NOTCH TOUGHNESS VARIABILITY IN A572 GRADE 50 AND A588 STEEL PLATES

by

David Raymond Horos, B.S.

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APPROVED:

Karl H. Frank

Joseph A. Yura

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To my parents, Ray and Camille, and sister, Kristen,
for their love and for teaching me that
hard work always pays off.

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INTRODUCTION

1.1 Background

The majority of bridge failures throughout the world involve, in one way or another, fracture. Fracture mechanics is a broad based science which involves the general study of fracture. The scale of disciplines within fracture mechanics ranges the atomic scale of materials science through applied mechanics to full scale engineering applications.

The fracture process begins in a material with an initial crack which is often microscopic in size. The stress condition at the crack tip (often caused by cyclic loads) causes the crack to grow. Growth is slow initially but as the crack length increases the crack growth rate increases until a critical crack size is reached. When the critical crack is attained the crack propagation is no longer stable and rapid or brittle crack growth occurs.

Fracture failure is normally avoided through the use of a comprehensive fracture control plan which encompasses material properties, design, fabrication, inspection, erection, and operating conditions. Redundancy is a desired design feature in the fracture control plan for bridges but members are sometimes used which are not redundant. Non-redundant members are known as fracture critical members.

A vital part of a fracture control plan involves material properties. If a material is inherently susceptible to fracture, it is not used as a structural material. Glass is a good example of such a material. Fracture toughness is the property used to describe a material's ability to resist unstable crack growth. Because fracture mechanics is a relatively new science, fracture toughness is a property which is not well understood. Numerous tests exist to determine the toughness parameter including the Charpy V-Notch, the K_{IC}, the Crack Tip Opening Displacement, and the J integral tests.

The K_{IC} term is known as the critical stress intensity factor. It is the point beyond which unstable crack propagation occurs and the parameter which is most useful. The expression for K_{IC} includes the stress, σ, the crack size, a, and a constant, F, which accounts for the geometry of the crack. The expression is $K_{IC} = F\sigma\sqrt{(\pi a)}$.

The preferred test procedure used to determine fracture toughness in bridge steels is the Charpy V-Notch test. The Charpy test specimen is used because it is inexpensive and gives toughness values which can be correlated to the more useful K_{IC} values. The normal procedure involved in testing steel plates to be used in a bridge requires that toughness testing be done at the rolling mill and that the results be provided in a mill test report.

The American Association of Highway and Transportation Officials (AASHTO) has a toughness criterion for fracture critical members in their guide specifications involving Charpy V-Notch levels [1]. Current AASHTO fracture toughness requirements for bridge steels specify that plates meet minimum Charpy V-Notch toughness levels based on service temperature, thickness, grade of steel, and fastening method. AASHTO requires that the average toughness of three Charpy V-Notch specimens at an appropriate test temperature exceed a specified minimum value and that no single test result be below another, lower value. For a fracture critical member, AASHTO specifies a "P" or plate testing frequency as opposed to the normal "H" or heat testing frequency. The "P" sampling frequency provides a measure of the individual plate toughness. Heat treating of individual plates may be necessary to reach required toughness levels and "P" testing reflects the effect of heat treatment. Scrap material cropped from the end of each fracture critical plate is used to make the specimens.

Bridge failures in recent years have led to concern involving fracture toughness variability in bridge steels. Studies on A514, A517, and A36 steels have been conducted to learn more about toughness variability in general and to prescribe necessary testing procedures and requirements [2,3]. These studies attempted to give the engineer a feel for the type of variability that should be expected in plates and led to the requirement of "P" testing for fracture critical members. In response to the fracture of fracture critical bridge members, AASHTO developed an interim specification which lowered the test temperatures and required that test specimens be taken from each end of fracture critical plates.

The interim requirement of testing at two locations doubles the cost and time allotted to testing in the rolling mills. This requirement launched studies on A572 Grade 50 and A588 steel by the American Iron and Steel Institute (AISI) and the University of Texas at Austin to expand the database of toughness values to steels previously not studied. This report uses the Charpy V-Notch data from the 1984 AISI study on A572 Grade 50 and A588 steel to study fracture toughness variability in bridge steel plates [4].

Some additional information concerning fracture toughness variation and the effect of temperature on fracture toughness may be useful. Figure 1.1 shows the assumed relationship between notch toughness and temperature. In general, the notch toughness increases as the temperature of the material increases. There is a temperature region known as the transition temperature within which notch toughness changes rapidly with small changes in temperature. Scatter which may occur in test results may be a result of three factors: the test temperature, the transition temperature region of the material, and the toughness of the material. Figure 1.1 shows arbitrary notch toughness-temperature curves for three locations on a plate. In the figure, locations 1 and 2 have the same toughness values at high and low temperatures but the transition temperature for location 1 is less than that of location 2. Over a narrow temperature region, location 1 is tougher than location. If the test temperature is at A or C, there is no difference in toughness between the locations but location 1 is much tougher for test temperature B.

Location 3 on the other hand is not as tough as locations 1 and 2 for high temperatures. At temperature C, locations 1 and 2 are tougher. The transition temperature for location 3 is the same as that of location 2, however. While there is a difference in toughness at locations 1 and 2 for temperature B, there is no difference in toughness between locations 2 and 3 at the same temperature.

Because of the various factors which lead to scatter in test results, a common practice in research is to take specimens from the same location at many different test temperatures in an attempt to identify the shape of the transition curve of the steel at the location tested. Unfortunately, this is very impractical for a specification so a single test temperature is used. The AISI database includes results from three test temperatures. This is not a sufficient number of temperature points to accurately determine the shape of the transition curve.

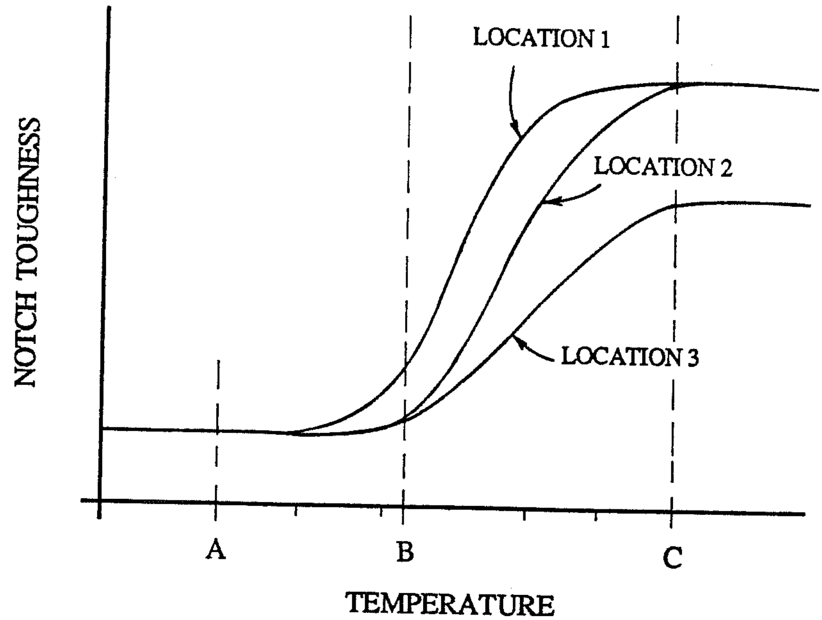

Figure 1.1 Notch Toughness Variation with Temperature

1.2 Scope

It was soon apparent upon studying fracture toughness variability that while the study of variability itself is a good and necessary task, applying the results of the variability study to the development of rationally based test requirements is an equally important aspect of this thesis. Thus, although the thesis begins with presentation of results from the variability study, the focus of the thesis is an attempt to answer a few practical questions which are outlined in this section.

This thesis limits itself to the database collected by AISI for their 1984 study. It is a large and probably the most complete database of its kind. Chapter 2 provides a brief description of the AISI database and a general look at fracture toughness values in the database.

After a familiarity with the database is gained in Chapter 2, Chapter 3 attempts to answer the question of location effect on fracture toughness within plates. Is the location in the plate from which specimens are taken an important factor to consider? Is the variation in toughness which may occur statistically real or is it just a result of the scatter involved with the test procedure? What are the effects of other parameters such as grade, manufacturer, thickness, length, and width on location significance?

Individual plate variability is studied using the statistical technique analysis of variance. The analysis of variance procedure is based upon an initial hypothesis that all of the average location toughnesses are equal. It yields results which identify the chance that the initial hypothesis is incorrect. If the hypothesis is incorrect, there is a real difference in toughness at at least one location and there is assumed to be some real location effect aside from that of scatter in the test procedure. Individual plates are analyzed at different test temperatures and individual results are grouped and compared to study the effect of the parameters. Toughness values are also grouped before analysis and the groups of data are analyzed as another way to study the effects of the parameters.

Following the analysis of variance in Chapter 3, an attempt is made in Chapter 4 to apply the knowledge of variability towards developing a rational method of setting required test levels. What test levels are needed in order to ensure a given performance level? What is the necessary performance level? How should the test levels be developed? What are the risks involved for the user and supplier for a given test level? How might the risks be altered?

Two procedures are used to find test levels for different test temperatures and different grades of steel. The first is a statistical distribution based procedure and the second is a direct procedure. Desirable toughness performance is established and distributions are created and used to determine necessary test levels for a specific confidence level. Two performance criteria are used in this report and both procedures are performed for each criterion. The results of the two procedures are compared to see if they lead to consistent results. The recommended test levels are then applied to the plates in the survey to observe their effect on the acceptance of the plates.

A complete description of the database and results of the analyses performed are contained in the Appendices.

CHAPTER 2
AISI SURVEY SU27 DATABASE

2.1 Introduction

In 1984, the American Iron and Steel Institute conducted a survey of American steel manufacturers to study fracture toughness variation in steel bridge plates. The survey is entitled SU27. Before the results of this study were published, AISI supplied the University of Texas a complete listing of the database compiled in the survey for use in this report.

With the possible exception of a similar AISI survey SU24 conducted in 1979, the author believes the SU27 survey to be the largest and most complete survey of its kind. Previous surveys performed normally studied fracture toughness as it related to a particular failure and were usually limited in scope to the steel type, plate sizes, and thicknesses involved in the failure. "Variability of Fracture Toughness in A514/517 Plate" by the Federal Highway Administration (FHWA) is an example of this type of study. AISI survey SU27 offers a unique opportunity to study fracture toughness in steel plates not tested simply because they were involved in a failure.

This chapter includes a detailed description of the data presented by AISI in their survey SU27. This description will help familiarize the reader with the database and aid in the understanding of results presented in later chapters. The description is followed by a discussion of the general toughness characteristics of the database, the toughness variation at a location, and missing data in the survey. The author would like to note that the actual data in survey SU27 were collected by AISI. The author simply received the data from AISI. The producers and rolling mills included in the survey were not identified.

2.2 Description

The American Iron and Steel Institute Survey SU27 database consists of Charpy V-Notch absorbed energy and Lateral Expansion test data taken from 94 steel plates. The manufacturing requirements for the steel in the SU27 database are unclear. AISI states in their most recent report on the data that "It should be recognized that while some of this product may have been ordered to a specific impact strength requirement, this was not a requirement for either study and has not been considered in any analysis of the data" [5].

Table 2.1 summarizes the general composition of the data in survey SU27. Steel plates of two grades from four producers and eight rolling mills are included in the survey. Thicknesses range from three-eighths to four inches. Tests were performed at nine locations on the plates and at three temperatures. A total of 8078 Charpy tests were taken from the 94 plates. All specimens are quarter thickness specimens made and tested in accordance with ASTM Standard E23-72, "Notched Bar Impact Testing of Metallic Materials" [6]. Each rolling mill made and tested their own specimens. No information is provided on the processing or the chemical compositions of the plates in the survey.

AISI assigned identification numbers to the plates tested and rolling mills involved in the survey. The 94 plates have identification numbers of 1-94 and the eight rolling mills have identification numbers of 1-8. These identification numbers will be used in this document for purposes of consistency.

Table 2.1 General Description of AISI SU27 Database

2 Grades of Steel
4 Producers
8 Rolling Mills (ID #1-8)
94 Plates (ID #1-94)
9 or 10 Locations per Plate
3 Temperatures per Location
3 Specimens per Temperature
8078 Charpy Tests
Plate Thickness Range: $\frac{3}{8}$ - 4"

For a better understanding of the database, this description is broken down into the different variables included in the survey; temperature, location, grade, rolling mill, company, thickness, length, and width. A complete listing of the 94 plates included in the AISI SU27 survey is found in Appendix A. Each plate's identification number, rolling mill identification number, grade, length, width, and thickness are provided.

2.2.1 Temperature. The Charpy tests in survey SU27 were performed at three test temperatures; 0, 40, and 70 °F. Seventy degrees is the test temperature specified for zone I material by the AASHTO Base Metal Charpy V-Notch Requirements for Fracture Critical Members. Forty degrees is the specification temperature for zone II material. Zero degrees was chosen because it had been used in AISI's earlier survey SU24. It is a specification temperature for pressure vessel steel and survey SU24 included some pressure vessel steel. With the exception of missing data, an equal number of tests were performed at each temperature; 2693 test results at 70 °F, 2693 results at 40 °F, and 2692 results at 0 °F.

2.2.2 Location. Figure 2.1 shows the testing schedule for the plates in survey SU27. Nine locations in each plate were tested. The locations were chosen by AISI to determine the variation in fracture toughness in the plate. Nine specimens were tested at each location, three at each of the three test temperatures. Thus, ordinarily, a total of 81 specimens were tested for each plate. A tenth location was tested for many of the plates. This location was the same area as location 2 in the figure. Fifty nine of the 94 plates tested included tests at location 10. For purposes of this report, it will be assumed that the tenth location is an unique location for those 59 plates.

2.2.3 Grade. The grades of steel included in survey SU27 are A572 Grade 50 and A588 steel. Both are high strength low alloy structural steels with nominal yield strengths of 50 ksi. They are commonly used in bridges. A588 differs from A572 Grade 50 in that it is an atmospheric corrosion-resistant or weathering steel. Table 2.2 shows a breakdown by grade of the database.

Plates 1-47 are A572 Grade 50 plates. The thickness of these plates ranges from one to four inches. Eight rolling mills are represented. 4068 Charpy tests are taken from plates 1-47.

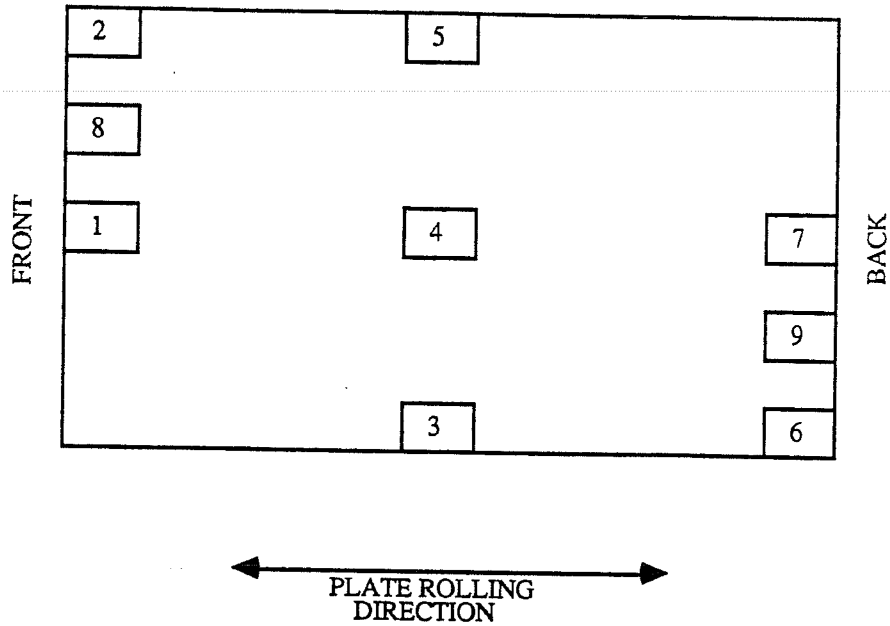

Figure 2.1 Layout of Test Locations

Table 2.2 AISI SU27 Database by Grade

Grade	A572 Grade 50	A588
# Plates	47	47
Plate ID #'s	1-47	48-94
# Rolling Mills	8	6
Rolling Mill ID #'s	1-8	1,2,3,5,7,8
# Charpy Tests	4068	4010
Thickness Range	1-4"	$\frac{3}{8}$-4"

Plates 48-94 are A588 plates. The thickness of these plates ranges from three-eighths to four inches. Six rolling mills are represented. 4010 Charpy tests are taken from plates 48-94. Note that rolling mills 4 and 6 did not produce A588 steel for the survey.

2.2.4 Rolling Mill. Eight rolling mills are represented in the SU27 survey. They have been assigned identification numbers 1-8. Table 2.3 provides a breakdown of the survey by rolling mills.

Table 2.3 AISI SU27 Database by Rolling Mill

Rolling Mill	1	2	3	4
# Plates	24	20	20	6
A572 Grade 50	12	10	10	6
A588	12	10	10	0
Plate ID #'s				
A572 Grade 50	1-12	13-22	23-32	33-38
A588	48-59	60-69	70-79	-
# Charpy Tests	2160	1755	1791	486
Plate Thickness Ranges (in)				
Overall	$\frac{3}{4}$-4	$\frac{13}{16}$-3$\frac{1}{8}$	$\frac{3}{8}$-2$\frac{1}{2}$	1-4
A572 Grade 50	1$\frac{3}{4}$-3	1$\frac{1}{2}$-3	1$\frac{3}{8}$-2$\frac{1}{2}$	1-4
A588	$\frac{3}{4}$-4	$\frac{13}{16}$-3$\frac{1}{8}$	$\frac{3}{8}$-2$\frac{1}{2}$	-

Rolling Mill	5	6	7	8
# Plates	10	3	6	5
A572 Grade 50	3	3	1	2
A588	7	0	5	3
Plate ID #'s				
A572 Grade 50	39-41	42-44	45	46-47
A588	80-86	-	87-91	92-94
# Charpy Tests	806	243	486	351
Plate Thickness Ranges (in)				
Overall	1-2$\frac{1}{2}$	1$\frac{3}{4}$-2$\frac{1}{2}$	$\frac{3}{4}$-2$\frac{1}{2}$	1$\frac{7}{16}$-4
A572 Grade 50	1$\frac{1}{2}$-1$\frac{3}{4}$	1$\frac{3}{4}$-2$\frac{1}{2}$	2$\frac{1}{2}$	4
A588	1-2$\frac{1}{2}$	-	$\frac{3}{4}$-2$\frac{1}{2}$	1$\frac{7}{16}$-2$\frac{19}{20}$

Rolling mills 1-3 are by far the most heavily represented in the survey. These mills account for 71% of the Charpy specimens tested and 68% of the plates tested. Mills 4 and 6 did not have any A588 steel included in the survey and mill 7 had only a single A572 Grade 50 plate included. All thicknesses are fairly well represented in both grades by all rolling mills with the exception of A588 steel from mill 6 (its three plates only range from $1\frac{3}{4}$ to $2\frac{1}{2}$ inches in thickness), mill 7 (only one plate tested), and mill 8 (two four inch plates tested).

2.2.5 Producer. Four producers are represented in the SU27 survey. It is unclear from the AISI data which of the four producers operate the eight rolling mills. For the purposes of this report, the producer parameter is ignored. Each rolling mill will be considered a separate entity regardless of which producer operates the mill.

2.2.6 Thickness. The plate thicknesses in survey SU27 range from three eighths to four inches. Table 2.4 shows a breakdown of the database by thickness. The range divisions created for the table are arbitrary but two inches is chosen as one of the boundaries because it is a boundary used for A572 Grade 50 and A588 steel in the AASHTO specifications.

Table 2.4 AISI SU27 Database by Thickness

Thickness (in)	≤ 1	$1< \leq 2$	>2
# Plates	15	49	30
A572 Grade 50	1	29	17
A588	14	20	13
# Rolling Mills	6	8	8
A572 Grade 50	1	6	7
A588	5	6	6
# Charpy Tests	1287	4273	2518
A572 Grade 50	81	2538	1449
A588	1206	1735	1069

The majority of the plates tested have thicknesses between one and two inches. A588 plate thicknesses are distributed more evenly than A572 Grade 50 thicknesses. Note that only a single A572 Grade 50 plate with a thickness less than or equal to one inch was tested as part of the survey.

Rolling mill representation for each thickness range is relatively thorough. All eight mills are represented in both ranges greater than one inch and six of the eight are represented in the less than or equal to an inch range. Again, A588 is the better represented of the two grades with all rolling mills represented for thicknesses greater than one inch.

2.2.7 Length. Plate lengths in survey SU27 range from 105 to 877 inches. Table 2.5 shows a breakdown of the database by length. The boundaries between short, intermediate, and long plates are chosen arbitrarily at 20 and 30 feet. The length and width of plate 91 is not provided in the database. It has been excluded from the description of length and width characteristics.

Table 2.5 AISI SU27 Database by Length

Length (in)	Short ≤ 240	Intermediate $240< \leq 360$	Long >360
# Plates	33	29	31
A572 Grade 50	18	20	9
A588	15	9	22
# Rolling Mills	7	5	6
A572 Grade 50	7	5	4
A588	3	4	5
# Charpy Tests	2841	2520	2636
A572 Grade 50	1539	1755	774
A588	1302	765	1862

The total number of plates in each category is nearly equally divided. Within each grade, however, the number of plates and number of specimens tested is not divided equally. There are only nine long A572 Grade 50 plates in the survey. This is much less than the number of short and intermediate A572 Grade 50 plates and not half the number of long A588 plates. There also are only nine intermediate A588 plates which is less than the number of short and long A588 plates. The number of intermediate A588 plates is only half the number of A572 Grade 50 intermediate plates. The number of test results follows these same characteristics proportionally. Also note that only three rolling mills produced short A588 plates.

All A588 plates from rolling mill 7 are long plates. The shortest of these plates is 425 inches long.

Rolling mill 8 added no short plates to the survey. Both of the A572 Grade 50 plates from rolling mill 8 are intermediate length plates and all three of the A588 plates are long plates.

2.2.8 Width. Plate widths in survey SU27 range from 42 to 115 inches. Table 2.6 shows the database broken down by width. The boundaries between narrow, intermediate, and wide plates are chosen arbitrarily at five and seven feet.

The total number of plates in each width category is not spread as evenly as in the thickness categories. Half of all the plates are intermediate plates and one quarter are narrow and wide. There are only seven wide A588 plates. Only three of the six rolling mills producing A588 plates for the survey produced narrow or wide plates. Again, the number of specimens tested follows the same characteristics described for the plates.

All A572 Grade 50 plates from rolling mill 3 have a width of 84 inches and all but two A588 plates from rolling mill 3 have a width of 84 inches.

