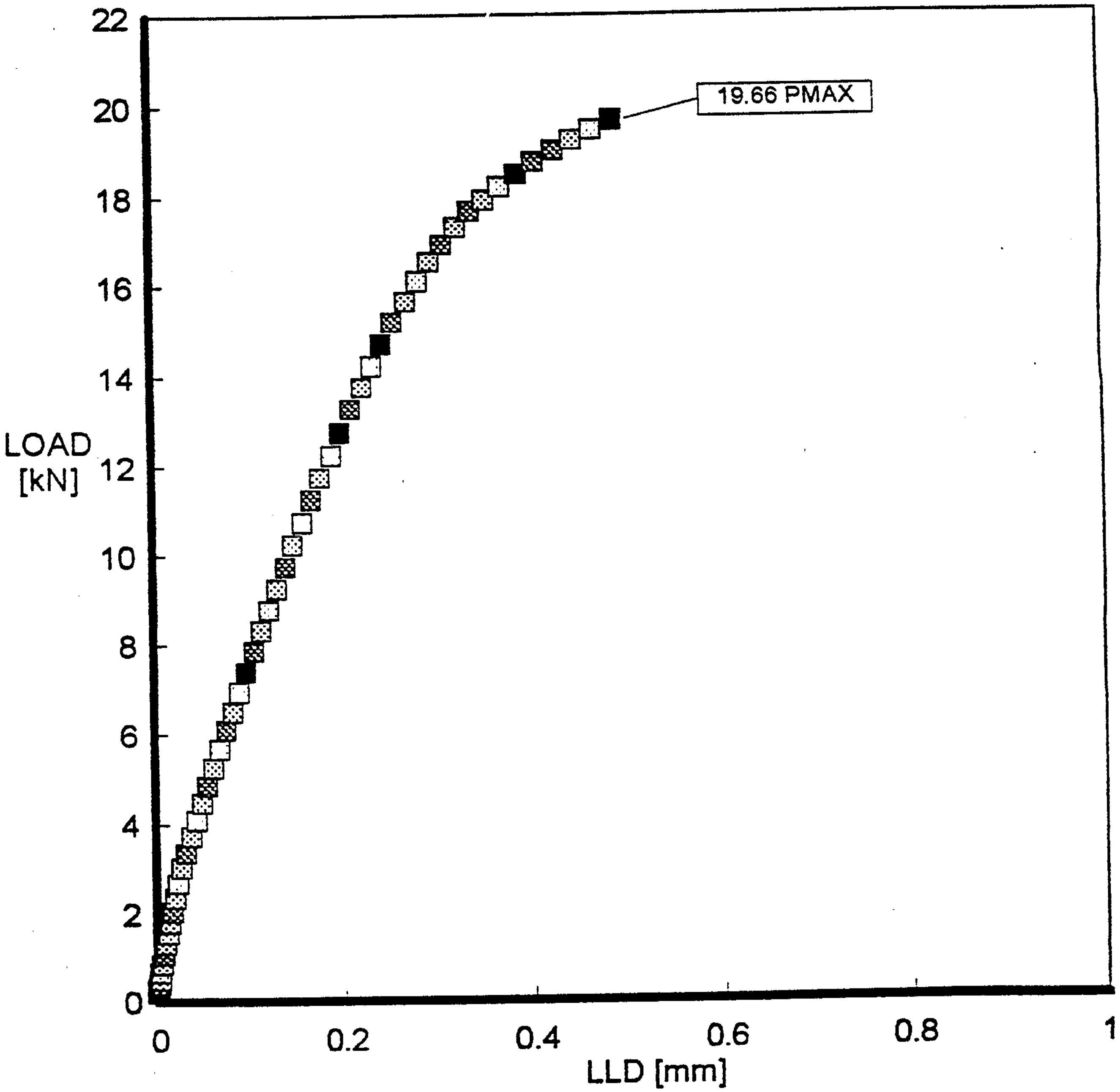

FIGURE A4.
SPECIMEN 350-5 LOAD VS. LLD PLOT AT -96C.