2.3 General Toughness Characteristics

The purpose of this section is to provide general background on the fracture toughness levels of the plates included in the survey. Table 2.7 presents for each grade of steel the average fracture toughness at each of the three test temperatures for the

Table 2.6 AISI SU27 Database by Width

Width (in)	Narrow ≤ 60	Intermediate $60< \leq 84$	Wide >84
# Plates	22	47	24
A572 Grade 50	11	19	17
A588	11	28	7
# Rolling Mills	6	6	7
A572 Grade 50	5	4	6
A588	3	6	3
# Charpy Tests	1851	4067	2079
A572 Grade 50	927	1692	1449
A588	924	2375	630

Table 2.7 Average Notch Toughness Levels by Grade (ft-lbs)

Grade	A572 Grade 50	A588
0 degrees F	21	41
40 degrees F	36	63
70 degrees F	52	86

entire database. In general, the A588 plates in the survey are tougher than the A572 Grade 50 plates.

The distributions of the average toughness at a location, for each grade and the three test temperatures, are shown in the frequency histograms of Figures

2.2-2.7. Figures 2.2-2.4 show the data from the A572 Grade 50 plates and Figures 2.5-2.7 show the data from the A588 plates.

The range for each of the A572 Grade 50 distributions is from 0 to 120 ft-lbs and each division represents five ft-lbs. Notice that as the test temperature increases, the distributions become more symmetric and the scatter increases. There are low average location toughnesses for each of the test temperatures but the number decreases as the temperature increases and the majority of the averages fall within higher toughness ranges as the temperature increases. At 0 °F, about 80% of the location averages are between 10 and 30 ft-lbs. At 40 °F, 80% of the averages are between 20 and 60 ft-lbs and at 70 °F, 80% are between 30 and 85 ft-lbs.

The location toughness data from the A588 steel behaves in much the same way as the A572 Grade 50 except the toughness values are generally higher and more dispersed. The range in Figures 2.5-2.7 is from 0 to 300 ft-lbs. At 0 °F, 80% of the average location toughness values are between 10 and 120 ft-lbs. Eighty percent of the values fall between 10 and 110 ft-lbs at 40 °F. The median average toughness increases from 34 ft-lbs for 0 °F to 56 ft-lbs for 40 °F. About 80% of the values at the 70 °F test temperature are between 40 and 170 ft-lbs.

The average fracture toughness results for each rolling mill are shown in Table 2.8, and rolling mill 3 results are consistently low for both grades of steel at all temperatures. Rolling mill 1 results are consistently low for A572 Grade 50 steel but high for A588 steel. Results from rolling mill 6 are low for A572 Grade 50 steel.

Table 2.9 presents the average fracture toughness levels by thickness. The average fracture toughness in A588 steel decreases as thickness increases. A572 Grade 50 steel does not show as clearly this same behavior especially at the 70 degree test temperature.

Tables 2.10 and 2.11 present the average fracture toughness levels for the SU27 database arranged by length and width. These two size related parameters would seem to be related but the results from the two tables do not show a consistent size effect. In Table 2.10, average fracture toughness increases with length for A588 steel. This does not occur with width. In Table 2.11, average fracture toughness increases with width for A572 Grade 50 steel. This does not occur with length.

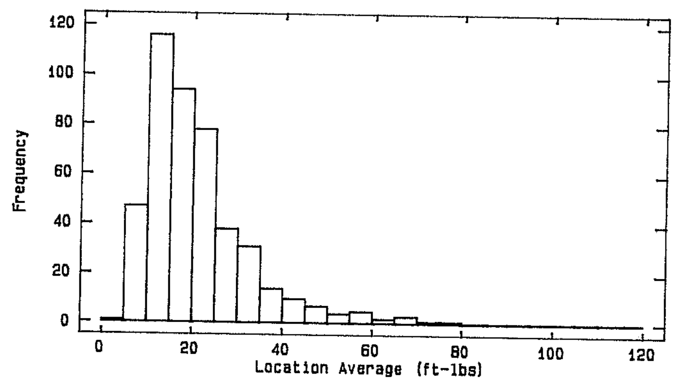

Figure 2.2 Location Average Histogram, A572 Grade 50, 0 °F

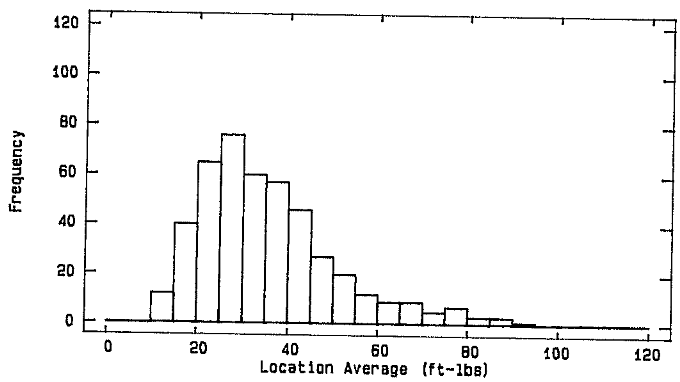

Figure 2.3 Location Average Histogram, A572 Grade 50, 40 °F

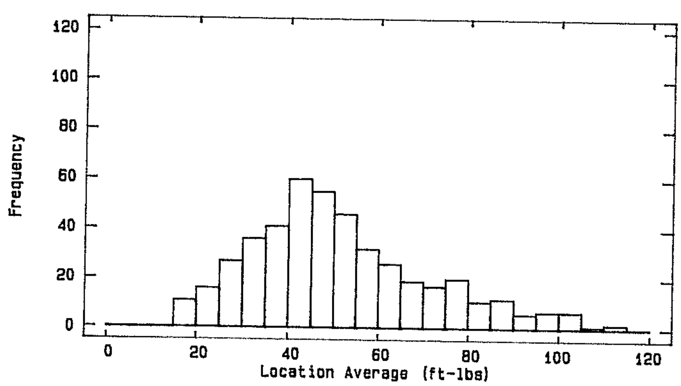

Figure 2.4 Location Average Histogram, A572 Grade 50, 70 °F

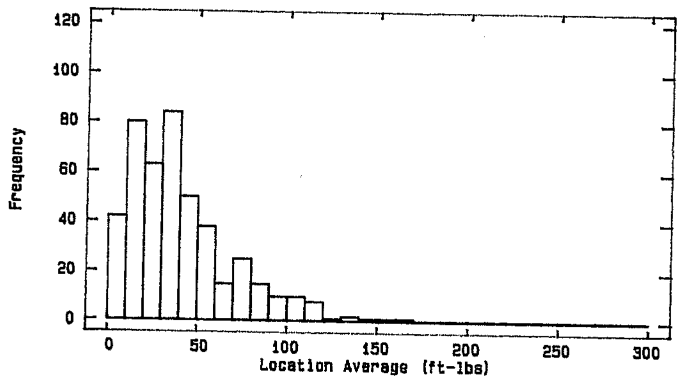

Figure 2.5 Location Average Histogram, A588, 0 °F

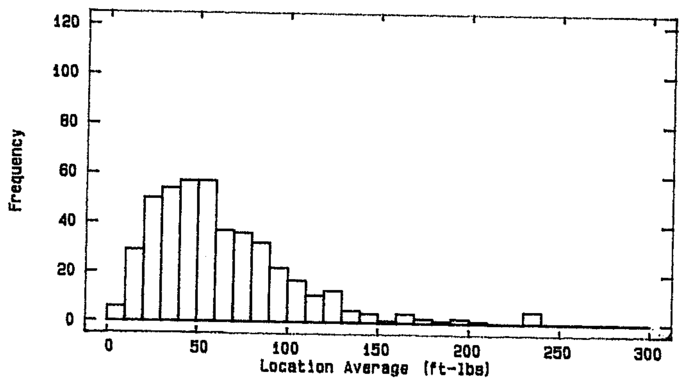

Figure 2.6 Location Average Histogram, A588, 40 °F

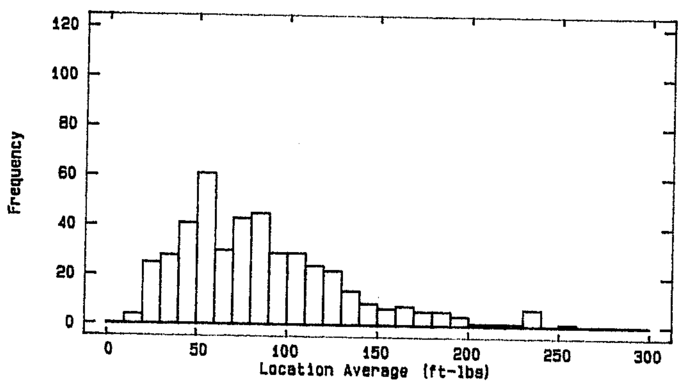

Figure 2.7 Location Average Histogram, A588, 70 °F

Table 2.8 Average Notch Toughness Levels by Rolling Mill (ft-lbs)

Rolling Mill	1	2	3	4	5	6	7	8
A572 Grade 50								
0 degrees F	15	24	18	35	31	19	13	21
40 degrees F	31	44	28	48	44	26	41	33
70 degrees F	48	64	36	64	62	36	60	47
A588								
0 degrees F	60	40	23	-	39	-	40	37
40 degrees F	93	64	38	-	56	-	57	60
70 degrees F	124	84	50	-	78	-	82	77

Table 2.9 Average Notch Toughness Levels by Thickness (ft-lbs)

Thickness (in)	≤ 1	$1< \leq 2$	>2
A572 Grade 50			
0 degrees F	28	22	21
40 degrees F	41	36	36
70 degrees F	58	51	53
A588			
0 degrees F	49	41	34
40 degrees F	74	64	50
70 degrees F	100	86	70

The two grades of steel also do not perform the identically with size. The A572 Grade 50 steel shows no increase in fracture toughness with length in Table 2.10 while the A588 does. The A588 shows no increase with fracture toughness with width in Table 2.11 while the A572 Grade 50 does.

Table 2.10 Average Notch Toughness Levels by Length (ft-lbs)

Length (in)	Short ≤ 240	Intermediate $240< \leq 360$	Long >360
A572 Grade 50			
0 degrees F	22	21	21
40 degrees F	35	37	35
70 degrees F	47	55	55
A588			
0 degrees F	31	39	49
40 degrees F	48	58	76
70 degrees F	66	79	102

Table 2.11 Average Notch Toughness Levels by Width (ft-lbs)

Width (in)	Narrow ≤ 60	Intermediate $60< \leq 84$	Wide >84
A572 Grade 50			
0 degrees F	19	22	23
40 degrees F	33	36	39
70 degrees F	49	50	55
A588			
0 degrees F	50	38	40
40 degrees F	75	60	61
70 degrees F	98	81	86

2.4 Toughness Variation at a Location

The purpose of this section is to provide general background on the variation of three Charpy test results which can be expected for tests at a single location. Figures 2.8 and 2.9 show the distributions of the difference between the maximum and minimum test results at a location. Figure 2.8 shows the distribution for A572 Grade 50 and Figure 2.9 shows the distribution for A588 steel. The horizontal axis of the figures is a multiple of the plate average at the test temperature under consideration. A value of 1 suggests that the range of the test results at a location is equal to the plate average. Thus, if the plate average at 40 °F is 25 ft-lbs, a value of 1 suggests that the difference between the maximum and minimum of the three test values at a location tested at 40 °F is 25 ft-lbs. The distributions, on the other hand, do not provide information on the average toughness at the location. While the range is 25 ft- lbs, the distribution does not determine whether or not the results range from 15 to 40 ft-lbs or 35 to 60 ft-lbs.

It may be concluded from a frequency tabulation of Figure 2.8 that 93 % of the ranges of test results are less than or equal to the plate average for A572 Grade 50 steel. Thus, if a plate average is equal to 40 ft-lbs, there is a good chance that the range of three values taken at a single location will be less than 20 ft-lbs. Half of the location ranges are less than 0.4 of the plate average. The average range taken from the distribution is a little less than half of the plate average (0.46). The results for A588 steel from Figure 2.9 are not much different. Ninety two percent of the ranges are less than or equal to the plate average and half are below 0.4 of the plate average. The average range is also a little less than half of the plate average (0.48).

The range distributions from the figures were used to find the worst conditions of scatter within a location in the database. The locations which have ranges greater than twice the plate average are shown in Table 2.12. It is seen that some very large variation can be present in the notch toughness of three Charpy tests taken at a single location.

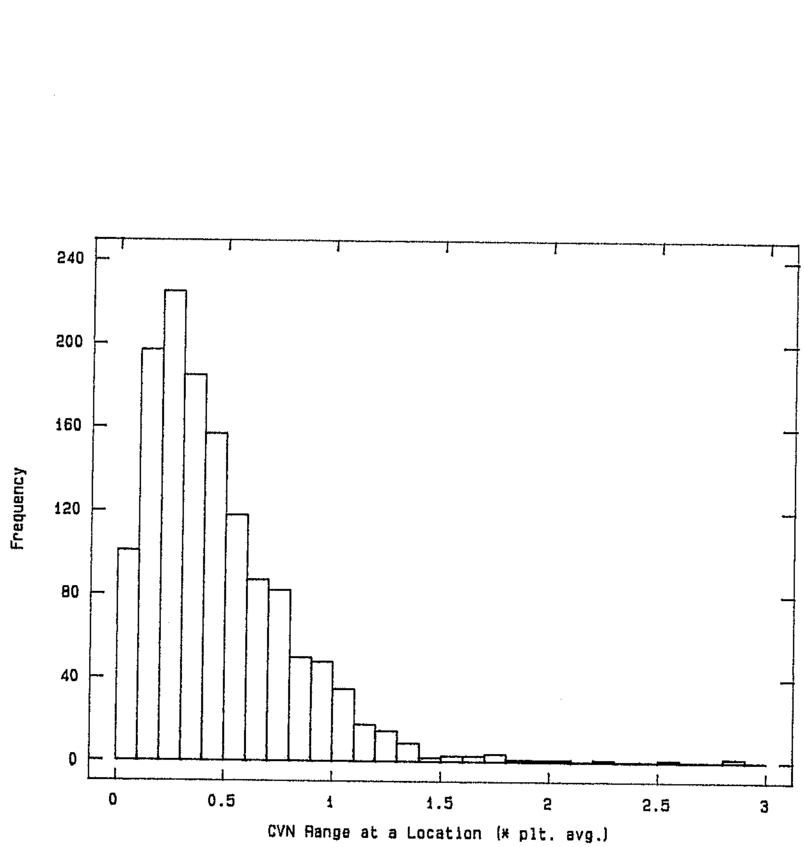

Figure 2.8 Distribution of Range Within Location, A572 Grade 50

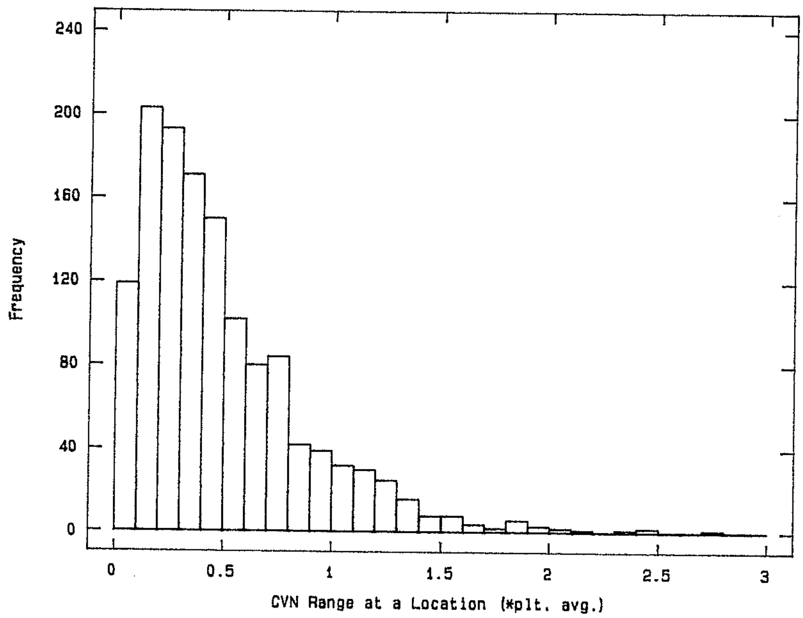

Figure 2.9 Distribution of Range Within Location, A588

Table 2.12 Locations with Toughness Range Greater than Twice the Plate Average

Plate	Location	Temp.	Plt. Avg. (ft-lbs)	Rep. 1 (ft-lbs)	Rep. 2 (ft-lbs)	Rep. 3 (ft-lbs)
1	4	0 °F	13	31	13	4
2	7	40 °F	27	53	52	10
2	9	0 °F	12	34	19	7
14	10	0 °F	19	60	40	5
45	8	40 °F	41	144	93	29
48	10	0 °F	42	191	130	16
52	1	0 °F	52	140	26	11
52	2	0 °F	52	139	75	35
71	3	0 °F	11	37	20	7
71	4	0 °F	11	34	11	8
72	2	40 °F	21	55	19	5
72	3	0 °F	11	32	16	10
91	3	0 °F	41	186	100	97

2.5 Incomplete Data

The following comments regarding the AISI SU27 survey database are provided to enhance the reader's understanding of the data included in the survey. As was previously mentioned, the SU27 survey database is not complete for all plates tested. Only 59 of the 94 plates have a tenth test location. Six other plates are missing all the data from at least one location other than location 10 and three more plates are missing a total of four individual Charpy test values.

Rolling mills 4 through 8 did not provide the survey with the tenth test location. These plates have identification numbers 33-47 for A572 Grade 50 and 80-94 for A588 steel. This accounts for 30 of the 35 plates without location 10. The other five plates without a tenth test location are plates 20, 60, 64, 65, and 69. These plates are all produced by rolling mill 2.

Five of the six plates missing all of the data from at least one location other than location 10 are rolling mill 8 plates. The rolling mill 8 A572 Grade 50 plates, plates 46 and 47, are missing all of the data from location 4 in addition to that of location 10. Two of the three rolling mill 8 A588 plates, plates 93 and 94, are also missing all of the data from location 4. The third rolling mill 8 A588 plate, plate 92, is missing all of the data from locations 3 and 4 in addition to location 10. Lastly, plate 74 from rolling mill 3 is missing all of the data from location 8.

Three plates are missing individual Charpy test values. All are A588 plates from rolling mill 5 and all of the missing values are at location 9 of the plates. Plate 82 is missing a single test result at the 40 degree test temperature. Plate 83 is missing one of the three test results at the 70 degree test temperature and plate 86 is missing two test values at the 0 degree test temperature.

CHAPTER 3
ANALYSIS OF VARIANCE

3.1 Introduction

A primary goal of analyzing the AISI survey SU27 database is to study fracture toughness variation in A572 Grade 50 and A588 steel plates. Valid and rational specification levels can be set if a statistically significant variation is found in the survey and if that variation can be modeled using a distribution function.

The technique which will be used to study variation in this chapter is analysis of variance (ANOVA). A description of the procedure and of the results obtained from the procedure are presented. A discussion of the studies performed and a presentation of the results follow. Lastly, an interpretation of the results is included in the chapter.

3.2 Background

Analysis of variance is a statistical procedure used to study variation. It provides an unbiased, statistically based method of performing hypotheses tests on multiple populations. The null or initial hypothesis of the technique assumes that there is no significant difference in the means of each of the populations. Conversely, the alternate hypothesis assumes that at least one of the individual population means is not equal to the others. Thus, there is no statistically valid variation present if the null hypothesis is found to be true.

Analysis of variance is a sum of squares procedure in which a large pool of data is broken into multiple populations. The populations are defined by specifying the variable or variables to be studied. Both single variable and multiple variable analyses may be performed using the technique. Single variable analysis of variance (known as one way analysis of variance) tests the effect of a single variable and ignores any effects which may be present due to other variables. Multiple variable analysis of variance tests the effect of more than one variable on the data and studies any interaction which may be present between variables.

3.2.1 Description. Table 3.1 shows the general form of the simplest type of analysis of variance; a completely randomized single variable design. Variation can be present in two forms; between treatments (regression) and within treatments (error). The result of the analysis is the F ratio in the right hand column. The F ratio depends on both types of variation.

Table 3.1 ANOVA for a Completely Randomized Single Factor Design

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Between Treatments (Regression)	$k-1$	$n\sum_{j=1}^{k}(\overline{y}_j - \overline{y}_{total})^2$	s_T^2	$\frac{s_T^2}{s_e^2}$
Within Treatments (Error)	$k(n-1)$	$\sum_{j=1}^{k}\sum_{i=1}^{n}(y_{ij} - \overline{y}_j)^2$	s_e^2	
Totals	$kn-1$	$\sum_{j=1}^{k}\sum_{i=1}^{n}(y_{ij} - \overline{y}_{total})^2$		

The single variable analysis of variance technique is described through use of an example of an analysis performed on one of the plates in the SU27 survey. An analysis of variance is performed on plate 1 to study the effect of location on the value of the Charpy tests. Table 3.2 shows the completed analysis for the plate. Plate 1 has no missing data and therefore has 90 CVN values; three at each of three temperatures at each of ten locations. The variable being studied is location. The effect of temperature is not considered. The procedure requires breaking down the 90 variables into ten unique treatments of nine CVN values each; one for each location.

The between treatments source of variation is the variation from one location to another. The number of degrees of freedom between treatments is equal to nine or the number of locations minus one. The sum of squares between treatments is equal to the product of the number of tests at each location (nine) and the sum of the squares of the difference between the location mean and the overall plate mean.

The mean square is the ratio of the sum of squares and the number of degrees of freedom.

The within treatments source of variation is the variation of the nine CVN values at each location. The number of degrees of freedom within treatments is equal to eighty or the product of the number of locations (ten) and the number of tests at a location minus one (eight). The sum of squares within treatments is obtained by summing the nine squares of the difference between the CVN value and the location mean for each location and finally summing the ten location sums. The mean square is again the ratio of the sum of squares and the number of degrees of freedom.

3.2.2 Interpretation of Results. The result obtained from an analysis of variance is the F ratio. The F ratio is equal to the ratio of the mean square between treatments and the mean square within treatments. It, along with the number of degrees of freedom may be used to obtain a result known as the significance level. In Table 3.2, the significance level is 0.4599, the F ratio is 0.984, and the total number of degrees of freedom is 89 (one less than the number of test results).