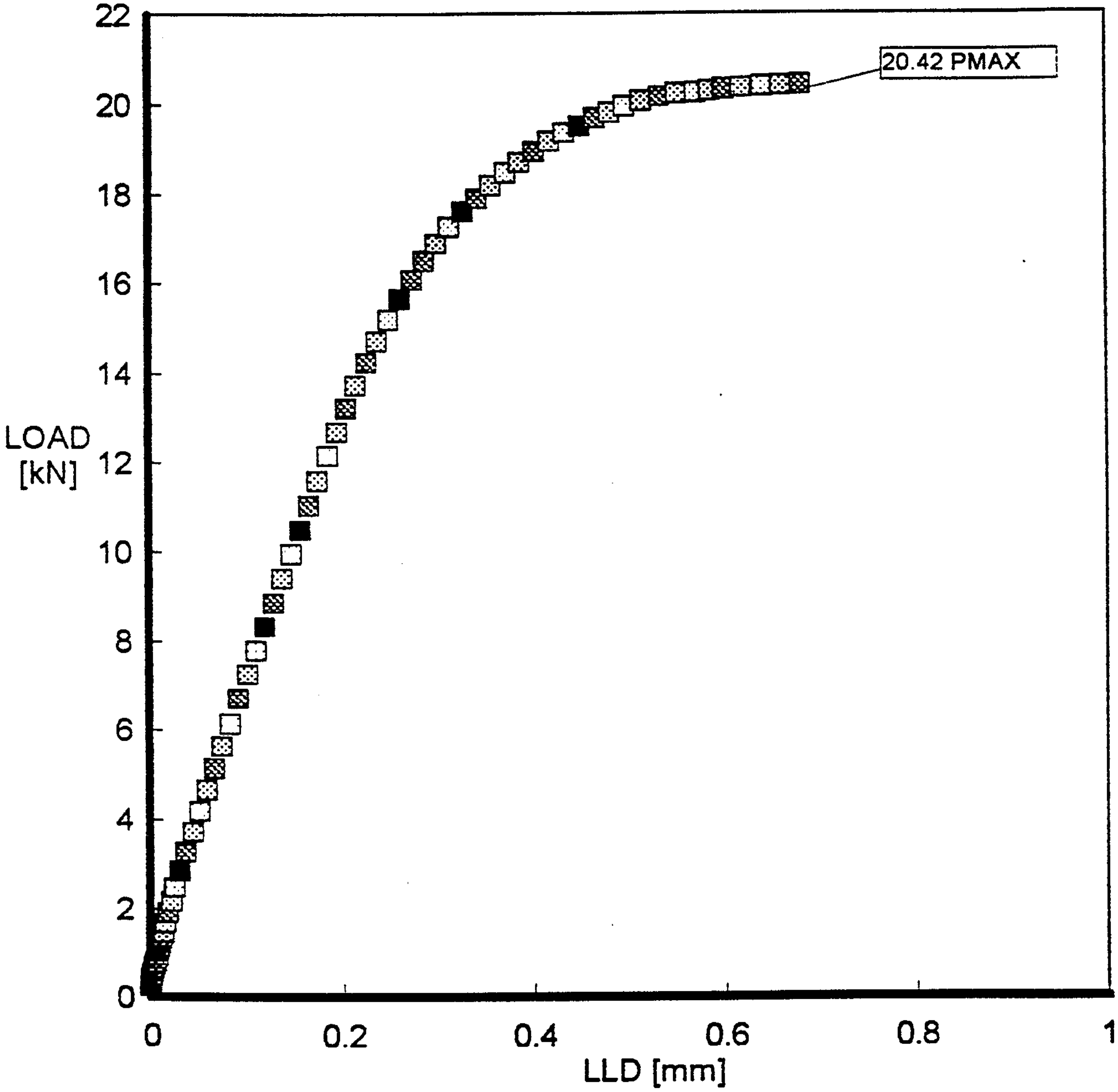

FIGURE A5.
SPECIMEN 350-6 LOAD VS. LLD PLOT AT -96C.

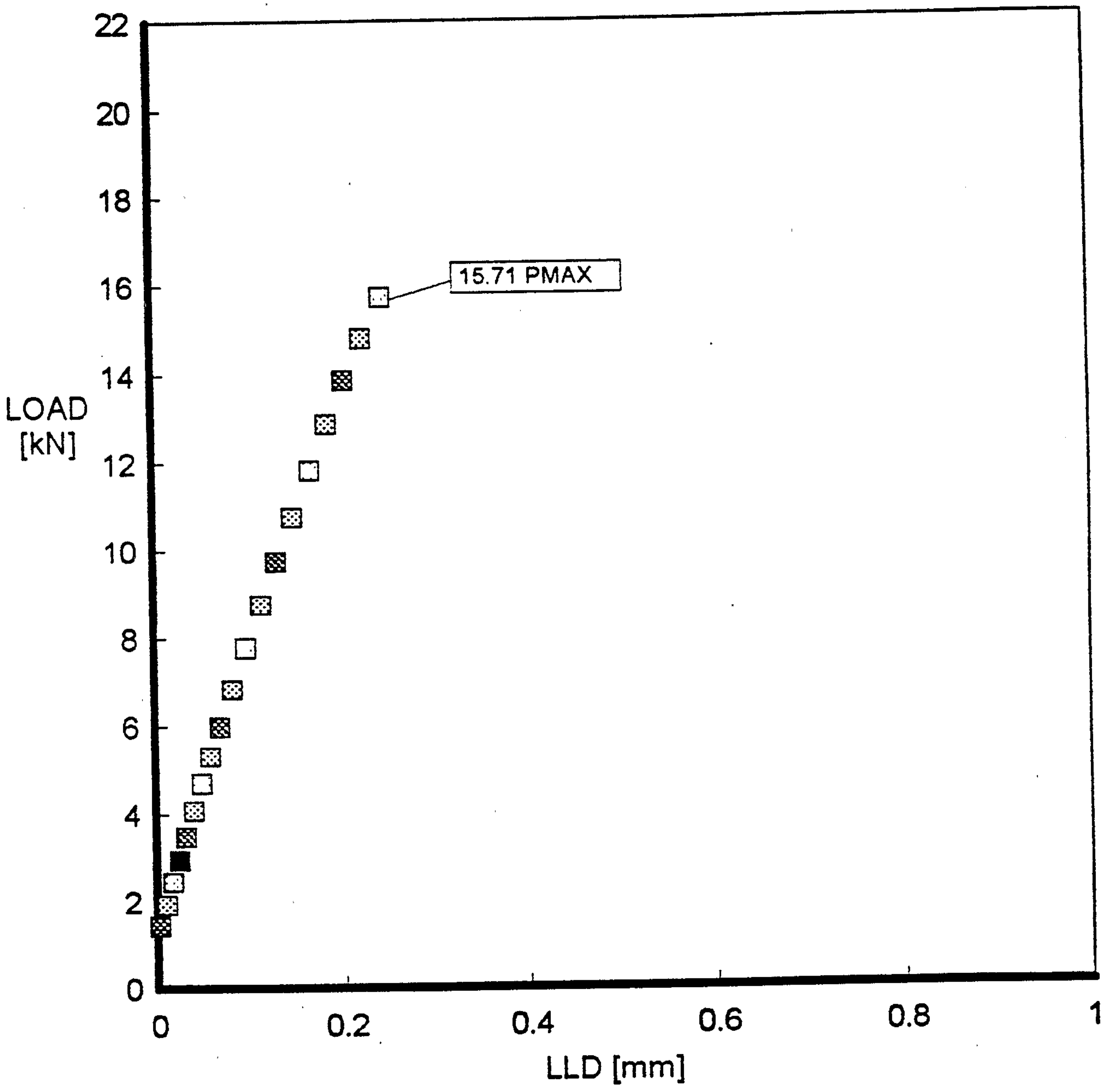

FIGURE A6.
SPECIMEN 350-7 LOAD VS. LLD PLOT AT -96C.

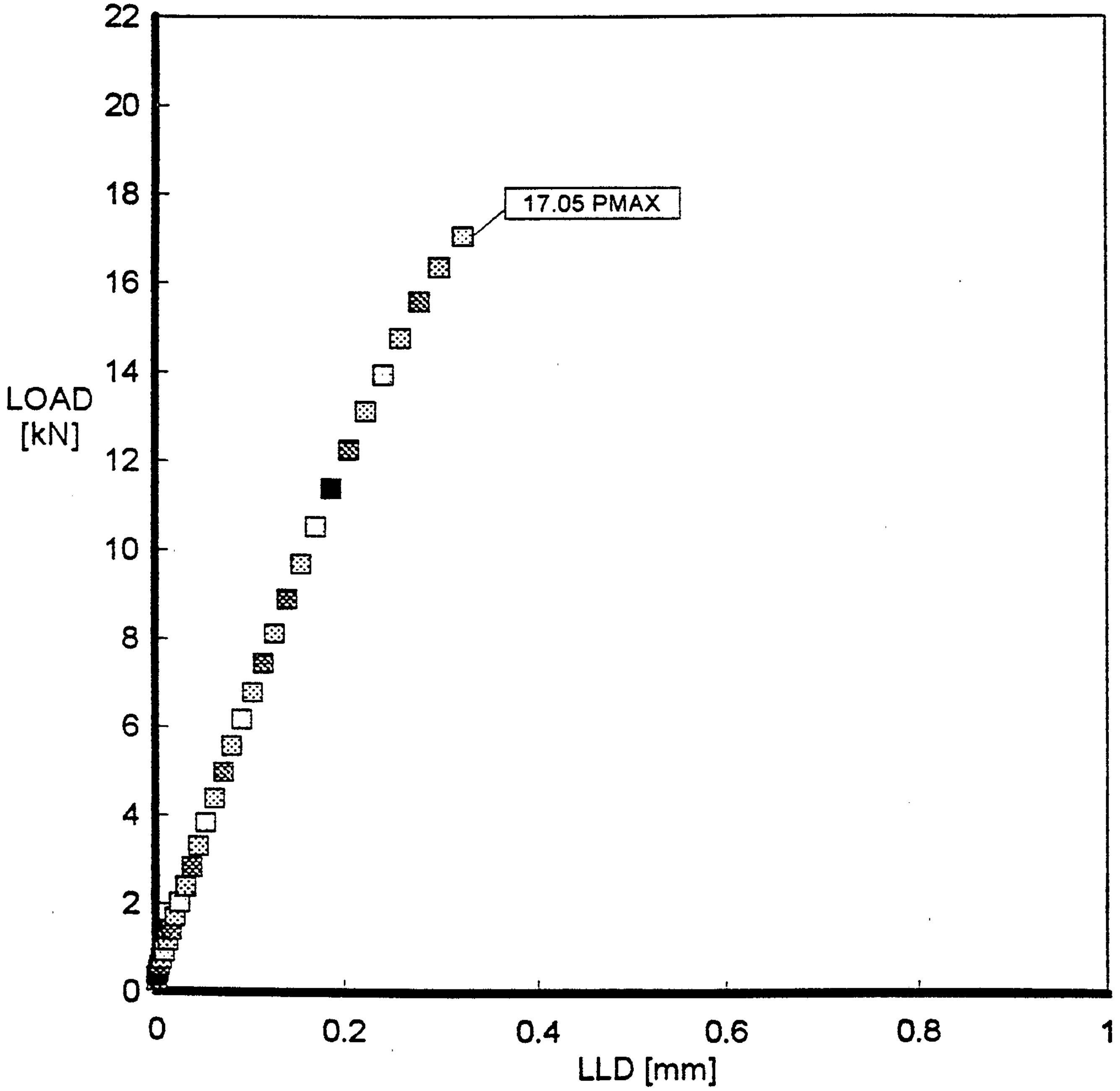

FIGURE A7.
SPECIMEN 350-8 LOAD VS. LLD PLOT AT -96C.