Table 3.2 Sample One Way ANOVA Results

Analysis of Variance

Source of Variation	Sum of Squares	d.f.	Mean Square	F ratio	Sig. Level
Between Groups	1710	9	190	.984	.4599
Within Groups	15453	80	193		
Total (corrected)	17163	89			

The significance level is better known as the alpha error or type I error. In statistical terms, this is the probability that the null hypothesis will be rejected when it is actually true. Because it is a probability, the significance level ranges between zero and one. It may be interpreted as follows: The null hypothesis assumes that the means of individual treatments are equal. A significance level of 0.05, for instance, suggests that there is a 5% risk of rejecting the null hypothesis falsely. That is, there is a 5% risk that the analysis will lead to the conclusion that the variable, location, is significant when it is actually not significant. As the significance level decreases, we may conclude with decreasing risk that the null hypothesis is actually false or that the variable does indeed have a statistically significant effect on the results. More simply, it may be inferred that as the significance level decreases, the effect of the variable increases. A significance level of 0.4599 in Table 3.2 suggests that the null hypothesis may easily be rejected falsely and that location does not have a large effect on the results of the Charpy tests for this plate.

Ordinarily, the F ratio is used solely as an intermediate step in finding the significance level. But for an equal number of degrees of freedom such as is the case for many of the analyses in the survey, it may be used alone as a means to study variation. The F ratio and the significance level are inversely related. As the F ratio increases, the significance level decreases and the effect of the variable on the data increases.

The significance level and F ratio values are both helpful in analysis because they allow a quantitative measure of variation. In many cases, though, the F ratio is helpful when the significance level is not. It is for this reason that the F ratio is included in the results. Briefly, the significance level approaches zero in many of the analyses. When this happens, the F ratio is large and easier to use when studying variation. The fact that the significance level approaches zero is not unexpected. It occurs because the analysis of variance procedure does not reflect the magnitude of difference between treatment means. Rather it just determines if a statistically real difference does exist. For the case of fracture toughness in steel plates, it is entirely possible that a small difference in fracture toughness does exist from one location to the next. This is reflected in a significance level near zero. F values may be different for two near zero significance levels. The F values can be used to compare the magnitude of the effect of a variable.

The significance level, F ratio, and the number of degrees of freedom are presented as results for the analyses of variance performed. The degrees of freedom are listed in the case where F ratios are used to study variation and it is desirable to observe the effect of the degrees of freedom on the comparison.

3.3 Normalization of Data

As part of the analysis of variance, single plate analyses and grouped data analyses are performed. The data are normalized when performing analyses of variance with location as the variable being studied on multiple temperature and multiple plate populations. The F ratio from which the significance level is determined depends both on scatter between treatments and within each treatment. Any unrealistic values in either of these scatters results in inaccurate conclusions. Performing analyses on multiple temperature or multiple plate populations can lead to unrealistic scatter within treatment.

Figures 3.1 and 3.2 illustrate the need for normalization when analyzing data from multiple temperatures. Performing analyses on data from more than one temperature with location as the only variable does not account for scatter within each location due to temperature effects. The large scatter due to the change in toughness values with temperature is shown in Figure 3.1. This large within location scatter results in an unrealistically small F ratio of 0.606 and suggests a small effect of location on the data. Figure 3.2 shows the normalized data. A ratio of the CVN toughness value to the average CVN toughness of the plate for the corresponding temperature is used to normalize the data and remove temperature effects. The within location scatter is now smaller which results in a larger F ratio of 2.683 and suggests location has a more significant effect on the data. It is evident, for example, that location 7 has significantly less toughness than locations 3 and 5. Note that the F ratio can be used for comparison because the number of degrees of freedom are the same whether or not the data are normalized.

Likewise, analyses of data from more than one plate do not account for differences in overall plate toughness or for temperature effects. Figures 3.3 and 3.4 show A572 Grade 50 CVN toughness data from rolling mill 5. Plate 39 is significantly tougher than plates 40 and 41 in Figure 3.3. The large scatter within each location results in an F ratio of 0.603. The data can be normalized in the same manner as previously presented for temperature effects, by dividing the CVN toughness by the average toughness of the plate at the corresponding temperature. This normalization removes both temperature and individual plate effects. The normalized data shown in Figure 3.4 result in an F ratio of 4.505 and location is realistically seen to be more significant using the normalized data.

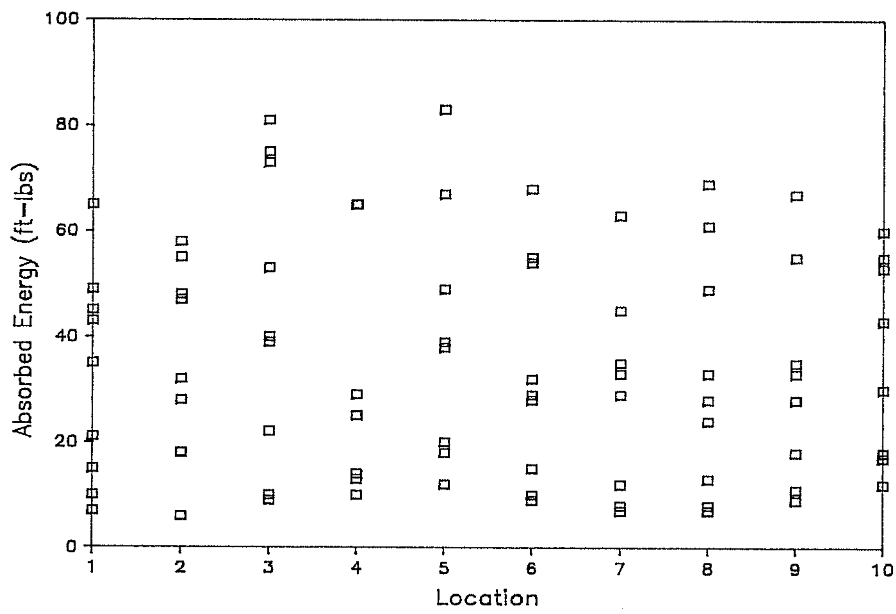

Figure 3.1 Data from Plate 9

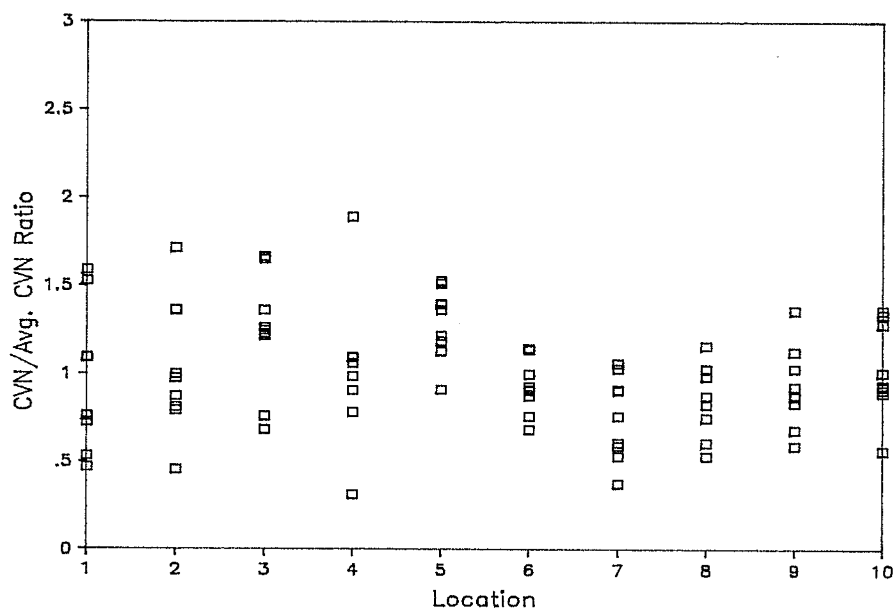

Figure 3.2 Normalized Data from Plate 9

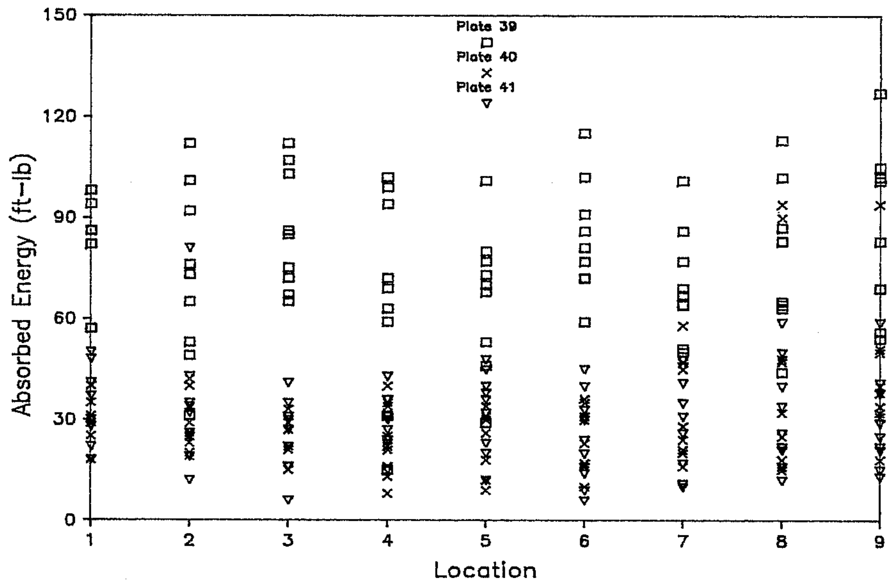

Figure 3.3 Data from A572 Grade 50, Plant 5 Material, Plates 39-41

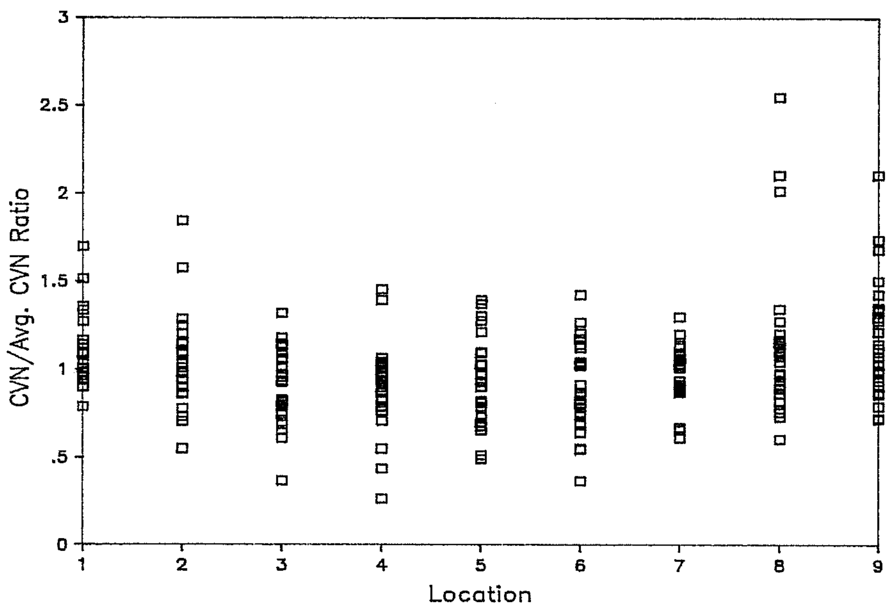

Figure 3.4 Normalized Data from A572 Grade 50, Plant 5 Material, Plates 39-41

3.4 Sample Analysis of Variance

This section presents a small, sample set of data which is not related to the AISI database but is designed to give a feel for the meaning of the analysis of variance results. The data used in the example are shown in Table 3.3. Five locations are to be studied labeled from one to five. Two temperatures are included, temperature A and temperature B. Five replicate values are measured at each location at each temperature resulting in a total of 50 test results. All values from temperature B are twice the corresponding value from temperature A.

Table 3.3 Example Data

Location	1	2	3	4	5	1	2	3	4	5
	Temperature A					Temperature B				
Rep. 1	60	65	70	65	60	120	130	140	130	120
Rep. 2	55	60	65	60	55	110	120	130	120	110
Rep. 3	50	55	60	55	50	100	110	120	110	100
Rep. 4	45	50	55	50	45	90	100	110	100	90
Rep. 5	40	45	50	45	40	80	90	100	90	80
	Normalized Temp. A					Normalized Temp. B				
Rep. 1	1.11	1.20	1.30	1.20	1.11	1.11	1.20	1.30	1.20	1.11
Rep. 2	1.02	1.11	1.20	1.11	1.02	1.02	1.11	1.20	1.11	1.02
Rep. 3	0.93	1.02	1.11	1.02	0.93	0.93	1.02	1.11	1.02	0.93
Rep. 4	0.83	0.93	1.02	0.93	0.83	0.83	0.93	1.02	0.93	0.83
Rep. 5	0.74	0.83	0.93	0.83	0.74	0.74	0.83	0.93	0.83	0.74

A plot of the data is shown in Figure 3.5. The data are normalized by the overall temperature average and the results are shown in Figure 3.6. Note that because the two temperature data sets are proportional, the normalized values are equal. Six analyses of variance were performed on the sample data to study the effect of location. The results of those analyses are found in Table 3.4.

Three analyses were performed using the actual values and three were performed using the normalized values. Because the results from temperatures A and B are proportional, the significance levels and F ratios for the value analyses are

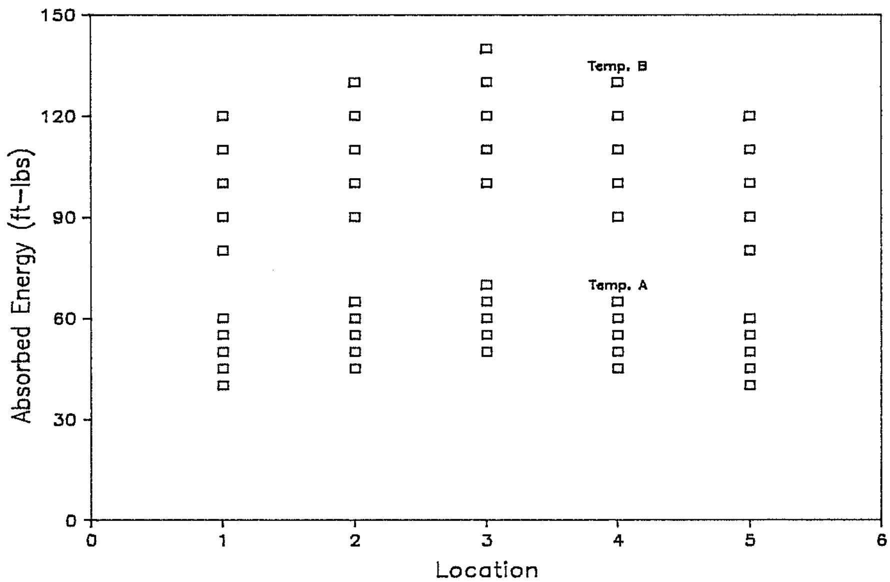

Figure 3.5 Example Data

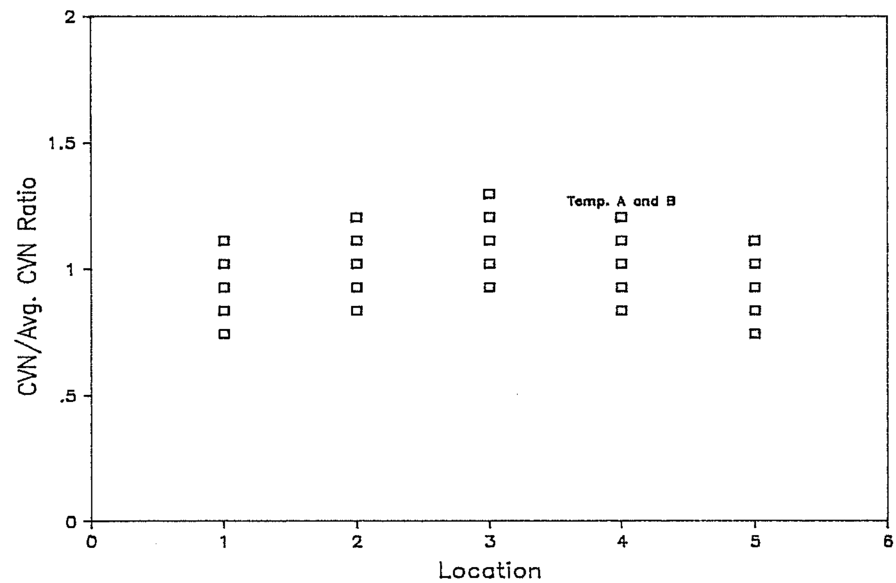

Figure 3.6 Normalized Example Data

Table 3.4 Results of ANOVA on Example Data

	Sig. Lev.	F ratio
Temperature A Values	0.27	1.40
Temperature B Values	0.27	1.40
Temperatures A and B Values	0.80	0.41
Temperature A Normalized	0.27	1.40
Temperature B Normalized	0.27	1.40
Temperatures A and B Normalized	0.02	3.15

equal. The significance level of 0.27 is relatively high which suggests that location does not have a statistically significant effect on the data. Although it appears that toughness increases from location 1 to 3 and decreases from location 3 to 5 in Figure 3.5, the scatter within each location is large enough that the trend is not significant. The analysis on data from both data combined but not normalized results in a significance level of 0.80 which is even higher and shows almost no chance that location has an effect on the values. This is because the scatter is even larger within each location when the temperatures are combined. The averages of each location for combined temperature A and B range from 75 to 90 but within the locations the values have a range of 80 at each location.

The normalized data are shown graphed in Figure 3.6. The F ratios and significance levels from the normalized analyses for the individual temperature A and temperature B analyses equal the non-normalized analyses results which is expected. The data from temperatures A and B were just divided by the overall average resulting in data which are proportional to the original data. The normalized combined temperature analysis results differ substantially from the combined non-normalized results. The significance level changes from 0.80 to 0.02. When the sets are combined, the scatter within locations is much smaller for the normalized data. Thus location is found to have a larger effect for this analysis and the significance level is lower.

Comparing the combined temperature normalized analysis to the individual temperature normalized analyses, the scatter within locations is the same but there is twice as much data when temperatures are combined. For a given variability, the scatter normally increases as the amount of data increases. In effect, the scatter is smaller for the combined normalized analysis than for the individual temperature normalized analyses. This can also be seen mathematically. The change in the sum of the squares within locations from the single temperature analysis to the combined temperature analysis is closely paralleled by a change in the number of degrees of freedom within locations. The change in the sum of the squares between locations, on the other hand, is not matched by a change in degrees of freedom as there are still five locations (four degrees of freedom between locations). Thus the mean square between locations increases while the mean square within locations remains nearly constant thereby increasing the F ratio and decreasing the significance level.

The effect on location significance when combining temperatures using normalized data is a common occurrence throughout the chapter. The normalized values do not change much for the three temperatures and when combined, the large amount of data causes the effective scatter to decrease. Location is found to have a significant effect in many more of the plates when temperatures are combined than when individual temperatures are studied.

3.5 Results of Analyses

Two types of analyses of variance will be performed as part of the analysis of the AISI survey SU27 database: single plate analyses and grouped data analyses. Both are one way analyses and study the effect of location on fracture toughness. The results of both single plate analyses and grouped data analyses will be compared to study consistency of the analysis procedures.

The results of the analyses are presented in the following sections. The results of the individual plate analyses are presented followed by the grouped analyses results. The figures which will be presented plot the results from the all temperature analyses and the tables show results from each temperature individually.

3.5.1 Single Plate Results. Single plate analyses study individual plate behavior. Fracture toughness variation within each plate was studied for the 94 plates in the survey. Four one way analyses of variance are performed; one using the data taken at 70 degrees, one using data at 40 degrees, one using data at 0 degrees, and one using the normalized data from all of the temperatures combined. This analysis procedure allows the cause of any variation that may be found to be isolated as an effect at only one temperature or an overall effect. Appendix B presents the results of the analyses of variance performed on the data for each of the 94 plates in the SU27 survey.

Most of the discussion of results will involve significance levels. A significance level less than 0.05 will be considered as suggesting that location has a statistically significant effect on the fracture toughness. In the instances where the F ratio is needed for discussion it is useful to know that the F ratio corresponding to the 0.05 significance level is 2.39 for the number of degrees of freedom common for single plate, single temperature analyses of variance. The F ratio corresponding to the 0.05 significance level is 2.00 for single plate analyses using the data from all three test temperatures, referred to as all-temperature single plate analyses.

The maximum significance level found for all of the data in any of the plates is 0.524 in plate 5. In this case, there is good reason to accept the null hypothesis that location has no effect on the fracture toughness. The normalized data from plate 5 are shown in Figure 3.7. Many of the plates have significance levels close to zero suggesting that location does have an effect. Of these plates, the largest F ratio is 60.53 for plate 34. It may be inferred that location has its greatest effect on this plate. The normalized data from plate 34 are shown in Figure 3.8. The average all-temperature significance level for the 94 plates is 0.029 and the average all-temperature F ratio is 6.64.

Table 3.5 Summary of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

All Temps	0 deg F	40 deg F	70 deg F
86	54	54	61

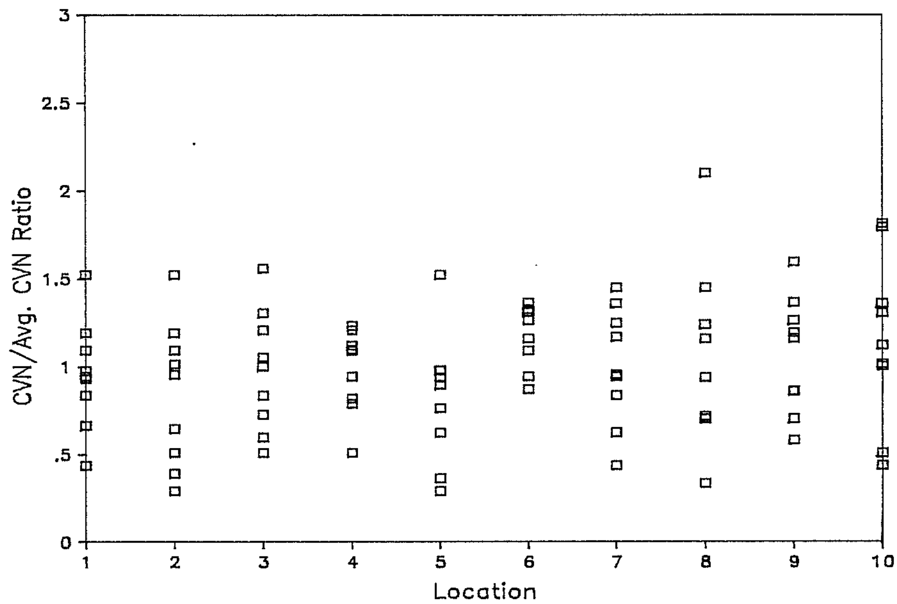

Figure 3.7 Normalized Data from Plate 5

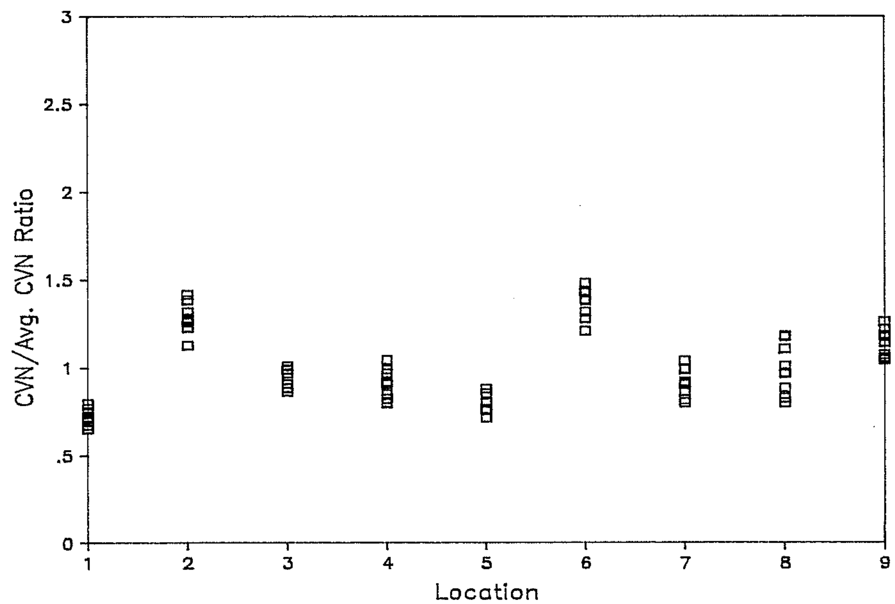

Figure 3.8 Normalized Data from Plate 34

Table 3.5 summarizes the significance levels for all of the single plate analyses. For the purposes of this report, a 5% significance level is chosen to represent an acceptable risk of incorrectly concluding that the effect of location is significant. Thus, Table 3.5 illustrates that location is determined to have a statistically valid effect in over half of the plates in the survey. The fact that many more of the all temperature analyses result in significance levels below 0.05 is caused by the large number of degrees of freedom and lower relative scatter as was discussed in Section 3.4. This difference was found throughout the various analyses. Note that there is not a large difference between the results at the three temperatures. This suggests that test temperature is not important in general.