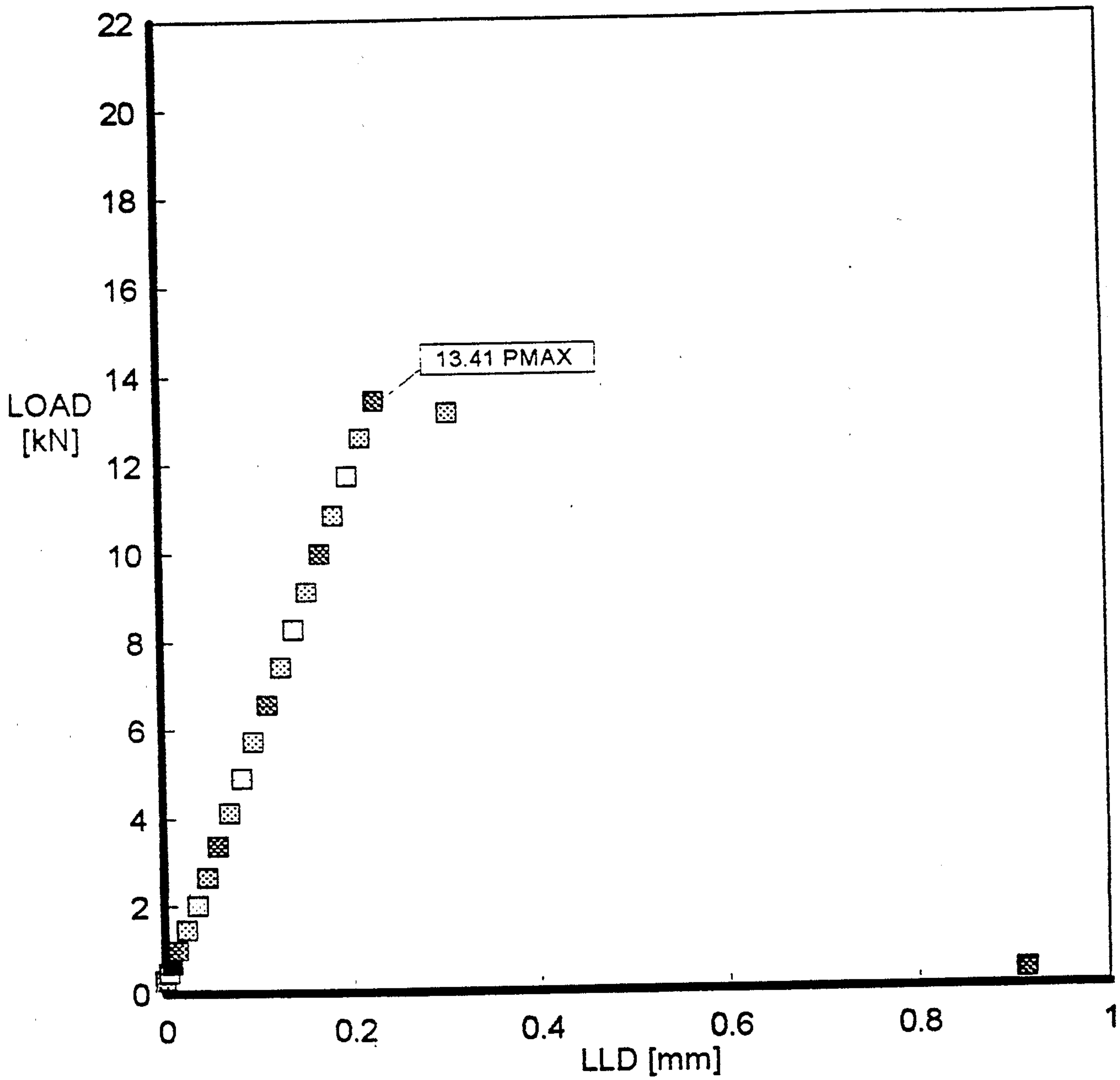

FIGURE A8.
SPECIMEN 350-9 LOAD VS. LLD PLOT AT -96C.

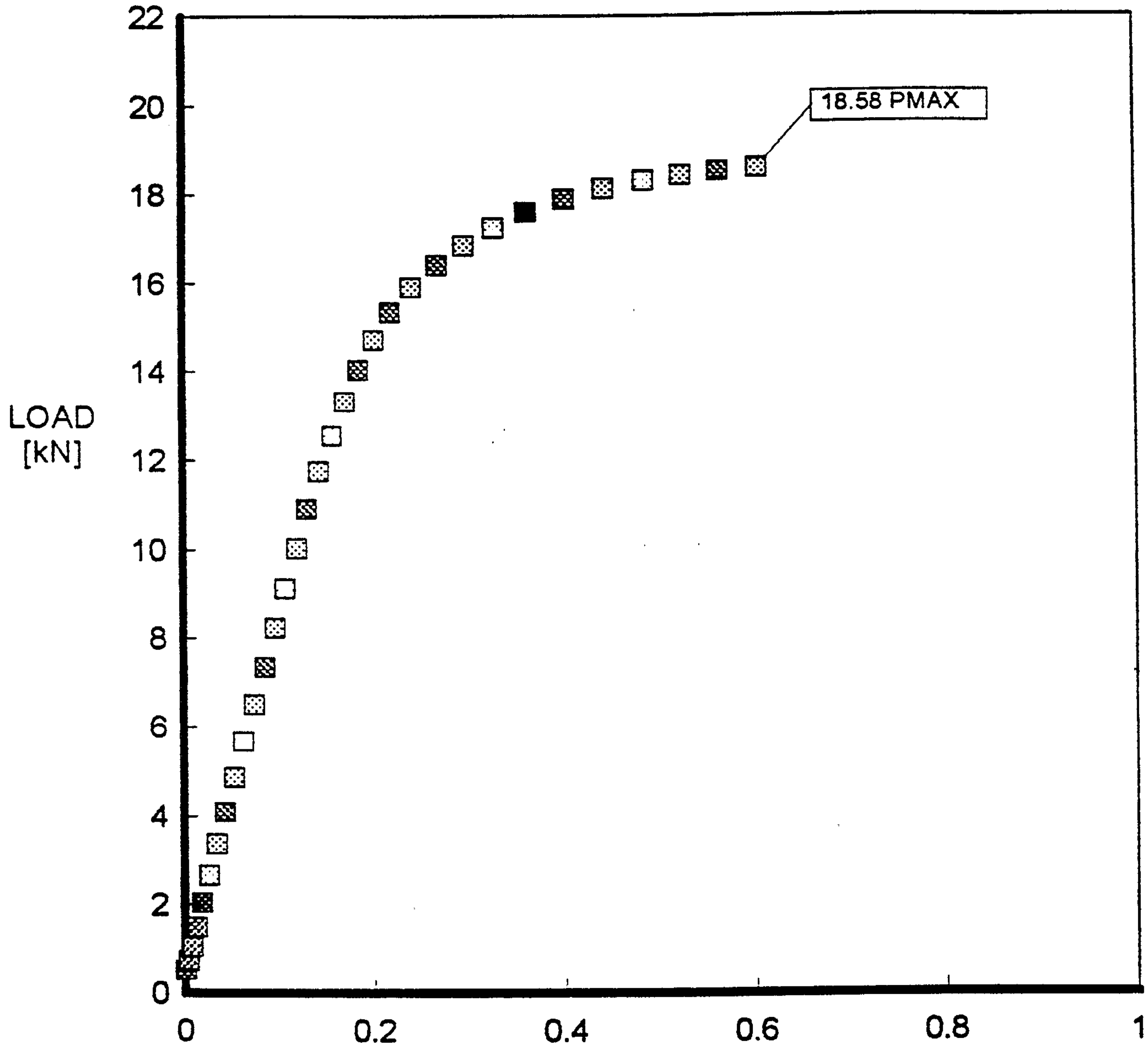

FIGURE A9.
SPECIMEN 350-10 LOAD VS. LLD PLOT AT -96C.

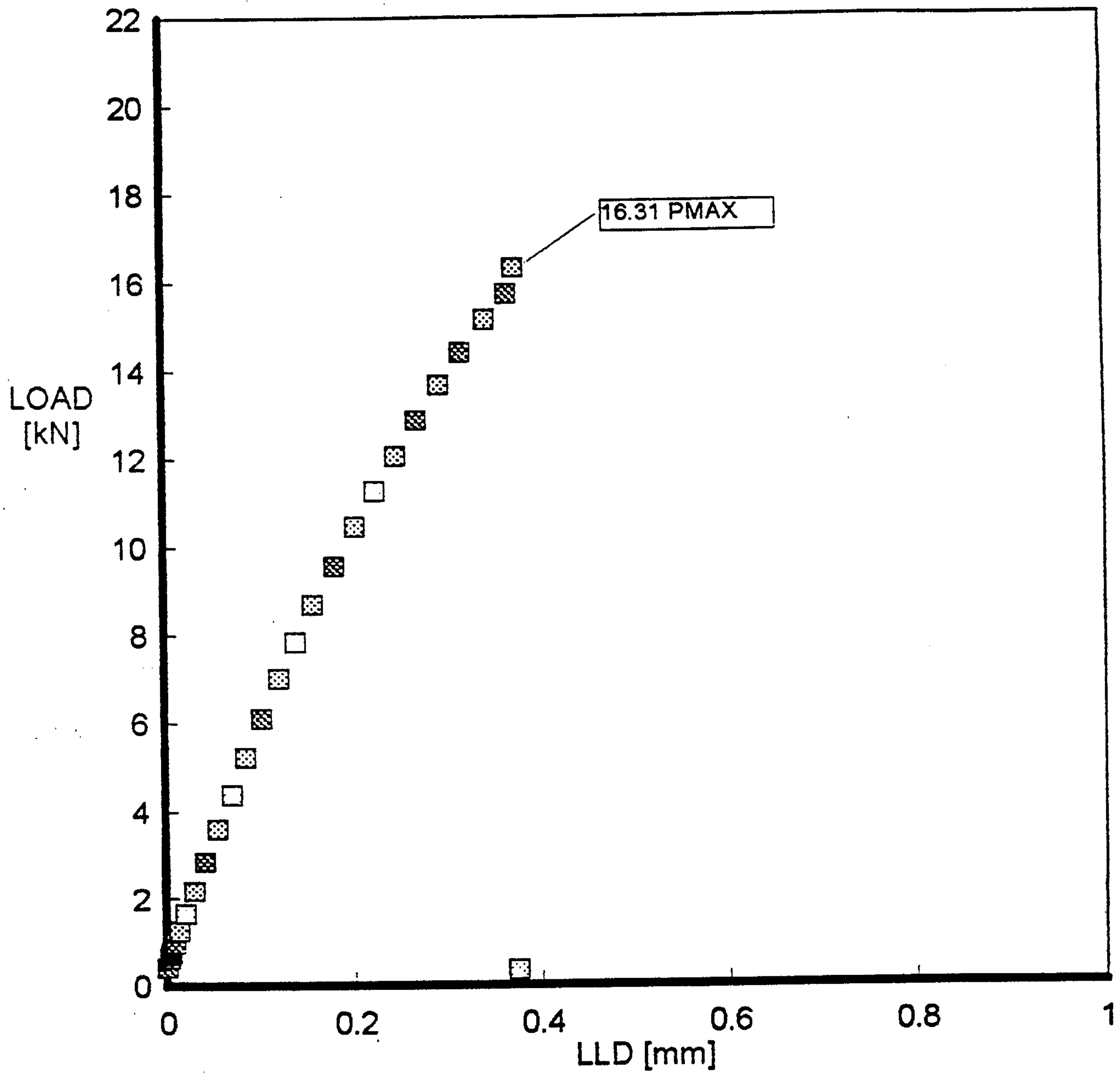

FIGURE A10.
SPECIMEN 350-11 LOAD VS. LLD PLOT AT -96C.