The following sections of the report, not unlike the database description of Chapter 2, serve to summarize the results of the single plate analyses. Plates are grouped by grade, rolling mill, thickness, length, and width.

3.5.1.1 Grade. The results of the individual plate analyses are divided by grade in this section to study the effect of grade on location significance. Figure 3.9 shows the number of plates by grade which have F ratios for particular ranges. The F ratios are a preferable way to compare results in this instance because while many of the significance levels are close to zero for plates in each grade of steel, there is still a noticeable difference in the F ratios. Note that for low ranges of F ratios, there are many more A572 Grade 50 plates. As the F ratio range increases, there are more A588 plates. This suggests that location has a larger effect in a greater number of A588 plates than A572 Grade 50 plates. The F ratios in the figure are taken from the normalized all temperature analyses. The results are similar for the single temperature analyses.

Table 3.6 gives a summary of the number of plates for each grade and temperature which have location as a significant effect at the 5% alpha error level. Note that the number of A588 plates with location as a significant effect is greater than the number of A572 Grade 50 plates again suggesting that location has a greater effect in A588 steel.

3.5.1.2 Rolling Mill. Figures 3.10 and 3.11 present the F ratios for the normalized all-temperature analyses grouped by rolling mill. Figure 3.10 shows the A572 Grade 50 results and Figure 3.11 shows the A588 results. A number of

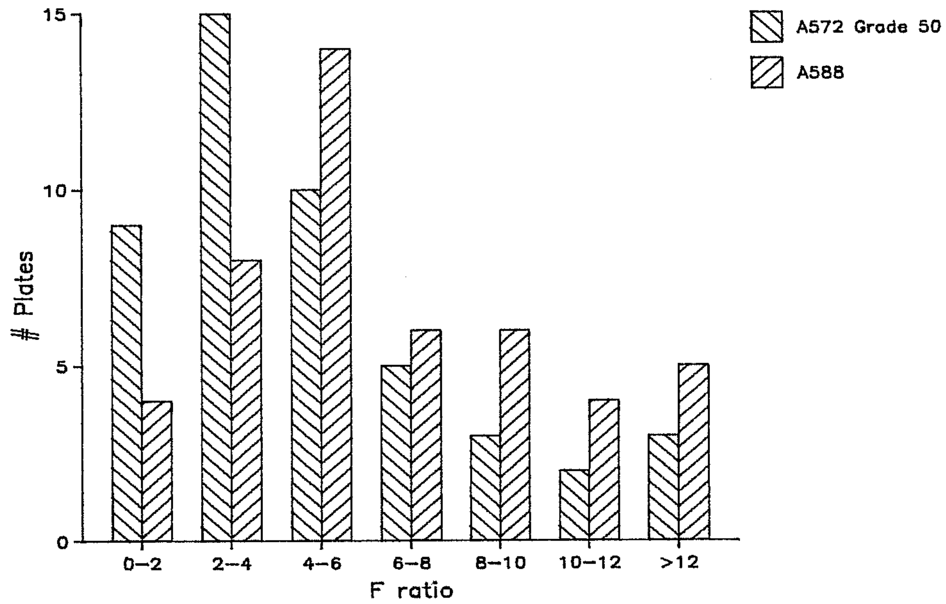

Figure 3.9 Plate F Ratios by Grade

Table 3.6 Summary by Grade of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

Grade	A572 Grade 50	A588
All Temps.	81	91
0 degrees F	40	68
40 degrees F	45	64
70 degrees F	51	70

observations concerning location effects from one rolling mill to another and from one grade to the other within the same rolling mill can be made from these figures.

The plates from rolling mill 8 show consistently high location effects. The F ratio for plates 46 and 47 is 28.1 and 28 respectively. While the A588 F ratios are lower, there is still no plate from rolling mill 8 with an F ratio below five. Rolling mill 8 clearly shows large location effects for all plates included in the survey. Figure

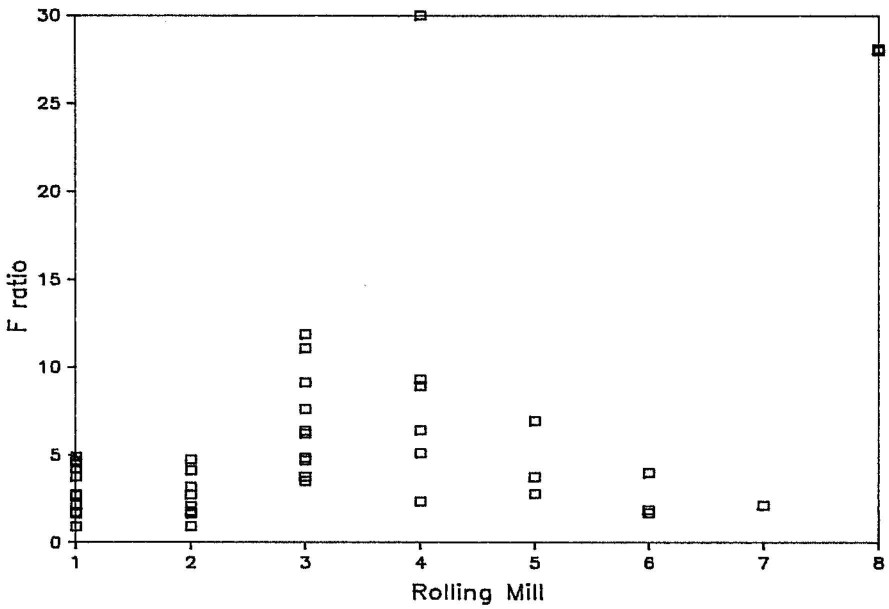

Figure 3.10 A572 Grade 50 Plate F Ratios by Rolling Mill

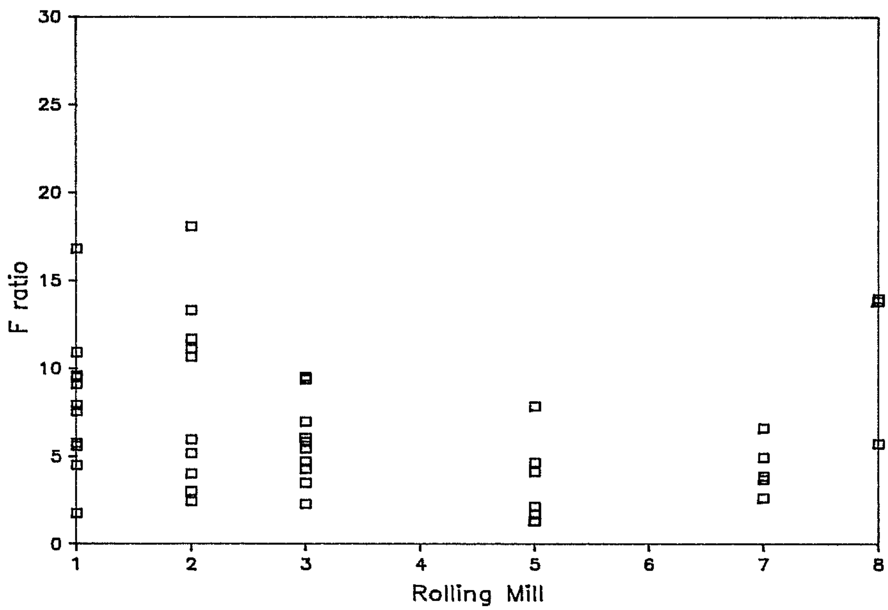

Figure 3.11 A588 Plate F Ratios by Rolling Mill

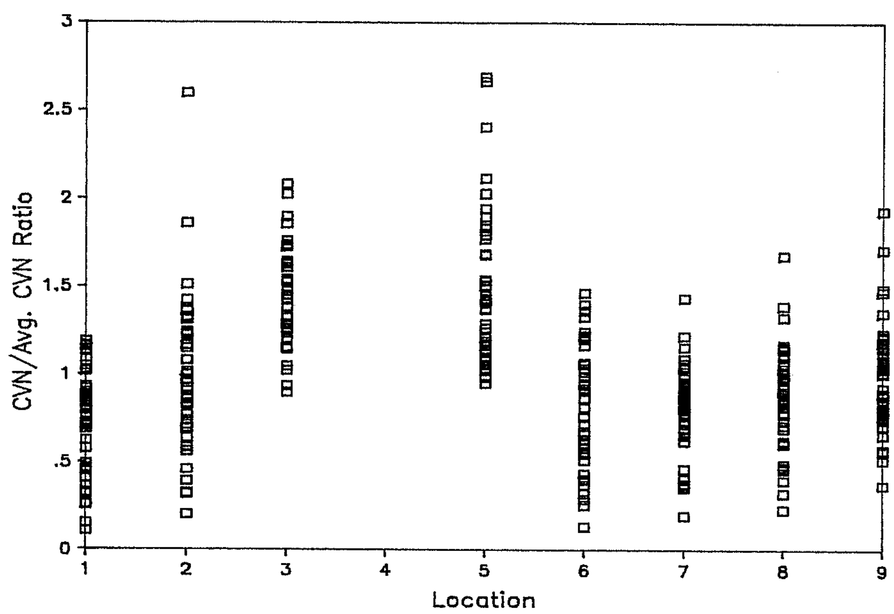

Figure 3.12 Normalized Data from Plant 8

3.12 shows a plot of the normalized ratio values for all of the rolling mill 8 plates. Location effect is obvious with locations 3 and 5 giving consistently higher results.

In Figures 3.10 and 3.11, rolling mills 1 and 2 had consistently low F ratios for A572 Grade 50 steel but had high F ratios for some A588 plates. This is also seen in Table 3.7 and is a good illustration of the difference between location effects for the two grades. In Table 3.7, the percentage of plates with a significant location effect at the 0.05 alpha level increases dramatically at each of the three test temperatures for mills 1 and 2.

Figures 3.10 and 3.11 and Table 3.7 show the opposite effect of grade for the plates from rolling mill 3. The A572 Grade 50 plates show larger location effects than the A588 plates for this mill. The percentage of A572 Grade 50 plates with significance levels below 0.05 ranges from 70 to 90% at the individual temperatures while the percentage of A588 plates ranges from 50 to 70%. Rolling mill 5 shows to

Table 3.7 Summary by Rolling Mill of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

Rolling Mill	1	2	3	4	5	6	7	8
A572 Grade 50								
All Temps.	75	60	100	100	100	33	100	100
0 deg F	8	20	90	83	0	0	0	100
40 deg F	8	20	80	100	33	33	100	100
70 deg F	50	40	70	33	33	0	100	100
A588								
All Temps.	92	100	100	-	57	-	100	100
0 deg F	67	80	70	-	29	-	80	100
40 deg F	100	60	50	-	29	-	60	66
70 deg F	92	80	60	-	0	-	100	100

some extent the same behavior as rolling mill 3 with regards to location significance. The lowest F ratios from the analyses of rolling mill 5 data come from A588 plates.

3.5.1.3 Thickness. The individual plate significance levels are plotted against the plate thicknesses for A572 Grade 50 and A588 steels in Figures 3.13 and 3.14 to study the effect of thickness on location significance.

There is no noticeable thickness effect with one possible exception. Location is significant in more of the thick plates than the thin ones. It cannot be concluded, though, that location effects increase as thickness increases. The thickness effect is not as clear or certain as some of the previous observations regarding grade and rolling mill effects. The survey does not include a complete enough spectrum of thicknesses to make any clearer observations. The thickness grouping in Table 3.8 does not show any consistent thickness effect for the three test temperatures.

3.5.1.4 Length. The results of the individual plate analyses of variance are grouped by length to study the effect of length on location significance. Figures 3.15 and 3.16 show the significance levels for the A572 Grade 50 and A588 plates plotted versus their lengths. It is seen that significance levels are lowest in general for longer plates. The observation is clearer for A588 steel in Figure 3.16. Table

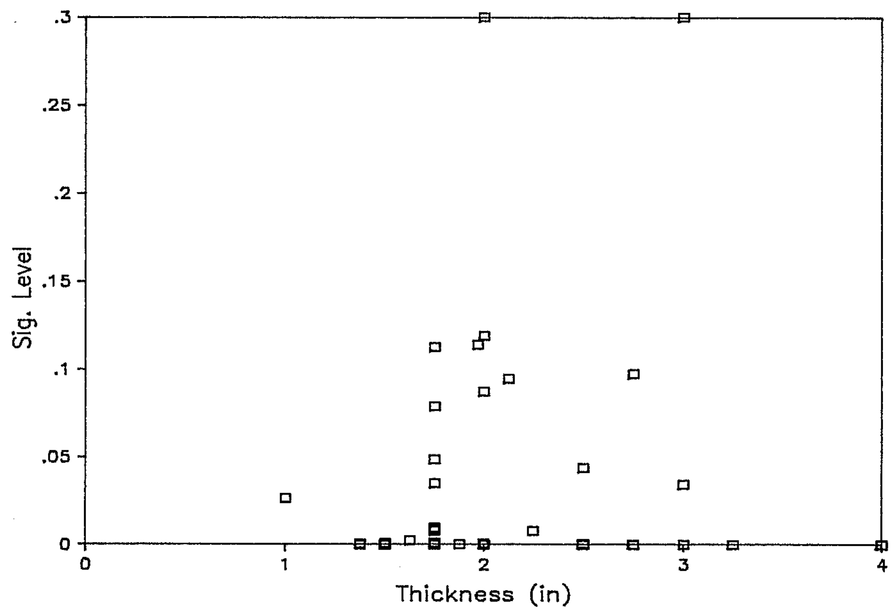

Figure 3.13 A572 Grade 50 Plate Significance Levels by Thickness

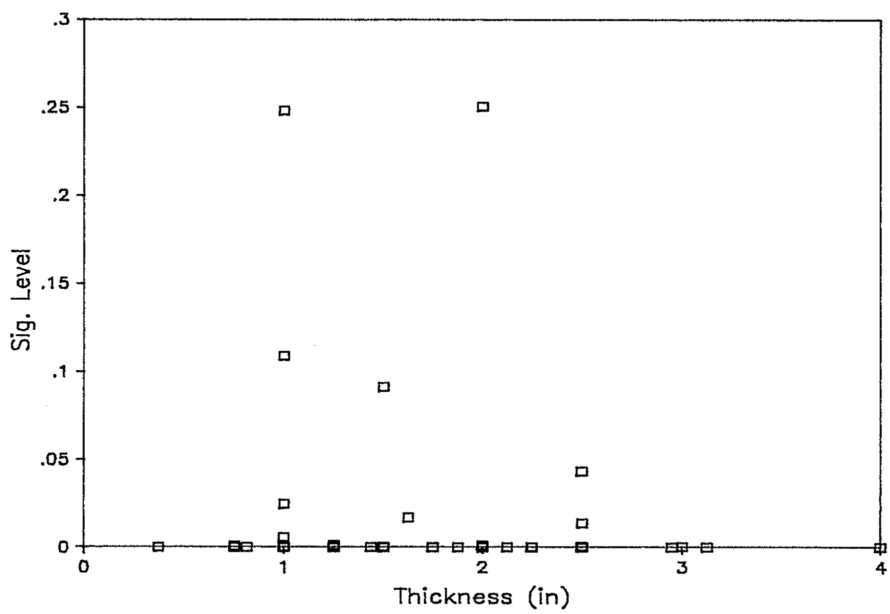

Figure 3.14 A588 Plate Significance Levels by Thickness

Table 3.8 Summary by Thickness of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

Thickness (in)	≤1	1< ≤2	>2
A572 Grade 50			
All Temps.	100	79	82
0 deg F	0	38	47
40 deg F	100	38	53
70 deg F	0	41	71
A588			
All Temps.	86	90	100
0 deg F	64	65	77
40 deg F	71	55	69
70 deg F	64	75	69

3.9 also supports the conclusion for A588 steel that location effects more of the long plates than the short or intermediate ones. The table does not support the location effect for A572 Grade 50 steel at the 0 and 40 degree test temperatures.

Table 3.9 Summary by Length of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

Length (in)	≤240	240< ≤360	>360
A572 Grade 50			
All Temps.	83	70	100
0 deg F	50	40	22
40 deg F	61	35	33
70 deg F	56	45	56
A588			
All Temps.	93	78	95
0 deg F	73	33	77
40 deg F	40	56	77
70 deg F	53	56	86

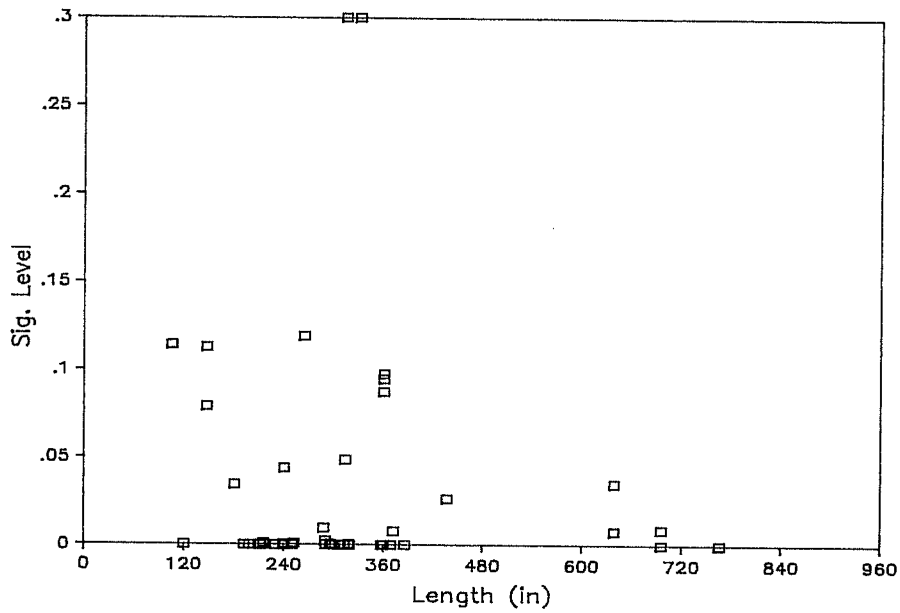

Figure 3.15 A572 Grade 50 Plate Significance Levels by Length

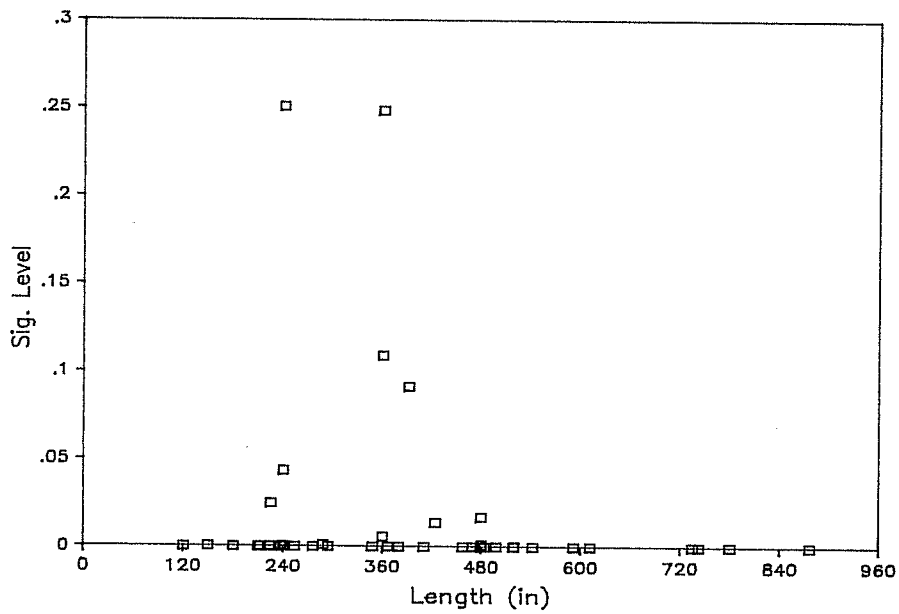

Figure 3.16 A588 Plate Significance Levels by Length

3.5.1.5 **Width.** Figures 3.17 and 3.18 along with Table 3.10 show the results of the individual plate analyses grouped by width. There is no consistent width effect which occurs at each of the test temperatures and the normalized all temperature analyses for either of the two grades of steel.

Table 3.10 Summary by Width of Location Effect for Single Plate ANOVA

% of Total with Significance Level < 0.05

Width (in)	≤60	60< ≤84	>84
A572 Grade 50			
All Temps.	91	79	76
0 deg F	27	47	41
40 deg F	36	37	59
70 deg F	45	63	41
A588			
All Temps.	79	96	100
0 deg F	45	75	71
40 deg F	45	64	86
70 deg F	45	79	71

3.5.2 Grouped Data Results. The grouped data analyses study isolated trends in the database. Data within the SU27 database were combined based on a variable or combination of variables to study trends which may occur within that data. The primary difference between the individual plate analyses and the grouped analyses is that while the individual plate data were summarized by groups after it was analyzed, the grouped data analyses divide the data prior to the analysis of variance procedure. Because grouped analyses do not treat individual plates separately many of the observations made previously in the individual plate results section are clearer in the grouped data analyses. Some of the observations previously made are not supported by the results of the grouped analyses.