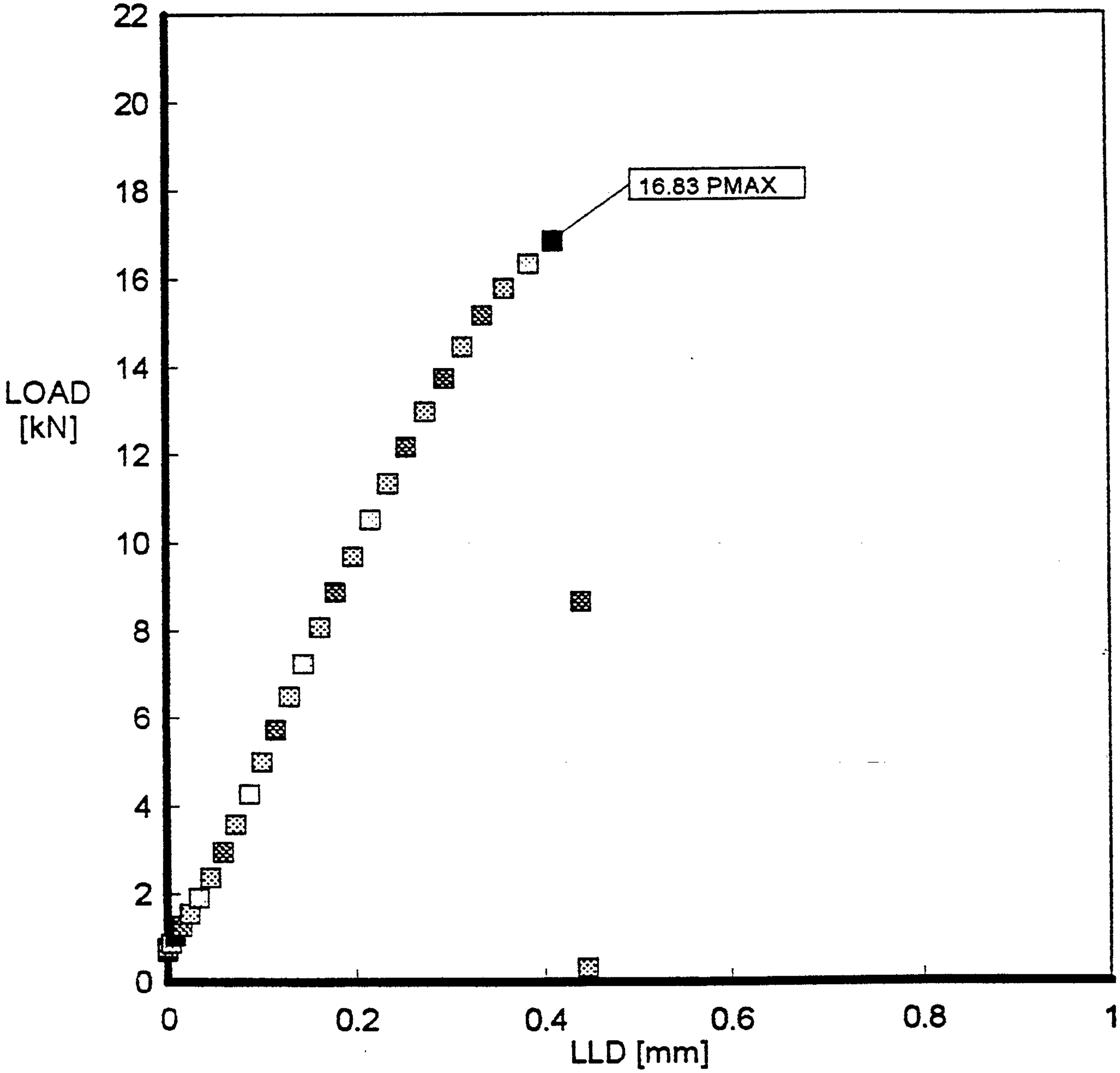

FIGURE A11.
SPECIMEN 350-13 LOAD VS. LLD PLOT AT -96C.

APPENDIX B.
CSA 350WT TENSILE RESULTS.

Table of Contents.

Figure No. Name

Figure No.	Name
B1.	Tensile Specimen 350-T1 Load Vs. Disp. Plot at -96°C.
B2.	Tensile Specimen 350-T2 Load Vs. Disp. Plot at -96°C.
B3.	Tensile Specimen 350-T3 Load Vs. Disp. Plot at -96°C.
B4.	Tensile Specimen 350-T4 Load Vs. Disp. Plot at -96°C.

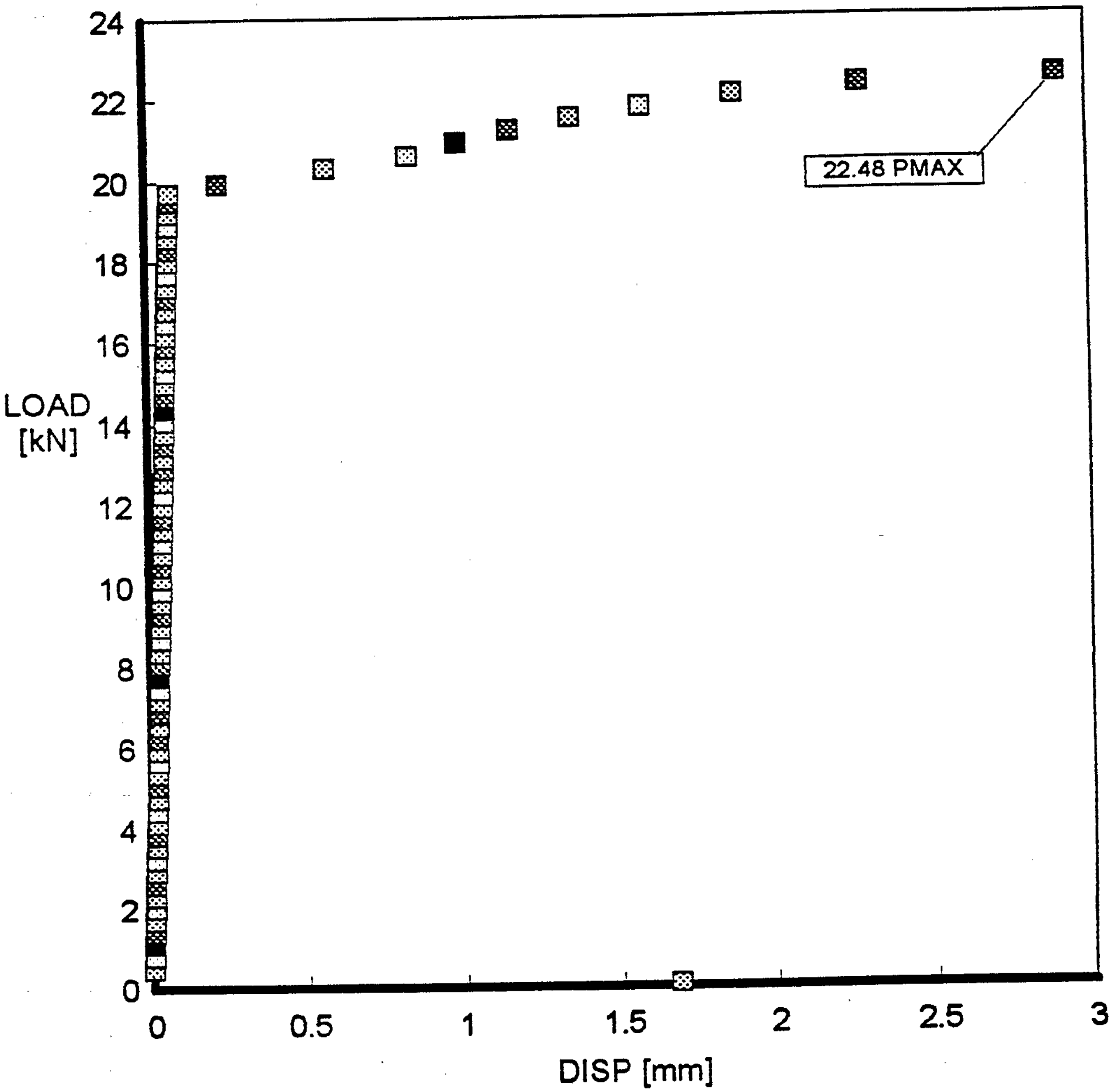

FIGURE B1.
TENSILE SPECIMEN 350-T1 LOAD VS. DISP. PLOT AT -96C.