All of the grouped data analyses performed in the study were divided initially by grade and temperature. Each grouped analysis is performed for each of the two steel types and at each of the test temperatures. Thus, each grouped data analysis is performed for eight subgroups of data. These eight groups are shown in

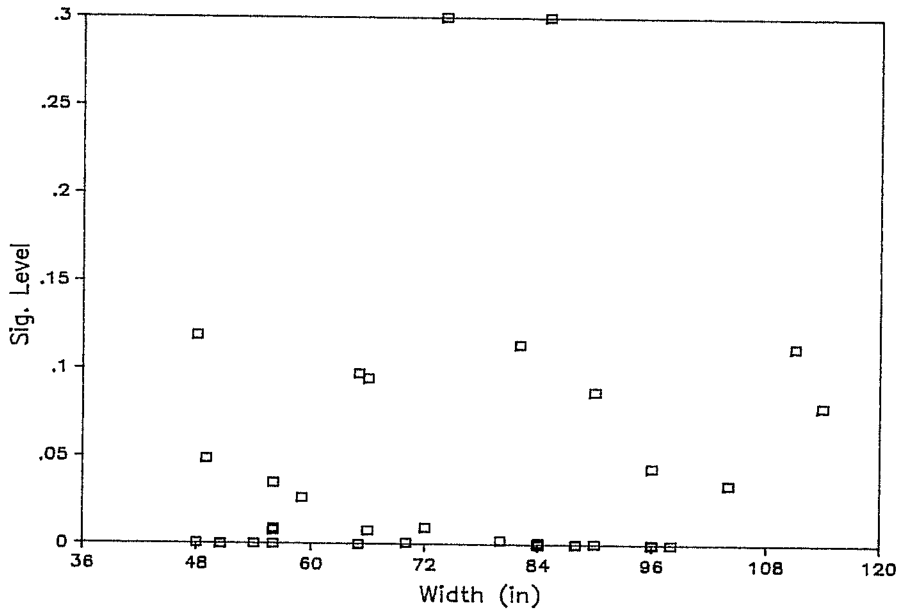

Figure 3.17 A572 Grade 50 Plate Significance Levels by Width

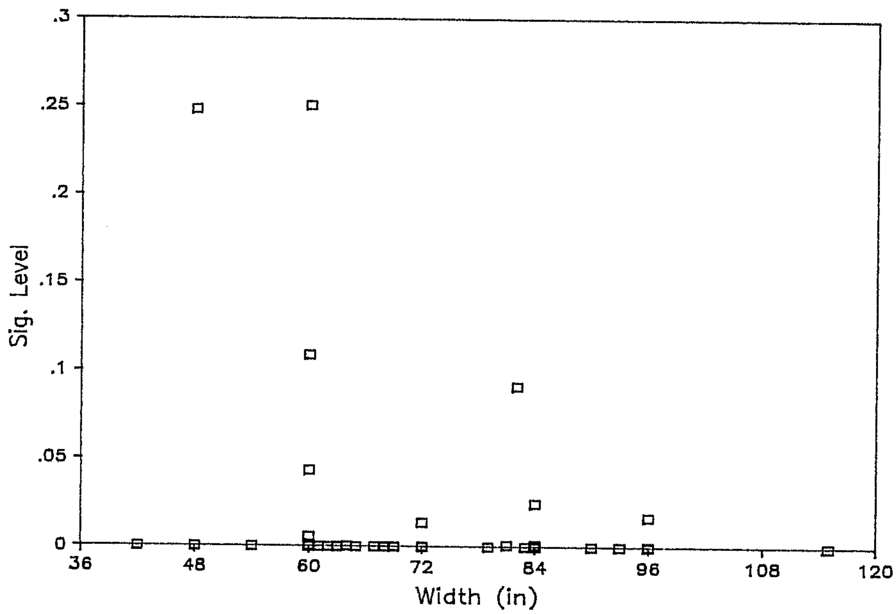

Figure 3.18 A588 Plate Significance Levels by Width

Table 3.11. The purpose of this subgrouping is not unlike the subgrouping of the individual plate data by temperature. It allows the cause of any variation which may be found to be isolated as an effect at only one temperature or grade of steel or as an overall effect.

Table 3.11 Summary of Grouped Data ANOVA Performed

A572 Grade 50	A588
All Temperatures	All Temperatures
0 degrees F	0 degrees F
40 degrees F	40 degrees F
70 degrees F	70 degrees F

Analyses of variance were performed on portions of the SU27 database divided into the same groupings which were used to study the individual plate location significance. The effect of grade alone, the effect of rolling mill, the effect of thickness, the effect of length, and the effect of width will be studied using grouped analysis of variance.

The significance levels, F ratios, and the degrees of freedom are listed for each of the eight subgroup analyses. Because of the large number of degrees of freedom involved in the grouped analysis and the small range of the normalized data values, the significance levels are commonly close to zero. In these cases, it is easier to study the meaning of the results by studying F ratios instead of significance levels. Much of the discussion in the following sections deals with F ratios rather than significance levels. Note that comparisons between F ratios are made only when the degrees of freedom are similar.

3.5.2.1 **Grade.** Table 3.12 shows the results of the analyses of variance performed on the SU27 data grouped by grade. Note that in Table 3.12 all of the significance levels are zero or close to zero. This suggests that location has a statistically significant effect for all of the data for each grade and at each temperature. While this is a useful result, the F ratio is more useful in this case. It allows a comparison between the significance of location between the two grades and between the different temperatures. Note that all of the ratios for A588 steel are larger than those for A572 Grade 50 steel. This suggests that location has a larger effect for

A588 steel than for A572 Grade 50. This effect was seen earlier in the individual plate results. Also note that the number of degrees of freedom for the analyses differ by only about 2% between the grades.

Table 3.12 SU27 Grouped by Grade ANOVA Results

Grade	A572 Grade 50	A588
Significance Level		
All Temps.	0	0
0 deg F	0.007	0
40 deg F	0	0
70 deg F	0	0
F ratio		
All Temps.	7.31	22.30
0 deg F	2.52	9.05
40 deg F	3.41	8.08
70 deg F	5.29	8.28
D.O.F.		
All Temps.	4067	4009
0 deg F	1355	1335
40 deg F	1355	1336
70 deg F	1355	1336

3.5.2.2 **Rolling Mill.** The results of the analysis of variance performed on the SU27 database grouped by rolling mill are shown in Table 3.13. The observations of section 3.5.1.2 are clearly shown in this table. Rolling mill 8 again shows consistently low significance levels and high F ratios. The large effect of grade within rolling mill 1 is seen again. F ratios are much higher and significance levels much lower for A588 analyses than for A572 Grade 50 analyses. This illustrates the large effect of location in A588 plates relative to A572 Grade 50 plates for rolling mill 1 materials. Rolling mill 2 results also show the same behavior with the exception of the 70 degree test temperature analysis. The behavior is not as pronounced for rolling mill 2 as it is for rolling mill 1 though.

While the individual plate summary showed that the effect of location on A572 Grade 50 from rolling mill 5 is greater than the effect of location on A588 plates, Table 3.13 does not fully support this observation. It does support the observation for the all-temperature and the 70 degree analyses but not the 0 and 40 degree

Table 3.13 SU27 Grouped by Rolling Mill ANOVA Results

Rolling Mill	1	2	3	4	5	6	7	8
A572 Grade 50								
Significance Level								
All Temps.	0.002	0	0	0	0	0.001	0.044	0
0 deg F	0.415	0.003	0.122	0.002	0.081	0.222	0.121	0
40 deg F	0.095	0.163	0.025	0.010	0.249	0.084	0.027	0
70 deg F	0.049	0	0.010	0.655	0.002	0.056	0.001	0
F ratio								
All Temps.	2.92	5.17	4.49	3.96	4.51	3.53	2.13	46.52
0 deg F	1.03	2.91	1.58	3.19	1.86	1.38	1.91	17.72
40 deg F	1.67	1.46	2.17	2.63	1.32	1.84	2.96	28.21
70 deg F	1.91	3.74	2.48	0.74	3.54	2.02	6.02	15.31
D.O.F.								
All Temps.	1079	890	899	485	242	242	80	143
0 deg F	359	296	299	161	80	80	26	47
40 deg F	359	296	299	161	80	80	26	47
70 deg F	359	296	299	161	80	80	26	47
A588								
Significance Level								
All Temps.	0	0	0	-	0	-	0	0
0 deg F	0	0	0	-	0.045	-	0	0
40 deg F	0	0.053	0.002	-	0.170	-	0.648	0
70 deg F	0	0	0	-	0.012	-	0.229	0.016
F ratio								
All Temps.	27.23	8.83	8.31	-	3.67	-	3.80	12.35
0 deg F	11.16	5.17	3.77	-	2.03	-	4.45	5.64
40 deg F	9.98	1.89	2.95	-	1.47	-	0.75	5.00
70 deg F	13.06	2.83	4.04	-	2.54	-	1.34	2.73
D.O.F.								
All Temps.	1079	863	890	-	562	-	404	206
0 deg F	359	287	296	-	186	-	134	68
40 deg F	359	287	296	-	186	-	134	206
70 deg F	359	287	296	-	186	-	134	206

analyses. In the 0 and 40 degree case, though, location is not seen to have a large effect for either grade.

The grouped data results also do not correspond to the individual plate observations regarding rolling mill 3. While the individual plate results showed that location had a greater effect for A572 Grade 50 plates the grouped analyses results suggest that the A588 steel has a larger location effect.

3.5.2.3 Thickness. The results of the analyses of variance by thickness are shown in Table 3.14. This table, as did the individual plate results, shows a general thickness effect for A572 Grade 50 steel in which the effect of location increases as thickness increases. All A572 Grade 50 analyses follow the trend with the exception of the 40 degree test temperature material with thickness greater than two inches. A588 material does not show a consistent thickness effect.

Table 3.14 SU27 Grouped by Thickness ANOVA Results

	A572 Grade 50			A588		
Thickness (in)	≤1	1< ≤2	>2	≤1	1< ≤2	>2
Significance Level						
All Temps.	0.027	0	0	0	0	0
0 deg F	0.419	0.341	0.010	0	0.001	0
40 deg F	0.042	0.001	0.030	0	0	0
70 deg F	0.368	0.127	0	0	0	0
F ratio						
All Temps.	2.35	3.51	6.00	11.74	9.92	12.21
0 deg F	1.08	1.13	2.44	3.97	3.22	6.67
40 deg F	2.64	3.12	2.08	6.03	4.19	4.97
70 deg F	1.17	1.55	6.06	5.72	6.34	3.71
D.O.F.						
All Temps.	80	2537	1448	1205	1734	1068
0 deg F	26	845	482	401	578	354
40 deg F	26	845	482	401	577	356
70 deg F	26	845	482	401	577	356

3.5.2.4 Length. The results of the analyses of variance on normalized data for length effects are found in Table 3.15. The observations shown in the single plate analyses of section 3.5.1.4 are shown much more clearly in this table. In all eight analyses performed on the three different length subdivisions, the significance levels found for the long plate analyses are the smallest. The results of the analyses

Table 3.15 SU27 Grouped by Length ANOVA Results

Length (in)	A572 Grade 50 ≤240	A572 Grade 50 240< ≤360	A572 Grade 50 >360	A588 ≤240	A588 240< ≤360	A588 >360
Significance Level						
All Temps.	0	0.006	0	0	0.004	0
0 deg F	0.325	0.031	0.002	0.001	0.637	0
40 deg F	0.011	0.214	0.002	0	0.173	0
70 deg F	0.009	0.269	0	0	0.001	0
F ratio						
All Temps.	3.76	2.57	8.33	9.88	2.14	21.02
0 deg F	1.15	2.07	3.02	3.33	0.78	10.57
40 deg F	2.41	1.34	3.01	3.91	1.44	7.61
70 deg F	2.47	1.24	4.36	4.58	3.30	5.82
D.O.F.						
All Temps.	1538	1754	773	1301	764	1861
0 deg F	512	584	257	432	254	620
40 deg F	512	584	257	434	254	619
70 deg F	512	584	257	433	254	620

grouped by length strongly support the idea that location has the greatest effect on long plates.

3.5.2.5 **Width.** Table 3.16 presents the results of the analyses of variance for the SU27 database grouped by width. The observations from this table do not agree with the observations of the single plate analyses in section 3.5.1.5 in total. Section 3.5.1.5 found no width effect in the results. Table 3.16 suggests with the exception of the 0 degree test temperature that the effect of location increases as width decreases for A572 Grade 50 plates. Location effects are the greatest for narrow plates according to the table. The width effect for the A588 steel is opposite that of the A572 Grade 50 steel in Table 3.16. With the exception of the 70 degree test temperature, the narrow A588 plates have the smallest location effect of the plates.

Table 3.16 SU27 Grouped by Width ANOVA Results

Width (in)	A572 Grade 50 ≤60	60< ≤84	>84	A588 ≤60	60< ≤84	>84
Significance Level						
All Temps.	0	0	0	0	0	0
0 deg F	0	0.080	0.006	0.005	0	0.001
40 deg F	0	0	0.437	0.026	0	0.001
70 deg F	0	0	0.171	0.002	0	0.014
F ratio						
All Temps.	11.81	5.93	3.49	6.12	16.27	6.37
0 deg F	4.15	1.73	2.62	2.70	5.48	3.28
40 deg F	4.50	3.63	1.00	2.14	7.09	2.89
70 deg F	5.24	4.60	1.43	3.03	6.31	2.37
D.O.F.						
All Temps.	926	1691	1448	923	2374	629
0 deg F	308	563	482	306	791	209
40 deg F	308	563	482	308	790	209
70 deg F	308	563	482	307	791	209

3.6 Interpretation of Results

In general, there are three types of plates in the survey; one in which location is found to be significant at all temperatures, one in which location is found to be not significant at all temperatures, and one in which location is significant at one temperature and not significant at another. Examples of each of these types of plates is shown in Figures 3.19-3.27. Plate 34 is a plate in which location has a significant effect at all temperatures. Plate 22 is an example of a plate in which location is not significant at each temperature. Plate 14 is a plate which does not have a consistent location significance for the three temperatures. Table 3.17 presents the significance levels for the three plates at each of the test temperatures.

The significance levels for each temperature are equal to zero for plate 34. This is a result primarily due to the very low scatter within location as seen in Figures 3.19-3.21. The denominator of the F ratio is small resulting in a large F ratio and a low significance level. Thus, it made be said with high certainty that

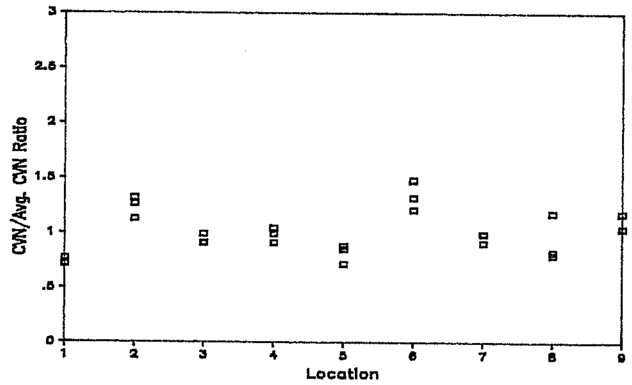

Figure 3.19 Normalized Data from Plate 34, 0 °F (Sig. Lev.= 0.000)

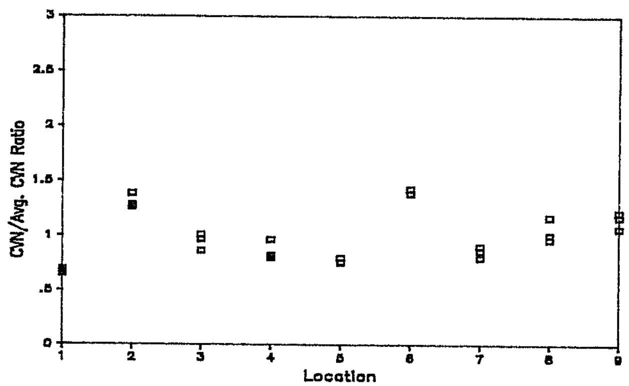

Figure 3.20 Normalized Data from Plate 34, 40 °F (Sig. Lev.= 0.000)

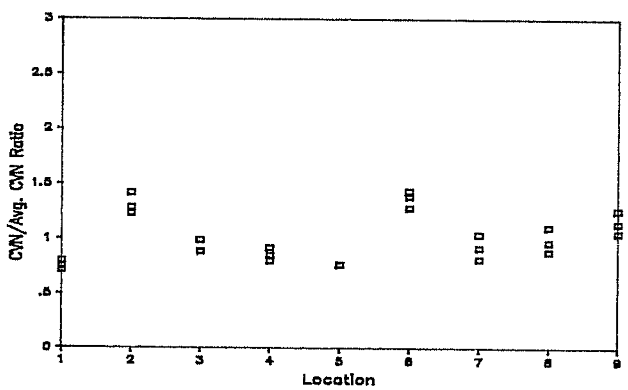

Figure 3.21 Normalized Data from Plate 34, 70 °F (Sig. Lev.= 0.000)

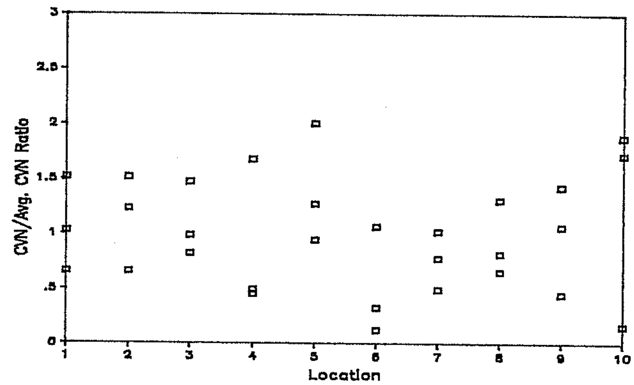

Figure 3.22 Normalized Data from Plate 22, 0 °F (Sig. Lev.= 0.719)

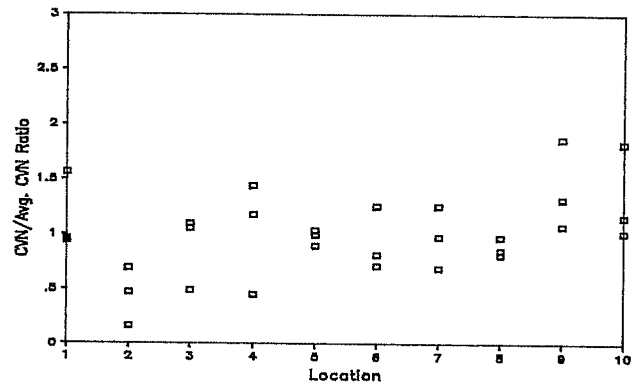

Figure 3.23 Normalized Data from Plate 22, 40 °F (Sig. Lev.= 0.097)

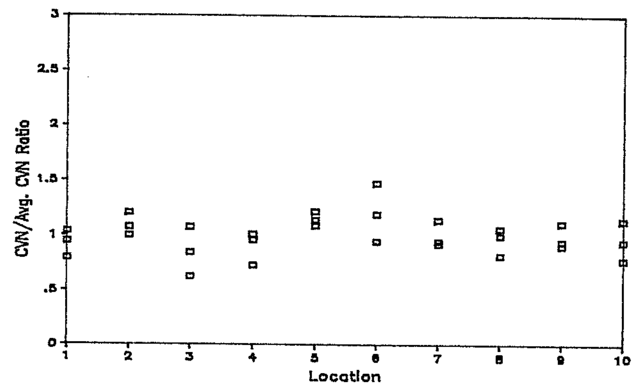

Figure 3.24 Normalized Data from Plate 22, 70 °F (Sig. Lev.= 0.202)

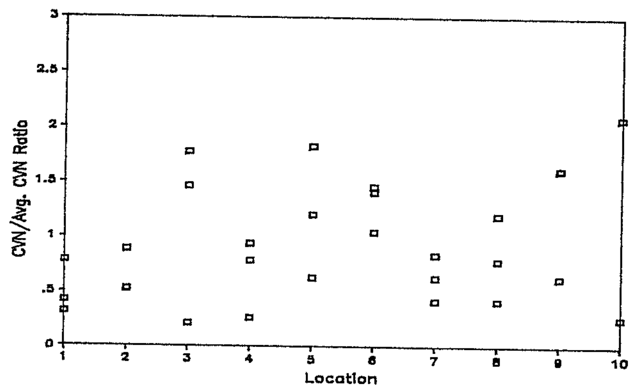

Figure 3.25 Normalized Data from Plate 14, 0 °F (Sig. Lev.= 0.278)

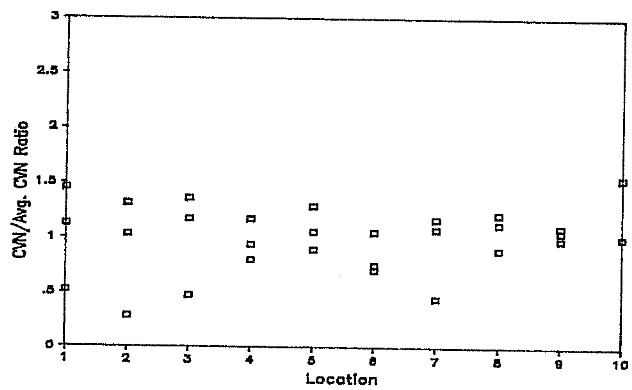

Figure 3.26 Normalized Data from Plate 14, 40 °F (Sig. Lev.= 0.963)

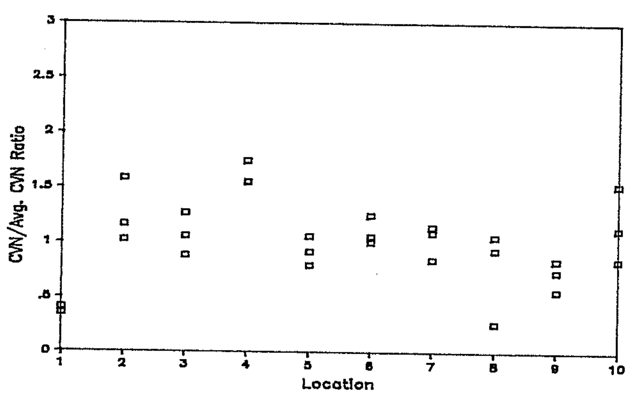

Figure 3.27 Normalized Data from Plate 14, 70 °F (Sig. Lev.= 0.000)

Table 3.17 Significance Levels for Plates 14, 22, and 34

	Plate 14	Plate 22	Plate 34
0 degrees F	0.278	0.719	0
40 degrees F	0.963	0.097	0
70 degrees F	0	0.202	0

the means at each location are not equal and location is indeed significant at all temperatures.

Analysis of plate 22 results in relatively high significance levels for all temperatures. This suggests that location is not significant in the plate as shown in Figures 3.22-3.24. This result appears to occur for different reasons at different temperatures. Within location scatter at 70 °F in Figure 3.24 is small but between location scatter is also small. The F ratio is a small number over a small number and is equal to 1.539. The 0 degree test temperature in Figure 3.23, on the other hand, contains both large between and within location scatter. The F ratio is a large number over a large number and is equal to 0.679. Both temperatures, though, lead to the conclusion that location is not significant in the plate.

Plate 14 is a combination of the previous two examples. The 70 degree test temperature shows small scatter within locations and large scatter between locations in Figure 3.27 resulting in the conclusion that location has a significant effect at this test temperature. At 40 °F in Figure 3.26 the opposite occurs, a larger within location scatter and smaller between location scatter. This results in a low F ratio of 0.308 and a high significance level. Thus, location is found to be not significant at the 40 degree test temperature.

Plates 14, 22, and 34 are the most severe examples of how location significance can change with test temperature. They were included to show that test temperature can also be a factor in location significance but in general, the effect is not a large or consistent one.

3.7 Summary

The primary purpose of Chapter 3 was to study fracture toughness variation within the steel plates of AISI Survey SU27. The effects of grade, rolling mill, thickness, length, and width on the variation were also considered. Analysis of variance was the method used to study variation.

Analysis of variance was used to study variation for two reasons: 1) It is a statistically unbiased procedure. No objective decisions are made in performing the procedure. The results are based solely on the data. 2) Analysis of variance answers the simple question of whether or not the location from which test specimens are taken within a plate is important. In other words, does location have a statistically significant effect on fracture toughness? The answer to this simple question has great ramifications on the philosophy behind setting a test limit. If location is not important the test limit can be set at the desired toughness performance level. But if location is significant, variation within plates must be accounted for in the test limit development.

A number of conclusions were made from the analysis of variance results: 1) The results of the analyses of variance performed on the individual plates summarized in Table 3.5 indicated that for over half of the plates in the survey location was significant at at least one test temperature. 2) Table 3.6 showed that a larger percentage of A588 plates relative to A572 Grade 50 plates had location as a significant effect. 3) Figures 3.10 and 3.11 showed that rolling mill had a large effect on location significance. For example, plates from rolling mill 8 had a location effect which was much greater than plates from rolling mills 1 and 2 for A572 Grade 50 steel. 4) The thickness parameter was not found to have a very large effect on location significance. 5) Figures 3.15 and 3.16 showed that location was significant in a greater percentage of the plates as length increases. 6) The width parameter was not found to have any consistent effect for all test temperatures and both grades of steel.

There are two major limitations in using the analysis of variance procedure for the purposes of this study. The procedure does not give the cause of the conclusion it reaches regarding location significance and it does not consider the level of fracture toughness in the plates.

While knowing the answer to the question of whether or not it is important where the test specimens are taken is useful, it is much more useful to know the magnitude of difference which can be expected from one location to the next. Analysis of variance did not provide this answer. This chapter explained that location significance as found by analysis of variance is dependent on the inter-relationship between within location scatter and between location scatter. Plates which show small within location scatter and small between location scatter are not necessarily a concern although analysis of variance results may show that location is significant. In fact, the plate with the largest F ratios in the study was plate 34 shown in Figure 3.8. The large F ratios were primarily a factor of small scatter within location for the plate. While it was obvious that location had a significant effect when viewing the figure, the overall scatter was not very large relative that of many other plates in the survey including that of plate 5 in Figure 3.7 which showed the lowest F-ratios in the survey. Alternatively, large within location scatter many times causes location to be insignificant although large location scatter is not necessarily desirable.

The second major limitation of the analysis of variance procedure is that the level of fracture toughness is not considered in the analysis. Variation which may occur in high toughness plates is not nearly the concern as variation in lower toughness plates. Although normalized values were used to remove temperature and toughness effects, the example analyses results of Table 3.4 showed that normalizing does not effect the results of one test temperature, one plate analyses. The results are independent of toughness.

If the data could be manipulated to address the limitations of the analysis of variance procedure cited above, the results would be much more useful. Ideally, both of the limitations could be minimized but there seems to be no simple way of finding the cause of location significance without judging subjectively from graphs. The remainder of the summary, on the other hand, to account for the effect of toughness level. Location significances will be examined for the plates with lower toughness levels.

A set of arbitrary limits has been used to screen the data to determine the plates which are of lower toughness. The screening methods are; 1) any A572 Grade 50 plate with an overall toughness average less than 40 ft-lbs at the test temperature and any A588 plate with an overall toughness average less than 50 ft-lbs, 2) any plate with a location toughness average less than 25 ft-lbs at the test temperature, and 3) any plate with a single test result less than 15 ft-lbs at the test temperature. The overall toughness average limit of A588 plates is higher than that of the A572 Grade 50 plates because A588 plates are generally tougher.

The significance levels for the plates not passing all of these screening criteria are summarized in Table 3.18. The all-temperature and 0 °F results are not presented in the table as they are not the temperatures which would ordinarily be used to test bridge plate.

Table 3.18 Summary of Location Effect for Low Toughness Plates

% of Total with Significance Level < 0.05

	40 deg F	70 deg F
A572 Grade 50	46	66
A588	58	33

The results in Table 3.18 differ substantially from the results for all of the plates which was shown in Table 3.6 with the exception of the percentage of low toughness A588 plates with a significant location effect at the 70 °F test temperature. Results in Table 3.6 were 45 and 51% for A572 Grade 50 steel at 40 and 70 °F respectively and 64 and 70% for A588 at 40 and 70 °F.

Because there are not large differences for the most part it is not accurate to conclude that low toughness plates perform any better or worse than all of the plates in general as far as location effect is concerned. The limitation of the analysis of variance procedure which does not account for differences in overall toughness between plates does not seem to be a major one.

CHAPTER 4
DEVELOPMENT OF TEST LEVELS

4.1 Introduction

The purpose of this chapter is to develop using a statistically based approach CVN Absorbed Energy test levels to compare with the current AASHTO fracture toughness specifications for fracture critical members. The AISI SU27 database of 1984 is used as the reference data from which the test levels are set and the analysis procedures developed. The starting point in any development of test limits is to determine the performance required by the user, in this case the fracture toughness required in a bridge. This is discussed in this chapter and required test limits are developed for two different performance criteria.

Chapter 3 showed that fracture toughness varies throughout many of the plates in survey SU27. If there was no variation, test limits could be set at the required performance criteria. Plates could be accepted if the sample test results exceeded the criteria. But because of the variation, it is to be expected that the test limits imposed will be higher than the desired performance criteria required by the user.

Recommended test limits are arrived at from two approaches; from a purely statistical standpoint and from a direct procedure. The statistical method is developed by obtaining a toughness level frequency distribution from the SU27 database. Using the distribution, the necessary test levels can be calculated for a desired toughness criterion and confidence level. The direct procedure does not require the intermediate step of determining a distribution function. Instead, it is a procedure which involves setting arbitrary test limits, imposing them on the data, and observing the results. Based on the results, the limits producing the most favorable results can be chosen. Test levels in this chapter will be set for both grades of steel at the 40 and 70 degree test temperatures. Test limits will not be set for the 0 degree test temperature because this is not one of the test temperatures which is used by AASHTO in their specifications.

The rationale behind the distribution based test criteria is described in Section 4.3 and the results of the analysis follow. A description of the direct procedure and a summary of the results from the procedure are next presented in Section 4.4. A comparison is made between the results of the two procedures in Section 4.5 and lastly, a summary provides a detailed look at the results of applying the recommended test levels.

4.2 Performance Criteria

Barsom and Rolfe [7] describe in their book methods used to determine performance criteria for fracture toughness in steel. A minimum CVN toughness of 15 ft-lbs is commonly viewed as an acceptable level of toughness for A572 Grade 50 and A588 steel. The AASHTO specifications are shown in Table 4.1. Average toughness levels of three Charpy test results are set at 25 and 30 ft-lbs in an attempt to minimize the chances of a single test result falling below the 15 ft-lb level. As time progressed, two trains of thought have emerged, one which suggests that 25 ft-lbs average toughness be required throughout the plate because the specifications are set at 25 ft-lbs and the other which suggests that an average toughness level of 15 ft- lbs is sufficient.

Two performance criteria will be used in this report. It is desired that no three tests at a location result in an average less than 15 ft-lbs in one criterion or less than 25 ft- lbs in the other. These criteria represent two distinctly different views. One suggests that the average toughness anywhere in a plate be greater than 25 ft-lbs, the current mill test requirement, and the other suggests that the average toughness anywhere in a plate be greater than 15 ft-lbs, thought to be the basis for the current mill test requirement. Note that these performance criteria are subjective. Others may be chosen but these represent current trains of thought. They allow test limits to be developed and evaluated and allow the procedures used to arrive at the test limits to be evaluated.

Table 4.1
Base Metal Charpy V-Notch Requirements[a] for Fracture Critical Members (from Ref. 1)

AASHTO	ASTM Designation	Thickness, Inches (mm)	Zone 1[b]	Zone 2[c]	Zone 3[d]
M183	A36	Up to 4" (101.6)	25 @ 70°F (33.9 Nm @ 21.2°C)	25 @40°F (33.9 Nm @ 4.4°C)	25 @ 10°F (33.9 Nm @ -12.2°C)
M223	A572*	Up to 4" (101.6) mechanically fastened	"	"	"
"	"	Up to 2" (50.8) welded	"	"	"
M222	A588*	Up to 4" (101.6) mechanically fastened	"	"	"
"	"	Up to 2" (50.8) welded	"	"	"
"	"	Over 2" to 4" (50.8-101.6) welded	30 @ 70°F (40.7 Nm @ 21.1°C)	30 @ 40°F (40.7 Nm @ 4.4°C)	30 @ 10°F (40.7 Nm @ -12.2°C)
M244	A514**	Up to 4" (101.6) mechanically fastened	35 @ 0°F (47.5 Nm @ -17.8°C)	35 @ 0°F (47.5 Nm @ -17.8°C)	35 @ -30°F (47.5 Nm @ -34.4°C)
"	"	Up to $2\frac{1}{2}$" (63.5) welded	35 @ 0°F (47.5 Nm @ -17.8°C)	35 @ 0°F (47.5 Nm @ -17.8°C)	35 @ -30°F (47.5 Nm @ -34.4°C)
"	"	Over $2\frac{1}{2}$" to 4" (63.5 - 101.6 welded)	45 @ 0°F (61 Nm @ -17.8°C)	45 @ 0°F (61 Nm @ -17.8°C)	(Not permitted) (Not permitted)

[a] The CVN impact testing shall be "P" plate frequency testing in accordance with AASHTO T-243 (ASTM A673). The Charpy test pieces shall be coded with respect to heat/plate number and that code shall be recorded on the mill test report of the steel supplier with the test result. If requested by the Engineer, the broken pieces from each test (three specimens, six halves) shall be packaged and forwarded to the Quality Assurance organization of the State. Use the average of three (3) tests. If the energy value for more than one of three test specimens is below the minimum average requirements, or if the energy value for one of the three specimens is less than two thirds (2/3) of the specified minimum average requirements, a retest shall be made and the energy value obtained from each of the three retest specimens shall equal or exceed the specified minimum average requirement.

[b] Zone 1: Minimum Service Temperature 0°F (-17.8°C) and above.

[c] Zone 2: Minimum Service Temperature from -1°F to -30°F (-18.3°C to -34.4°C)

[d] Zone 3: Minimum Service Temperature from -31°F to -60°F (-35°C to -51.1°C)

* If the yield strength of the material exceeds 65 ksi (448.159MPa) the temperature for the CVN value for acceptability shall be reduced by 15°F (8.3°C) for each increment of 10 ksi (68.947MPa) above 65 ksi (448.159MPa). The yield strength is the value given in the certified "Mill Test Report."

** ASTM A517 Charpy requirements are the same as for AASHTO M244 (ASTM A514).

4.3 Distribution Based Procedure

4.3.1 Development. Figures 4.1 and 4.2 show the distribution of average CVN test results from the SU27 database for A572 Grade 50 and A588 steel respectively. Ideally, a distribution function can be fit to the figures and test limits can be specified. But because of the temperature effect and difference in plate toughness effects which led to normalization in Chapter 3, the distributions of Figures 4.1 and 4.2 are not practical for use in specifying test limits. In addition, the distributions are obviously far from normal making any statistical procedures complex.

The form of the database which was used to specify test limits is a database of average normalized CVN test results. Figure 4.3 displays an example of this type of distribution. As in Chapter 3, the data are normalized by dividing the individual CVN test results by the average CVN level for all the data in a plate at the corresponding temperatures.

The distributions are assumed to be normal which simplifies the statistical procedures. A discussion of the ramifications of this assumption is included later in the chapter. Figure 4.4 shows the graphical representation of the philosophy behind the distribution based analysis procedure. A required minimum location average of 15 ft-lbs and a 95% confidence level is used in this example. By specifying a required minimum sample test average at a location and a confidence level, a required plate average can be calculated using the average ratio and the standard deviation of the ratios. This is the plate average that is required if only 5% of the location average test results are to less than 15 ft-lbs. The standard deviation which is used to obtain the necessary plate average is that of the average normalized values and is denoted σ_{AVG}.

Obviously, the actual plate average will never be ascertained using a small sample of three test values. A one- sided "t" or normal test (depending on assumptions) can next be used to determine for a selected confidence level whether or not a particular sample of three specimens is taken from the distribution of a plate with an average greater than or equal to the required plate average. Note that a plate average greater than the required plate average suggests that less than 5% of the location averages are below 15 ft-lbs which is acceptable. If the standard deviation of the plate is assumed equal to the standard deviation of the entire distribution,

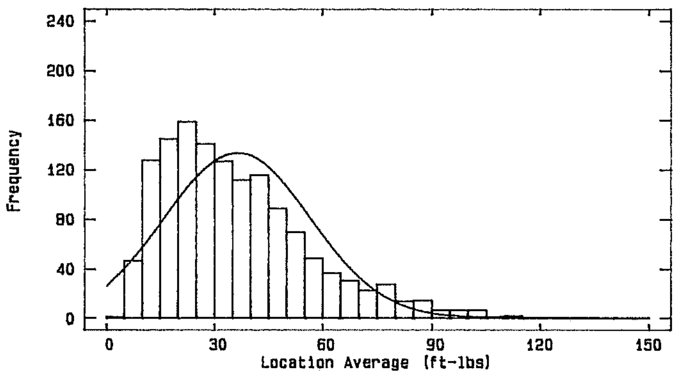

Figure 4.1 Location Average Distribution, A572 Grade 50, All Temps.

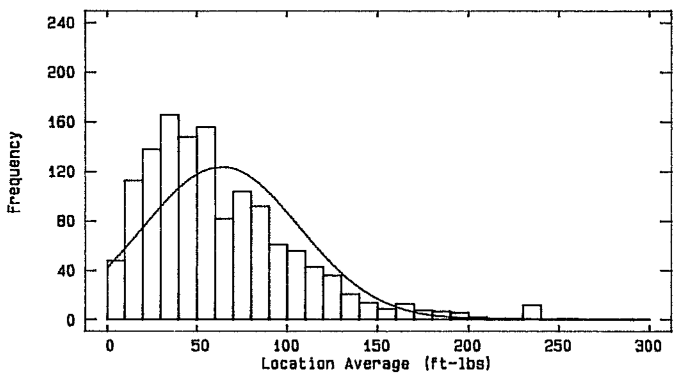

Figure 4.2 Location Average Distribution, A588, All Temps.

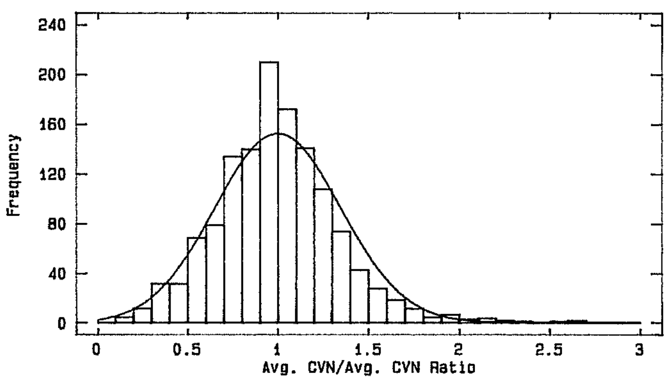

Figure 4.3 Normalized Location Average Distribution, A588, All Temps.

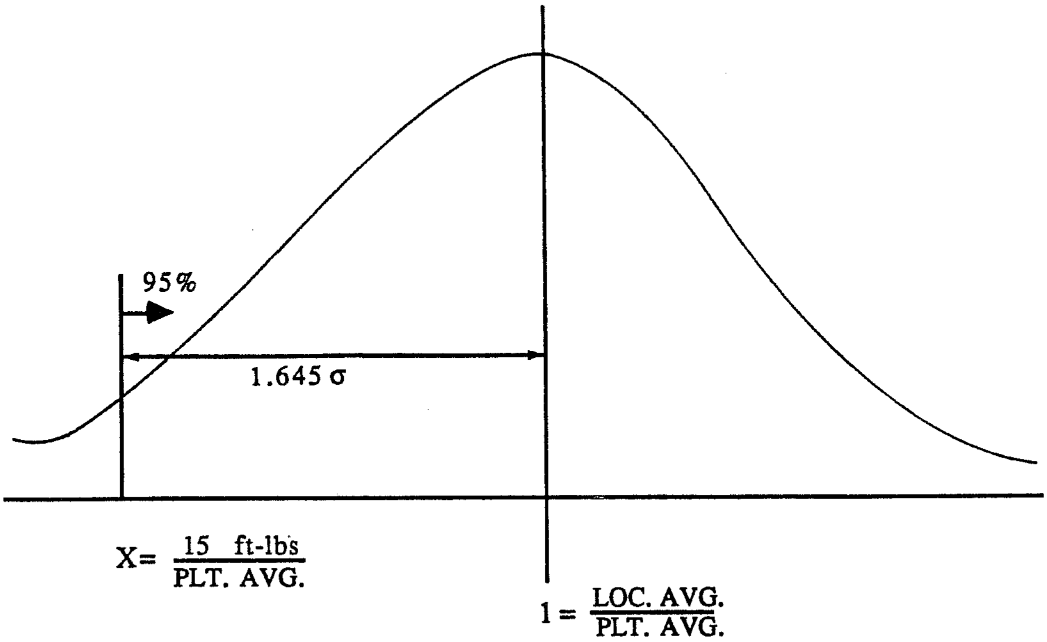

Figure 4.4 Diagram of Distribution Based Analysis

the one-sided normal test is used. Otherwise, the standard deviation of the plate can be estimated from that of the sample and the one-sided "t" test used.

For the purposes of this study, it will be assumed that the standard deviation of a plate is equal to that of the distribution. Estimating the standard deviation of a plate using the results of only three test results does not lead to practical results. For instance, it is entirely possible that the three test results be equal and this would suggest that there is no variation anywhere in the plate. This has been shown to be incorrect. Thus, the one-sided normal test is used in this study. The standard deviation of interest when developing the required location average from the previously derived required plate average is that of the individual normalized values. It is denoted as σ_{IND} in this report.

A set of sample calculations illustrating the distribution based procedure is presented below.

Sample Calculation

From Normal Distribution of Normalized Averages:

Average $= 1$ $\quad z_{95\%} = 1.645$

$$\sigma_{AVG} = 0.254 \qquad \sigma_{IND} = 0.359$$

$$95\ \%\ \text{confidence level} = 1 - (.254)(1.645) = 0.58$$

Require all Location Averages > 25 ft- lbs

$$\frac{25}{.58} = 42.9 \qquad 42.9\ \text{ft-lbs is required Plate Average}$$

One Sided Normal Test: n = 3

$$u = \frac{1.645(.359)}{\sqrt{3}} = .341$$

$$X - 1 > .341$$

$$X > 1.341$$

$$(1.341)(42.9) = 57.6$$

57.6 ft-lbs is required Location Average

Given a standard deviation of 0.254, a confidence level of 95%, and a required minimum location average of 25 ft-lbs, the required minimum plate average is 42.9 ft-lbs. Given a sample size of three, and assuming that the standard deviation of a single plate is equal to that of the entire distribution or 0.359, a test average of 57.6 ft-lbs is necessary to conclude at a 95% confidence level that the overall toughness average of the plate is greater than or equal to 42.9 ft-lbs. Thus, a test level of 57.6 ft-lbs will allow no more than 5% of the location averages to be less than 25 ft-lbs for a distribution with a standard deviation of 0.254.

4.3.2 Description of Trial Distributions. The AISI SU27 database is used to construct trial distributions to develop test limits. This database represents 94 steel plates of varying toughness and variability. It may or may not be indicative of all fracture critical steel plates produced. In an attempt to represent the extremes for best and worst cases in the database with respect to variability, portions of the entire database have been collected to form several different distributions based on four screening processes. The distributions are analyzed and the differences in the results are discussed. If large differences in results are observed, recommendations can be made suggesting the type of plate which should be supplied to insure a satisfactory test level from the supplier's viewpoint. If there are no differences or small differences, it can be concluded that there is no need to change production procedures because it will not make a large difference in resulting test levels.

The distributions are not created based on the divisions created in Chapters 2 and 3. It is impossible to, for instance, dictate from which rolling mill the steel for a job will come. Instead, the database is broken into subgroups which attempt to model real situations. In all cases, the data from each plate are never split up. A screening process chooses whether or not each plate is included in the distribution. If a plate is to be included in the distribution, all of the data from that plate are included. Twelve distributions and the rationale behind creating them are described in this section.

Table 4.2 describes the makeup of the twelve databases in the study. Three distributions are created for each of four screening methods, one including data from all of the test temperatures, one including the 40 degree data, and one including the 70 degree data. The all-temperature distributions provide a comprehensive use of the data and the individual test temperatures will be used to determine necessary test limits. The plates which are included in each of the distributions are listed in Appendix D. There are actually two distributions analyzed for each of the 12 distribution numbers in the table; one for each grade of steel.

The first three distributions include all of the plates in the study. Distribution 1 includes all of the data from all of the temperatures. Distribution 2 includes the 40 degree test temperature data from all of the plates and distribution 3 includes the 70 degree test temperature data from all of the plates. These distributions were chosen because they fully describe the entire SU27 database and may best represent all types of plates which may be produced.