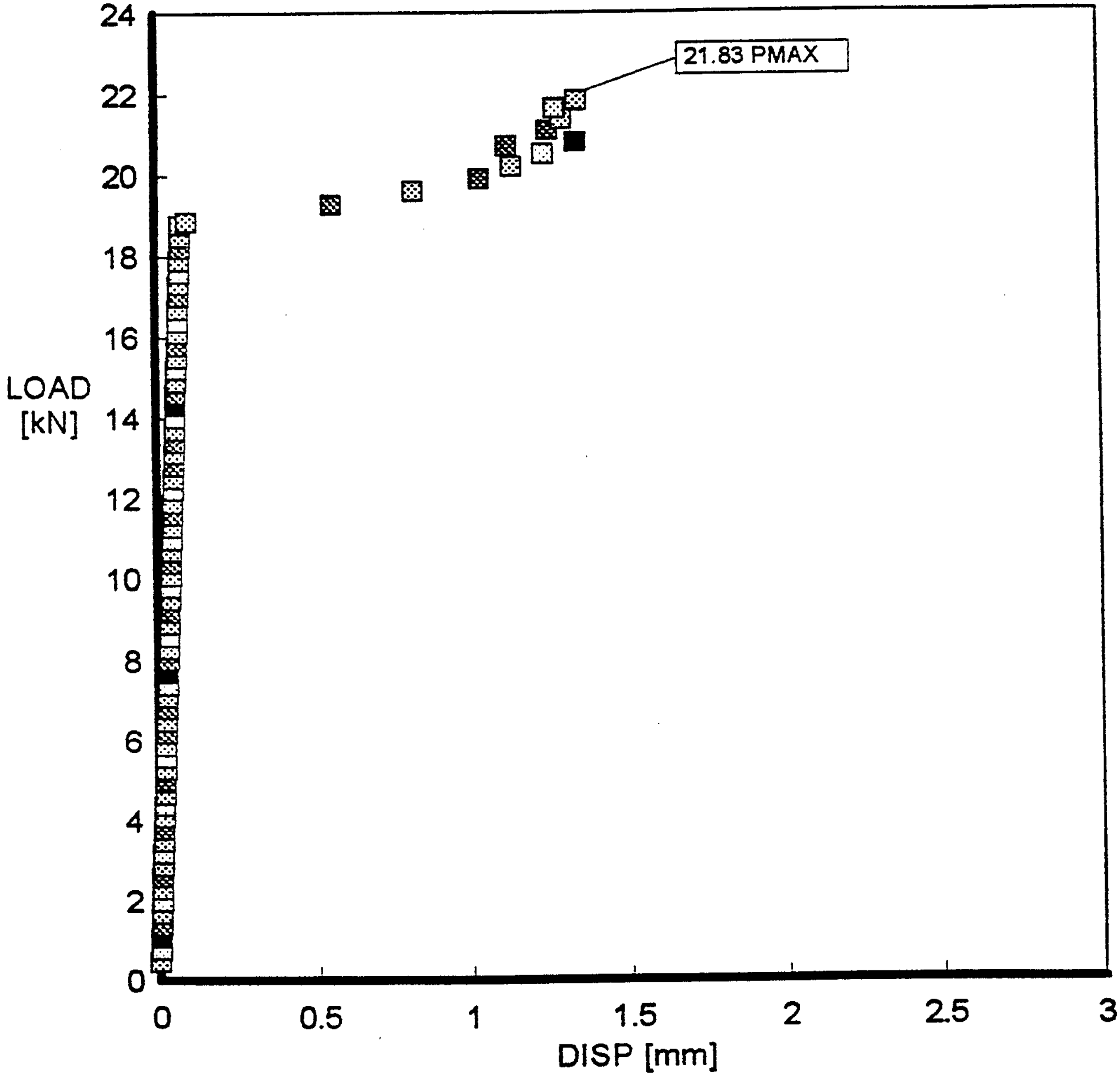

FIGURE B2.
TENSILE SPECIMEN 350-T2 LOAD VS. DISP. PLOT AT -96C.