Distributions 4-6 were created in an attempt to study the effect of eliminating plates with low toughness values relative to their average toughness. Plates included in distributions 4-6 would have small variation in the average toughness between locations (although location may still have an effect). The screening method used to assemble these distributions requires a plate have no location toughness average at a temperature below one half the overall plate toughness average at that temperature. Thus, if the overall plate average at 70 °F is 40 ft-lbs, 30 ft-lbs at 40 °F, and 20 ft-lbs at 0 °F, the plate is included in the distributions only if it has no location toughness averages less than 20 ft-lbs at 70 °F, 15 ft-lbs at 40 °F, and 10 ft-lbs at 0 °F. A plate must meet the requirement at all three temperatures to be included in the distributions. No limit is set for unusually high toughness averages as high toughness values are desirable. Twenty-five of the 47 A572 Grade 50 plates and 18 of the 47 A588 plates were accepted for distributions 4-6. Distribution 4

Table 4.2 Description of Distributions

Dist. #	Plates Included	Test Temps.
1)	All plates	All temperatures
2)	All plates	40 degrees F
3)	All plates	70 degrees F
4)	Minimum $\overline{\sigma}_{LOC} > \frac{1}{2}\overline{\sigma}_{PLT}$	All temperatures
5)	Minimum $\overline{\sigma}_{LOC} > \frac{1}{2}\overline{\sigma}_{PLT}$	40 degrees F
6)	Minimum $\overline{\sigma}_{LOC} > \frac{1}{2}\overline{\sigma}_{PLT}$	70 degrees F
7)	$\alpha > 0.05$	All temperatures
8)	$\alpha > 0.05$	40 degrees F
9)	$\alpha > 0.05$	70 degrees F
10)	$20 < \overline{\sigma}_{PLT} < 40$ ft-lbs at 40 °F	All temperatures
11)	$20 < \overline{\sigma}_{PLT} < 40$ ft-lbs at 40 °F	40 degrees F
12)	$20 < \overline{\sigma}_{PLT} < 40$ ft-lbs at 40 °F	70 degrees F

contains the data from all of the test temperatures, distribution 5 contains the data from the 40 degree tests, and distribution 6 contains the data from the 70 degree tests.

The results from the analysis of variance tests of Chapter 3 are used to create distributions 7-9. In these distributions are plates with a minimum significance level of 0.05. In Chapter 3, this was the definition used to conclude that location does not have an effect on test results. Thus, distributions 7-9 contain plates in which location does not have a significant effect. As seen in Chapter 3, location can have no effect for two reasons. The scatter within locations can be so large that scatter between locations is unimportant or there can be small within and between location scatter. The first reason is undesirable and would result in a high test level. The second reason would encompass uniform plates and would result in a low test level. These distributions are created to study which of these results occur.

Distribution 7 contains the plates which have significance levels greater than 0.05 for the combined three temperature analysis of variance. This amounts to only 9 A572 Grade 50 and 4 A588 plates. Distribution 8 contains the plates which show no location effect at the 40 degree test temperature and distribution 9 contains the plates with no location effect at the 70 degree test temperature. Distribution 8 contains 26 A572 Grade 50 plates and 17 A588 plates. Distribution 9 contains 23 A572 Grade 50 plates and 14 A588 plates.

One drawback of using the normalized values for analysis is that the distributions become independent of actual toughness levels. Distributions 10-12 are created to study the effect of this problem. These distributions employ an idea used by AISI in their report on the database which is to group the plates by plate toughnesses. A plate is included in distributions 10-12 if its overall plate toughness average at the 40 degree test temperature is between 20 and 40 ft-lbs. The distributions of the plates meeting the requirement at 40 °F were calculated for the 70 and 40 degree test temperatures and for all the test temperatures combined. The 40 degree test temperature is used for the requirement because it leads to the most reasonable distributions. Almost all of the 70 degree plate averages are greater than 40 ft-lbs and distributions based on this temperature would include very few plates.

In reality, it is only plates with average toughness levels between 20 and 40 ft-lbs which are in question relative to fracture toughness levels. Distributions 10-12 result in test limits which are generated from these borderline plates. Distribution 10 includes normalized location averages from all three test temperatures from the plates with an overall average toughness between 20 and 40 ft-lbs at the 40 degree test temperature, distribution 11 includes only the 40 degree test temperature normalized averages, and distribution 12 includes only the 70 degree test temperature normalized averages. Distributions 10-12 include 28 A572 Grade 50 plates and 12 A588 plates.

4.3.3 Results. For each of the 12 distributions, a required plate average and location average is found for each grade of steel. If an average of three CVN test results are greater than the required location average, five percent or less of any additional three test result averages are expected to be below the performance criterion. Tables are provided in this section which display the results of the analyses. Each table provides, for each of the 12 distributions and the grades of steel, the standard deviation of the normalized average values, the required plate average, the standard deviation of the individual normalized test results, and the location average required to insure that the necessary plate average is obtained. Table 4.3 displays results for the 15 ft-lb performance criterion and Table 4.4 displays the results for the 25 ft-lb criterion.

Table 4.3 Results of Distribution Based Analysis for 15 ft-lbs Criterion (ft-lbs)

	A572 Grade 50				A588			
Dist. #	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.
1)	0.254	25.8	0.359	34.6	0.350	35.4	0.443	50.2
2)	0.236	24.5	0.331	32.2	0.310	30.6	0.400	42.2
3)	0.211	23.0	0.278	29.0	0.241	24.9	0.301	32.0
4)	0.194	22.0	0.293	28.2	0.228	24.0	0.324	31.4
5)	0.183	21.5	0.265	26.9	0.205	22.6	0.294	29.0
6)	0.176	21.1	0.238	25.9	0.163	20.5	0.230	25.0
7)	0.205	22.6	0.340	29.9	0.233	24.3	0.390	33.3
8)	0.204	22.6	0.317	29.4	0.246	25.2	0.389	34.5
9)	0.140	19.5	0.216	23.5	0.177	21.2	0.293	27.1
10)	0.264	26.5	0.358	35.5	0.392	42.2	0.511	62.7
11)	0.240	24.8	0.330	32.6	0.355	36.1	0.485	52.7
12)	0.233	24.3	0.291	31.0	0.279	27.7	0.359	37.2

All of the preceding distributions are unsymmetric. Because there is a lower limit in fracture toughness and no upper limit, the distributions are all skewed to the right. Skewness values for the distributions reflect this lack of symmetry. In addition, the distributions are not normal. Standard skewness and standard kurtosis values for a normal distribution equal zero and these values differ largely from zero for the above distributions.

The questionable assumption of normality for the distributions is an important one. It was the basis of the distribution based procedure and if it is incorrect,

Table 4.4 Results of Distribution Based Analysis for 25 ft-lbs Criterion (ft-lbs)

	A572 Grade 50				A588			
Dist. #	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.
1)	0.254	42.9	0.359	57.6	0.350	58.9	0.443	83.7
2)	0.236	40.9	0.331	53.7	0.310	51.0	0.400	70.4
3)	0.211	38.3	0.278	48.4	0.241	41.4	0.301	53.3
4)	0.194	36.7	0.293	46.9	0.228	40.0	0.324	52.3
5)	0.183	35.8	0.265	44.8	0.205	37.7	0.294	48.3
6)	0.176	35.2	0.238	43.1	0.163	34.2	0.230	41.6
7)	0.205	37.7	0.340	49.9	0.233	40.5	0.390	55.6
8)	0.204	37.6	0.317	49.0	0.246	42.0	0.389	57.5
9)	0.140	32.5	0.216	39.1	0.177	35.3	0.293	45.1
10)	0.264	44.2	0.358	59.2	0.392	70.4	0.511	104.6
11)	0.240	41.3	0.330	54.3	0.355	60.1	0.485	87.8
12)	0.233	40.5	0.291	51.7	0.279	46.2	0.359	62.0

the problem is complicated tremendously. To examine the effect of the assumption of normality on results, 12 additional distributions were evaluated. As in the previous 12, each of these distributions are created for A572 Grade 50 and A588 steel separately. They were created using the same screening processes as their corresponding unsymmetric counterparts previously analyzed but are forced to be symmetric. All normalized values greater than one (the overall plate average) are ignored and the lower halves of the distributions (average normalized values between zero and one) are mirrored to create new upper halves for the distributions. Thus, the distributions are bounded by the normalized values of zero and two and are symmetric.

The same analysis procedure performed on the twelve unsymmetric distributions is performed on the symmetric distributions and the results are shown in Tables 4.5 and 4.6. The reasoning behind creating the symmetric distributions is that the high end of the distribution is not the critical end. The symmetric distributions throw out the higher toughness values which are not a concern. AISI uses this reflection concept in their analysis of toughness data [8]. The results of the

Table 4.5 Results of Distribution Based Analysis for 15 ft-lbs Criterion (ft-lbs), Symmetric Distributions

	A572 Grade 50				A588			
Dist. #	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.
1)	0.226	23.9	0.319	31.1	0.310	30.6	0.398	42.2
2)	0.210	22.9	0.299	29.4	0.282	28.0	0.366	37.7
3)	0.188	21.7	0.249	26.5	0.221	23.6	0.293	30.1
4)	0.172	20.9	0.267	26.2	0.208	22.8	0.312	29.6
5)	0.161	20.4	0.246	25.2	0.195	22.1	0.282	28.0
6)	0.159	20.3	0.215	24.5	0.144	19.7	0.220	23.8
7)	0.190	21.8	0.321	28.5	0.200	22.4	0.372	30.3
8)	0.189	21.8	0.298	27.9	0.222	23.6	0.350	31.5
9)	0.127	19.0	0.208	22.7	0.158	20.3	0.287	25.8
10)	0.233	24.3	0.316	31.6	0.313	30.9	0.429	43.5
11)	0.210	22.9	0.290	29.2	0.288	28.5	0.423	40.0
12)	0.206	22.7	0.256	28.2	0.215	23.2	0.318	30.2

Table 4.6 Results of Distribution Based Analysis for 25 ft-lbs Criterion (ft-lbs), Symmetric Distributions

	A572 Grade 50				A588			
Dist. #	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.	σ_{AVG}	Plate Avg.	σ_{IND}	Location Avg.
1)	0.226	39.8	0.319	51.9	0.310	51.0	0.398	70.3
2)	0.210	38.2	0.299	49.0	0.282	46.6	0.366	62.8
3)	0.188	36.2	0.249	44.8	0.221	39.3	0.293	50.2
4)	0.172	34.9	0.267	43.7	0.208	38.0	0.312	49.3
5)	0.161	34.0	0.246	42.0	0.195	36.8	0.282	46.7
6)	0.159	33.9	0.215	40.8	0.144	32.8	0.220	39.6
7)	0.190	36.4	0.321	47.5	0.200	37.3	0.372	50.4
8)	0.189	36.3	0.298	46.5	0.222	39.4	0.350	52.5
9)	0.127	31.6	0.208	37.8	0.158	33.8	0.287	43.0
10)	0.233	40.5	0.316	52.7	0.313	51.5	0.429	72.5
11)	0.210	38.2	0.290	48.7	0.288	47.5	0.423	66.6
12)	0.206	37.8	0.256	47.0	0.215	38.7	0.318	50.4

symmetric distribution analyses can be compared to the unsymmetric results and the effect of the normality assumption can then be ascertained.

4.3.4 Discussion of Results. The results of the distribution based statistical procedure were shown in the Tables 4.3-4.6 of the previous section. The purpose of this section is to address the following points: the effect of assuming normality, the effect of different screening methods, and the determination of which of the test levels should be recommended as the proper test level. All of the results from the distribution based analyses are dependent on the standard deviations of the normalized individual and location average results. High standard deviations require a high plate average and in turn a high location average. Thus, the distributions with the highest scatter require the highest test levels.

Figures 4.5-4.8 show graphically the test levels which result from the distribution based analysis for the two performance criteria at 40 °F and 70 °F. Each of the four figures includes the results from both the symmetric and unsymmetric distributions for both grades of steel. For the most part in the four figures, the results are consistent within each distribution analyzed. The test levels are consistently higher for A588 steel which is due to the higher scatter which has been seen in Chapter 3. The most significant observation which can be made from the figures is that there is a consistent difference between the results from the different screening methods. Two screening methods resulted in the lowest test levels in general. These two methods are the one which included only the plates with no location averages less than half of the plate average and the one which included the plates with significance levels greater than 0.05. The distributions which included all of the plates and the ones which included the plates with overall averages between 20 and 40 ft-lbs at 40 °F result in high test levels. This suggests that the amount of variability present in the plates used to develop the test levels is an important one.

Table 4.7 shows the required test levels as obtained from distributions 2 and 3, the distributions which include the data from all of the plates in the survey at 40 °F and 70 °F respectively. The results from the original and symmetric distributions are provided. The most important observation which can be made is that there is not a large difference in the results between the unsymmetric distributions and the symmetric ones. For the A572 Grade 50 required location averages, there is a five to ten percent difference in the results and there is a ten to fifteen percent difference

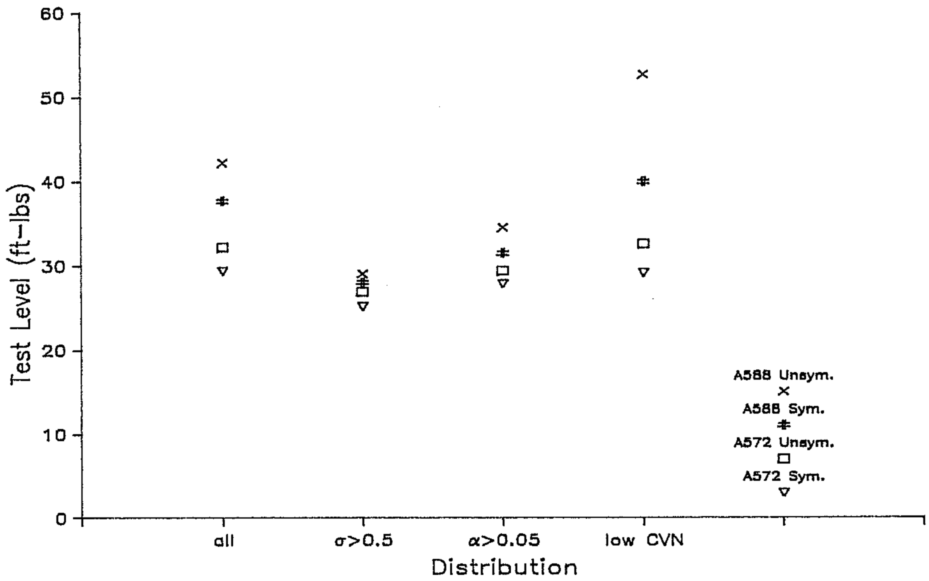

Figure 4.5 Required Location Averages for 15 ft-lbs Criterion, 40 °F

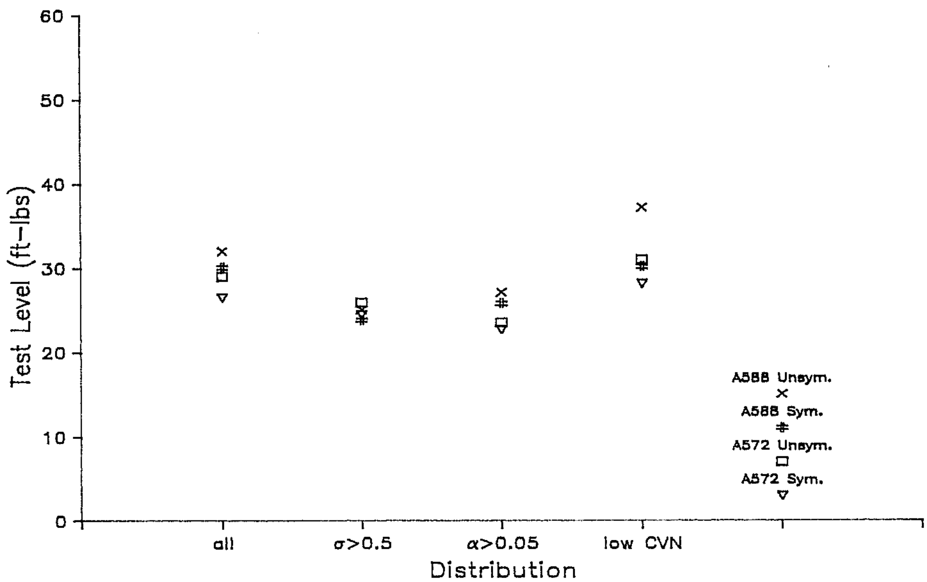

Figure 4.6 Required Location Averages for 15 ft-lbs Criterion, 70 °F

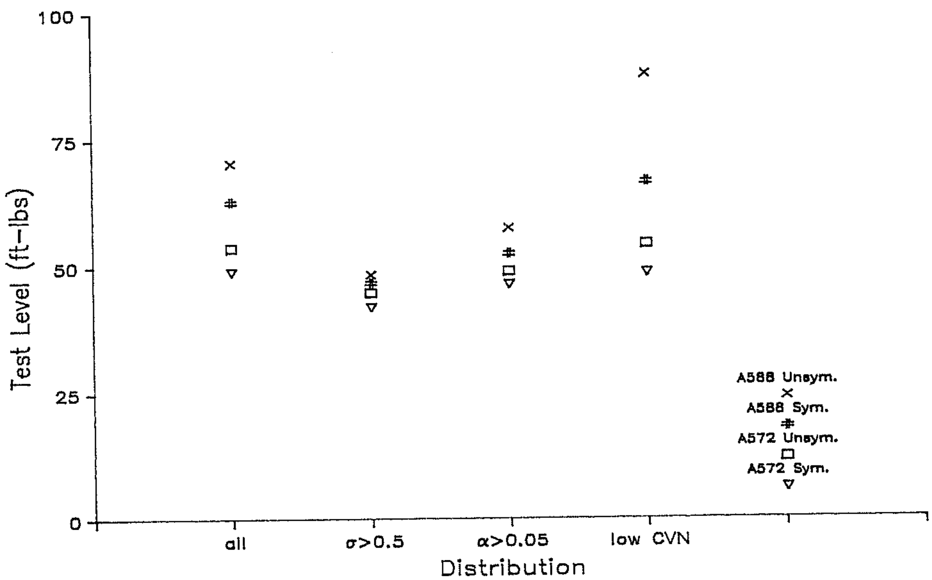

Figure 4.7 Required Location Averages for 25 ft-lbs Criterion, 40 °F

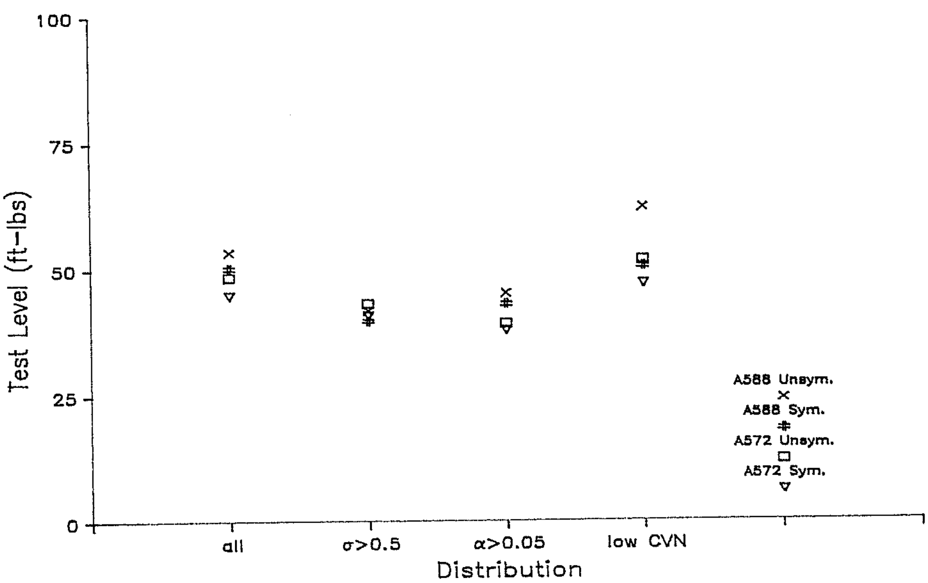

Figure 4.8 Required Location Averages for 25 ft-lbs Criterion, 70 °F

in the results for A588 plates. The test levels resulting from the symmetric analyses are always lower than those from the unsymmetric but this was expected. It is a result of eliminating the high toughness scatter. Relative to the differences between the results from each of the four screening methods, the differences between the unsymmetric and symmetric distributions is small.

Table 4.7
Test Levels from Distribution Based Analysis (ft-lbs)

		A572 Grade 50	A588
15 ft-lbs Criterion			
40 degrees F	symmetric	29	38
	unsymmetric	32	42
70 degrees F	symmetric	27	30
	unsymmetric	29	32
25 ft-lbs Criterion			
40 degrees F	symmetric	49	63
	unsymmetric	54	70
70 degrees F	symmetric	45	50
	unsymmetric	48	53

Taking into account that the effect of assuming normality is not a large one and that the screening method which is used to develop the test levels is important, the recommended test levels using the distribution based procedure are shown in Table 4.8. Basically, the results from distributions which include all of the plates are used and the values are set at even values close to both the symmetric and unsymmetric results. The results based on the 15 ft-lb performance criterion are, with the exception of the 40 °F limit for A588 steel, only five ft- lbs greater than the current requirements. The results based on the 25 ft-lb performance criterion are, on the other hand, much higher than the current requirements.

Table 4.8
Recommended Test Levels from Distribution Based Analysis (ft-lbs)

	A572 Grade 50	A588
15 ft-lbs Criterion		
40 degrees F	30	40
70 degrees F	30	30
25 Ft-lbs Criterion		
40 degrees F	50	65
70 degrees F	45	50

4.4 Direct Procedure

4.4.1 Background. A direct procedure can be developed which specifies a test limit and checks the number of plates which are accepted or rejected for that limit. The development and results of this procedure are presented in this section. For the purpose of the direct procedure, the two performance criteria discussed in Section 4.2 are used. Plates meeting the criteria are those which have no location averages less than 15 ft-lbs at the test temperature in question for the 15 ft-lbs performance criterion and no location averages less than 25 ft-lbs at the test temperature in question for the 25 ft- lbs performance criterion. This is a simple definition of desirable performance. It can also be known as the user's requirement. The performance criteria of this section differ slightly from those used in the previous section in that they require that all location averages meet the minimum toughness levels of 15 or 25 ft-lbs. The previous development accepted a 5% risk that a location average may be below the criteria.