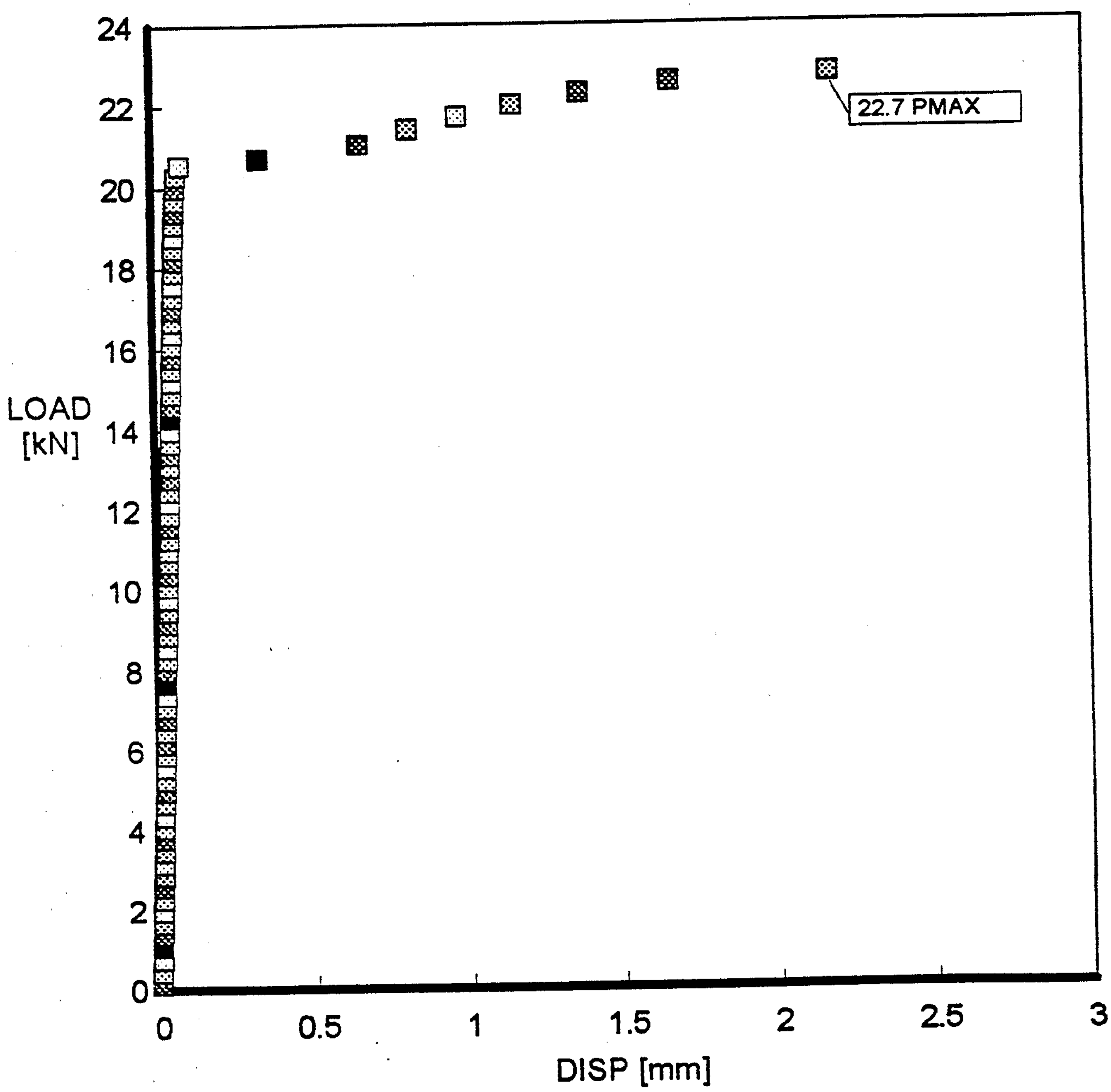

FIGURE B3.
TENSILE SPECIMEN 350-T3 LOAD VS. DISP. PLOT AT -96C.

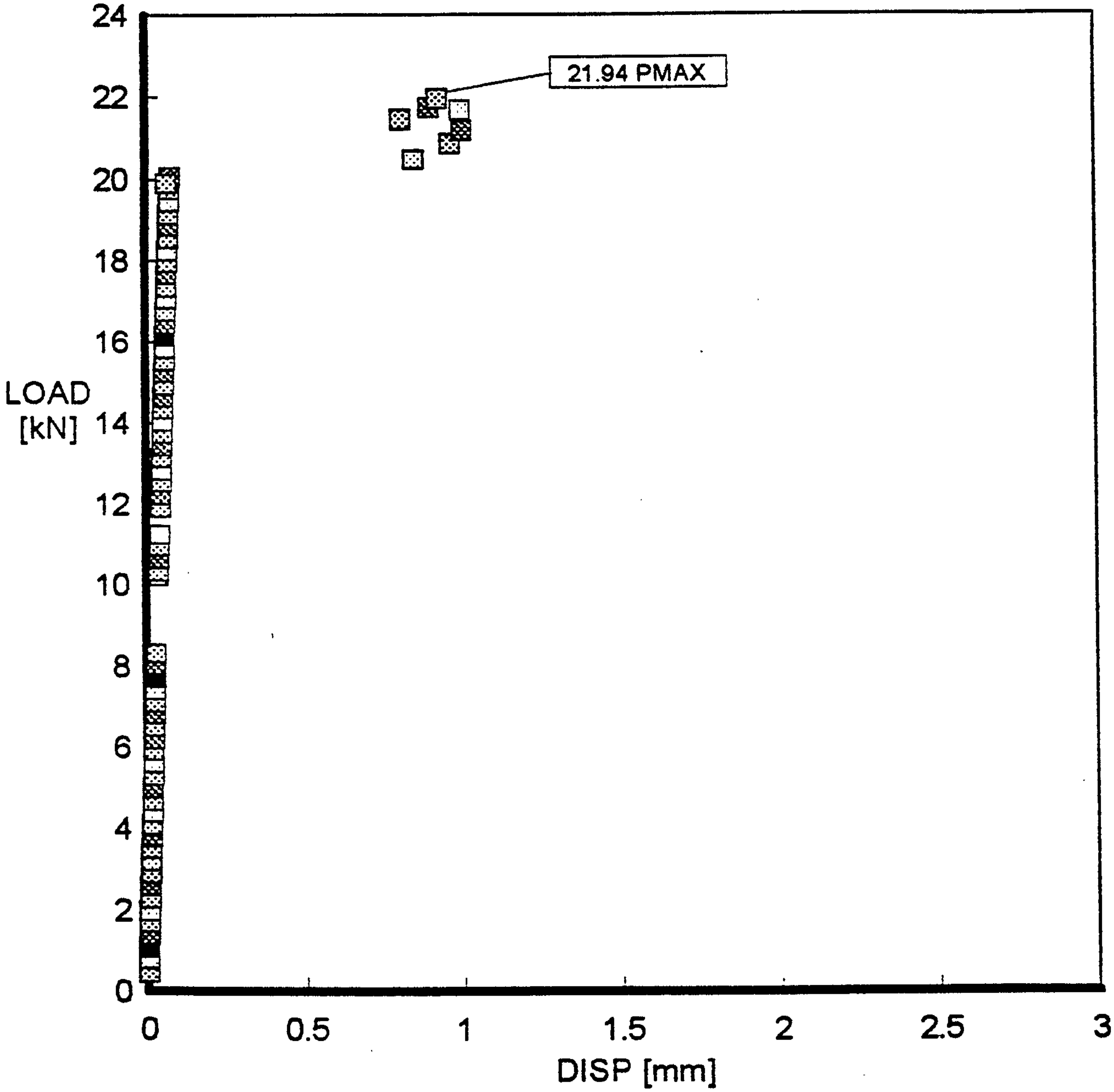

FIGURE B4.
TENSILE SPECIMEN 350-T4 LOAD VS. DISP. PLOT AT -96C.

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October1998

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0 references

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W7708-7-0705

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Quantitative measurements of cracking resistance are needed to assess the risk of brittle fracture under service conditions in warships. This requires laboratory toughness testing at the minimum service temperature and at loading rates equivalent to hull impact events such as wave slamming and minor collisions. Material specifications for ship steels have traditionally relied on tensile strength and Charpy impact energy for quality assessments and as an indicator of structural performance. Unfortunately the data from Charpy tests cannot be used rigorously to describe the fracture of larger components or in structural calculations, and is thus not able to demonstrate adequate damage tolerance in the welded hull.

A technique has recently been standardized by ASTM for determining the fracture toughness of ferritic marine construction steels and welds in the brittle-ductile transition range. K_{Jc} toughness transition curves are generated statistically from the analysis of toughness data populations using a master curve concept. This report describes a preliminary series of tests to evaluate CSA G21 350WT steel plate using this approach, and has established that such a procedure will provide useful data for structural integrity analyses. This work is being extended to include rate effects, plate orientation, and the study of welds.

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