Test levels are set arbitrarily and the results of comparisons between the location averages and test levels may be evaluated using the desirable performance criteria definitions. By directly comparing the location averages to the set test levels to determine whether or not a plate is accepted or rejected, the analysis is strictly valid for only the plates tested. In addition, the procedure in effect assumes that the 9 or 10 locations tested fully represent the true distributions while the analysis of the previous section fit a continuous distribution function to the data. For many practical test levels, it is not possible to say whether or not a plate will be accepted or rejected with certainty. Thus the outcome for a single plate is expanded to encompass the percentage of test locations in which a plate is either accepted or rejected.

Four outcomes are possible when performing any acceptance test such as the one in this study; a plate which meets the criterion can be accepted, a plate which meets the criterion can be rejected (producer's risk), a plate which does not meet the criterion can be rejected, and a plate which does not meet the criterion can be accepted (user's risk). Only two of the four possible results are satisfactory. Ideally, all plates which meet the criterion will be accepted and all plates which do not meet the criterion will be rejected. This is rarely the case given a small sample size and realistic variability. In a real situation, the goal of an acceptance test is to minimize both the producer's and user's risk for a specified performance criteria by employing a reasonable sample size and allowing reasonable variability.

A note is necessary at this time which explains the meaning of a satisfactory test level given the constraints of the AISI survey. Five factors are involved in creating a test level; the sample size, the variation, the performance criteria, the user risk, and the supplier risk. Most elementary statistics texts describe the interactions of these five factors. Normally, all are involved in setting a test level. In the case of this AISI database, though, the sample size is set at three and the variation already exists. Two performance criteria have been arbitrarily set. The only two remaining factors are the user and supplier risk. An inverse relationship exists between the two when all other factors are set. A satisfactory test level in the case of this report is one which causes the user's and supplier's risks to be equal. Both may be large or small but this report attempts to make them equal. Other philosophies such as setting test levels to insure that either the user's or supplier's risk is low at the expense of the other are not discussed. If the sample size and variability were not set, they could have been studied along with the user and supplier risk to arrive at the most economical testing procedure.

In addition, the parties which control the factors effecting user's and supplier's risk are different for each factor. Variability is controlled by the rolling mills and sample size and required performance levels are controlled by the specifying committee. Supplier's risk is not the same for each producer. User's risk includes all of the possible producers because it is not often possible to specify the producer who is to provide plate. A specification must take this into consideration by setting test levels and sample sizes which force suppliers to produce plates which are competitive as far as notch toughness is concerned.

The direct procedure has been summarized in tables throughout this section. The tables attempt to show the results of specifying various test limits. An explanation of the reasoning behind recommended test limits is provided along with the tables. The tables may also be used to study test limits which would insure low user's or supplier's risk.

4.4.2 Results of Applying Performance Criteria. Table 4.9 shows the number of plates with one or more location averages not meeting the requirement of the two criteria. As expected, the higher toughness 25 ft-lbs performance criterion results in a larger number of plates not meeting the criterion than the 15 ft-lbs criterion. In fact, none of the 47 A572 Grade 50 plates have a location average less than 15 ft-lbs at the 70 degree test temperature. Note that 33 of the 47 A572 Grade 50 plates do not meet the 25 ft-lbs criterion. Also, there are more of the lower toughness A572 Grade 50 plates than the A588 plates which fail to meet the criteria.

Table 4.9 Number of Plates Not Meeting Criteria

	A572 Grade 50	A588
15 ft-lbs Criterion		
40 degrees F	7	6
70 degrees F	0	1
25 ft-lbs Criterion		
40 degrees F	33	14
70 degrees F	13	6

`4.4.2.1 Test Levels for 15 ft-lbs Performance Criterion.` Table 4.9 showed the number of plates which do not meet the 15 ft-lbs performance criterion. The test levels for the 70 degree test temperature will be developed first. These limits are straight forward because the number of plates not meeting the criterion is very small for both grades of steel. Only one plate in the entire database has a location average less than 15 ft-lbs at 70 degrees. Thus the test levels can be set low enough to accept almost all of the plates.

The case of the A572 Grade 50 material at the 70 degree test temperature for the 15 ft-lbs performance criteria is the simplest of the cases. None of the A572 Grade 50 plates have a single location average less than 15 ft-lbs. Thus all 47 plates meet the criterion and theoretically a test level of 15 ft-lbs will work perfectly. All 47 plates will be accepted at each location. There is no user's or supplier's risk. As seen in Table 4.10, a higher test level will risk rejecting plates which meet the 15 ft-lbs criterion at 70 °F. The plates which are included as accepted or rejected in Table 4.10 are those which are accepted or rejected at all locations.

Table 4.10
Number of A572 Grade 50 Plates Correctly Accepted and Rejected at All Test Locations at 70 °F

Test Level (ft-lbs)	# Desirable Accepted of 47	#Undesirable Rejected of 0
15	47	-
20	42	-
25	34	-

The setting of a test level for A588 material at the 70 degree test temperature is almost equally straight forward. Plate 89 is the only A588 plate with a location average less than 15 ft-lbs at the 70 degree test temperature. Two of the nine locations tested at 70 degrees in plate 89 have toughness averages less than 15 ft-lbs. Table 4.11 shows the location averages for plate 89. A test level of 55 ft-lbs is necessary to reject the plate at all locations. This is unrealistically high and will cause many of the plates which meet the criterion to be rejected.

A test level of 30 ft-lbs will reject all of the locations except location two. But, as seen in Table 4.12, only 83% or 38 of the 46 plates which have no location averages less than 15 ft-lbs are accepted at all of the test locations.

A test level of 25 ft-lbs attempts to balance supplier's and user's risk. Plate 89 will be rejected at five of its nine locations and only five of the 46 plates meeting the criterion have a chance of being rejected. The number of tests which cause false rejection of the five plates are one of ten for plate 61, one of nine for plate 74, one of ten for plate 79, two of ten for plate 72, and four of ten for plate 71. These tests

Table 4.11 Plate 89 CVN Location Toughness Averages at 70 °F

Location	Toughness Average (ft-lbs)
1	11.3
2	54.3
3	28.7
4	13.3
5	23.0
6	26.0
7	18.7
8	21.7
9	28.7

Table 4.12
Number of A588 Plates Correctly Accepted and Rejected at All Test Locations at 70 °F

Test Level (ft-lbs)	# Accepted Correctly of 46	# Rejected Correctly of 1
15	46	0
20	45	0
25	41	0
30	38	0
35	32	0

total to nine of 49. Note that the standard test locations two and six as defined by AISI in their analysis result in plate 89 being accepted for a test level of 25 ft-lbs.

The development of the two test limits for the 70 degree test temperature and 15 ft-lbs performance criterion were relatively simple because of the small number of plates which did not meet the criterion. When the number of plates not meeting the criterion increases, the presentation of results in the form of Tables 4.9 and 4.10 becomes cumbersome. Thus a percent probability table involving user's and supplier's risk will be introduced to enhance the discussion and presentation

Table 4.13
User's and Supplier's Risk,
A588 Steel, 70 °F, 15 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
1 plate does not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
15	0	0	0	0	1	0
20	0	0	0	1	0	0
25	0	0	1	0	0	0
30	0	1	0	0	0	0
35	0	1	0	0	0	0

Supplier's Risk: # of plates rejected meeting criterion
46 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
15	46	0	0	0	0	0
20	45	1	0	0	0	0
25	41	3	2	0	0	0
30	38	4	2	2	0	0
35	32	9	2	3	0	0

of results for the remaining test limit developments. An example of the percent probability table is shown in Table 4.13.

Table 4.13 presents the same data as Tables 4.11 and 4.12 in a summarized form which will become advantageous for larger numbers of plates which do not meet the criteria. It contains results for the A588 steel plates at the 70 degree test temperature based on the 15 ft-lbs performance criterion. Table 4.13 is divided into two sections; one for user's risk and one for supplier's risk. In this standard tabular form, the user's risk includes the plates which have at least one location average less than the criterion at the test temperature and the supplier's risk includes the plates which have no location averages less than the criterion at the test temperature. In the case of Table 4.13, the user's risk portion summarizes the one plate with location averages less than 15 ft-lbs at 70 °F (plate 89) and the supplier's risk portion summarizes the 46 plates with no location averages less than 15 ft-lbs at 70 °F.

Each column in Table 4.13 represents the percentage of the locations in a plate which cause a false acceptance result. The percentage boundaries are chosen arbitrarily. The 0-15% category represents one of the test locations in a plate causing a false acceptance result. Each row represents the different possible test levels. The table lists the number of plates which fall in each of the percentage categories for each test level. For example, the first column lists the number of plates which have no locations causing false acceptance (for user's risk) or rejection (for supplier's risk). This is identical to the data presented in Table 4.10.

The user's risk portion of Table 4.13 summarizes the data in Table 4.11. It lists the number of plates falling in each of the percentage categories for each test level (in this case there is only one plate not meeting the criterion). At a test level of 25 ft-lbs, for instance, the one plate (plate 89) will be accepted at between 15 and 45% of the locations tested (the number is actually 44% or four of nine locations).

The supplier's risk portion of Table 4.13 presents the number of plates falling in each of the percentage categories which may be incorrectly rejected. This data were not previously put in a table as the user's risk data were in Table 4.11 because it would have been cumbersome and not useful. The results at the 25 ft-lbs test level show the five desirable plates which may be incorrectly rejected (three with one location test causing rejection and two with between 15 and 45% of the locations tests causing rejection).

The 15 ft-lbs performance criterion results in a similar number of plates not meeting the criterion for each grade for the 40 degree test temperature, seven for A572 Grade 50 and six for A588 material. This is a larger number of plates than for the 70 degree test temperature which complicates the direct procedure. The complicating factor in this instance is that many of the plates which meet the criterion have location averages which are greater than 15 ft-lbs but often less than 35 ft-lbs. This is a level of toughness which is in the region around which test levels may be set. This means that the supplier's risk will be larger if the user's risk is to be reasonable.

Table 4.14 summarizes the user's and supplier's risks for A572 Grade 50 steel at the 70 degree test temperature subjected to the 15 ft-lbs performance criterion. If a test level of 20 ft-lbs is used, none of the seven plates not meeting the criterion will be rejected at all locations and four will be accepted at greater than 75% of their locations. While the supplier's risk is low at a test level of 20 ft-lbs, the user's risk is high.

Table 4.14
User's and Supplier's Risk,
A572 Grade 50 Steel, 40 °F, 15 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
7 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
20	0	1	1	1	4	0
25	2	0	0	4	1	0
30	2	0	3	2	0	0
35	2	0	5	0	0	0

Supplier's Risk: # of plates rejected meeting criterion
40 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
20	27	5	8	0	0	0
25	14	8	12	6	0	0
30	9	6	7	12	6	0
35	5	6	7	6	13	3

If a test limit of 25 or 30 ft-lbs is used, the user's and supplier's risk for plates which are accepted or rejected at all locations in Table 4.14 are similar. Comparisons of the percentage categories greater than zero in the table point to a test level of 30 ft-lbs as being one which best matches user's and supplier's risk. At 30 ft-lbs, two of the seven or 29% of the plates not meeting the criterion will always be rejected and only two are accepted greater than 45% of their locations. Nine of the 40 or 23% of the plates which do meet the criterion are accepted at all test locations and 13 more are rejected at less than 50% of the locations. This supplier's risk seems quite high but user's risk is much higher for a test level of 25 ft- lbs. Five of the seven plates which do not meet the criterion are accepted at over half of the plate test locations. In this instance, both risks seem high which suggests that the sample size, variability, or performance criterion must be adjusted if the risks are to be lowered.

The direct procedure when applied to A588 material at the 40 degree test temperature leads to a test level identical to that of the A572 Grade 50 material just presented but the user's and supplier's risks are lower. In general, the higher toughness levels of the A588 material is seen in the supplier's risk results shown in the 0% column of Table 4.15. Relative to the A572 Grade 50 plates, there are more A588 plates meeting the 15 ft-lbs criterion at 40 °F which are accepted at all locations for each test level.

Forty one of the 47 plates are meet the 15 ft-lbs criterion at 40 °F and six do not. Over half of those A588 plates which meet the criterion are accepted at each location for test levels up to 30 ft-lbs. While none of the six plates not meeting the criterion are rejected at all locations until a test level of 25 ft-lbs is reached which is the same level as it was for A572 Grade 50 plates, the number of plates with a large number of locations causing incorrect acceptance is smaller for A588 than for A572 Grade 50 plates.

Based on the results of Table 4.15, a test limit of 30 ft-lbs for A588 material at the 40 degree test temperature is reasonable. 27 of the 41 plates which meet the criterion are accepted at all locations and only two of the remaining 14 plates are rejected at greater than 50% of the test locations. While only one of the six plates not meeting the criterion is always rejected, only one of the remaining five is accepted at greater than 45% of its locations. In fact this one plate is the only plate with greater than 25% of its locations causing incorrect acceptance. Using a higher test limit of 35 ft-lbs results in the rejection at all locations of a plate which meets the criterion and does not improve the user's risk while raising the supplier's risk.

4.4.2.2 Test Level Development for 25 ft-lbs Performance Criterion. The following section deals with setting test levels for the combinations of

Table 4.15
User's and Supplier's Risk,
A588 Steel, 40 °F, 15 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
6 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
15	0	0	1	1	4	0
20	0	1	1	2	2	0
25	1	0	4	1	0	0
30	1	3	1	1	0	0
35	1	3	1	1	0	0
40	2	2	2	0	0	0

Supplier's Risk: # of plates rejected meeting criterion
41 plates meet criterion
Supplier's Risk: 41 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
15	41	0	0	0	0	0
20	35	3	3	0	0	0
25	33	2	4	2	0	0
30	27	6	6	2	0	0
35	20	8	7	3	2	1
40	16	9	7	6	1	2

grade and temperature for the 25 ft-lbs performance criterion. This criterion designates plates with no location averages less than 25 ft-lbs as meeting the criterion and plates with any location average less than 25 ft-lbs as not meeting it.

Forty one plates meet the 25 ft-lbs criterion for A588 material at 70 °F and six plates do not. Table 4.16 presents the results of the direct procedure. These results point to a test level in the range of 35 to 45 ft-lbs.

User's risk in Table 4.16 is high for reasonable test levels. None of the plates which do not meet the criterion are rejected at all locations until test levels of 45 ft-lbs are reached. Even at 45 ft-lbs, two or one third of the plates not meeting

Table 4.16
User's and Supplier's Risk,
A588 Steel, 70 °F, 25 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
6 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	0	0	1	1	4	0
30	0	1	1	2	2	0
35	0	1	3	1	1	0
40	0	2	2	1	1	0
45	1	1	2	1	1	0

Supplier's Risk: # of plates rejected meeting criterion
41 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	41	0	0	0	0	0
30	38	3	0	0	0	0
35	32	8	1	0	0	0
40	29	10	1	1	0	0
45	28	6	6	0	1	0

the criterion are incorrectly accepted at over half of the locations tested and one of those two is accepted at greater than 75% of the locations tested.

Supplier's risk is relatively low for reasonable test levels. It is low relative to user's risk and is low relative to the supplier's risk seen in some of the previous direct method developments for the 15 ft-lbs criterion.

If a test level of 35 ft-lbs is used, only one of the nine plates which meet the 25 ft-lbs criterion and do not have all location averages greater than 35 ft-lbs has more than one location average between 25 and 35 ft-lbs. Plate 67 has three of ten location averages which could cause it to be incorrectly rejected. The other eight plates have only a single location average between 25 and 35 ft-lbs. The remaining average location toughnesses are all greater than 35 ft-lbs. Five of the six plates which do not meet the criterion have more than one location average greater than

35 ft-lbs. Plate 61 has six of ten location averages greater than 35 ft-lbs and plate 74 has eight of nine greater than 35 ft-lbs. Clearly the user's risk is greater than the supplier's risk and the test level should be higher than 35 ft-lbs.

A 40 ft-lbs test level is the most reasonable. Twenty nine of the 41 plates meeting the criterion are accepted at all locations and only two of the remaining 12 have more than one location average below 40 ft-lbs. Three of the six plates not meeting the criterion have more than one location average greater than 40 ft-lbs but only one plate has more than three quarters of its location averages greater than 40 ft-lbs. This is plate 74 which has an average toughness of 21.3 ft-lbs at location nine and no other location averages below 45 ft-lbs. There is a strong likelihood that this plate will be accepted for any reasonable test level even though it does not meet the 25 ft-lbs performance criterion.

A test level higher than 40 ft-lbs is not advised because the supplier's risk is raised significantly (although it is still not as high as the supplier's risk in some of the previous developments) and the user's risk is not improved much.

Thirty four A572 Grade plates meet the 25 ft-lbs performance criterion at the 70 degree test temperature and 13 do not. The user's and supplier's risk in Table 4.17 begin to converge in the 40 to 50 ft-lbs range. At 40 ft-lbs, 15 of 34 or 44% of the plates which meet the criterion are accepted at all locations and two of 13 or 15% of the plates which do not meet the 25 ft-lbs criterion are rejected at all locations. Twenty one percent of the plates meeting the criterion are accepted at all locations and 23% of the plates not meeting the criterion are rejected at all locations for a test level of 50 ft-lbs. But three plates which meet the criterion are also rejected at all locations for the 50 ft-lbs test limit. This is a large supplier's risk and suggests that 50 ft-lbs is too high for the limit.

Considering the entire Table 4.17 and not just the 0% and 100% columns leads to the conclusion that 40 ft-lbs should be chosen as the test level. While ten of the 14 plates which do not meet the criterion have more than one location average toughness greater than 40 ft-lbs, only five have more than a half greater than 40 ft-lbs, and only plate 14 has more than three quarters greater than 40 ft-lbs. Plate 14 has location averages greater than 50 ft-lbs at seven of ten locations. It will be

Table 4.17
User's and Supplier's Risk,
A572 Grade 50 Steel, 70 °F, 25 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
13 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	0	1	0	1	11	0
30	1	0	1	7	4	0
35	2	1	1	6	3	0
40	2	1	5	4	1	0
45	3	1	6	3	0	0
50	3	4	5	1	0	0

Supplier's Risk: # of plates rejected meeting criterion
34 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	14	8	12	0	0	0
30	9	6	7	12	0	0
35	5	6	7	6	13	3
40	15	6	9	3	1	0
45	10	5	7	9	3	0
50	7	5	7	6	6	3

accepted incorrectly (it does not meet the 25 ft-lbs performance criterion despite high toughness levels) in most cases.

The supplier's risk is lower than the user's risk for a 40 ft-lbs test level. Twelve of the 34 plates which meet the criterion will be rejected at more than one test location. Only four have greater than half of their location averages below 40 ft-lbs and only plate 44 has better than three fourths of its location averages below 40 ft-lbs and above 25 ft-lbs. It may be falsely rejected at seven of nine locations.

While the supplier's risk is lower than the user's risk for a test level of 40 ft-lbs, raising the test limit to 45 ft- lbs would benefit the user but would penalize the supplier much more. At a test level of 40 ft-lbs, only four of the 34 plates meeting the criterion are rejected at more than half of the locations tested, but that number triples to 12 if the test level is raised to 45 ft-lbs. In this development a test level somewhere between 40 and 45 ft-lbs is probably the best limit.

The final test level developments are the 40 degree test temperature combined with the 25 ft-lbs performance criterion levels. The A588 material has 14 plates which do not meet the 25 ft-lbs criterion at 40 °F and the A572 Grade 50 material has 33 of 47 plates which do not meet the criterion. This test level is a difficult one to set because many of the 40 degree toughness values are between 20 and 40 ft-lbs within which the 25 ft-lbs performance criterion is included. The plates are much tougher at 70 degrees and the direct procedure needed only to weed out the plates with abnormally low test values.

Table 4.18 suggests that the test limit for A588 steel at the 40 degree test temperature for the 25 ft-lbs performance criterion be from 40 ft-lbs to 50 ft-lbs. After examining the table, it appears that 45 ft-lbs is the preferable limit. Fourteen of the 33 plates meeting the criterion are accepted at all locations and only four of the remaining 19 are rejected at more than half of the locations. Seven of the 14 plates not meeting the criterion are rejected at all locations and none are accepted incorrectly at more than half of the test locations. 40 ft-lbs may also be an acceptable test level in this instance but the increase in user's risk in moving from a test level of 45 to 40 ft-lbs is greater than the decrease in supplier's risk. Not unlike the development of the A572 Grade 50 70 degree test limit, the ideal limit is between 40 and 45 ft-lbs. Raising the test level to 50 ft-lbs does not decrease the user's risk substantially but the supplier's risk continues to increase.

The A572 Grade 50 development at 40 °F is unique in that the majority of the plates does not meet the 25 ft-lbs criterion. Thirty three do not meet the criterion and only 14 do. The direct procedure is still the same, though, and the results are shown in Table 4.19. Table 4.19 suggests that the test level be set at either 35 or 40 ft-lbs. Both test levels cause high risks but this due to the large number of toughness values between 20 and 40 ft-lbs.

The deciding factor in this case comes from the fact that at a test limit of 35 ft-lbs only ten of the 47 plates are correctly accepted and rejected at all test locations, five accepted correctly and five rejected correctly. At 40 ft-lbs, only three

Table 4.18
User's and Supplier's Risk,
A588 Steel, 40 °F, 25 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
14 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	1	0	5	3	5	0
30	1	3	3	5	2	0
35	2	3	4	4	1	0
40	4	2	5	3	0	0
45	7	2	5	0	0	0
50	8	2	4	0	0	0

Supplier's Risk: # of plates rejected meeting criterion
33 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	33	0	0	0	0	0
30	27	5	1	0	0	0
35	20	7	5	1	0	0
40	16	9	6	2	0	0
45	14	4	11	4	0	0
50	12	2	12	6	1	0

of the 14 plates which meet the criterion are accepted at all locations. But 15 plates which do not meet the criterion are rejected at all locations. Eighteen of the 47 plates are always correctly accepted or rejected at the 40 ft-lbs limit. Note that at a test level of 40 ft-lbs, one plate which meets the 25 ft-lbs criterion is rejected at all locations. Increasing the test level beyond 40 ft-lbs does not improve user's risk nearly as much as it increases supplier's risk.

4.4.3 Discussion of Results. The results of the direct procedure presented in the previous sections are summarized in Table 4.20. The test levels range from 15 to 30 ft-lbs for the 15 ft-lbs criterion and from 40 to 45 ft-lbs for the 25 ft-lbs criterion. The test levels for the 15 ft-lbs criterion are similar to those in the AASHTO specifications. The test levels for the 25 ft-lbs criterion are about 15 ft-lbs

Table 4.19
User's and Supplier's Risk,
A572 Grade 50 Steel, 40 °F, 25 ft-lbs Criterion

User's Risk: # of plates accepted not meeting criterion
33 plates do not meet criterion

	% Locations Accepting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	2	0	2	14	15	0
30	2	4	16	4	7	0
35	5	8	13	3	4	0
40	15	2	10	3	3	0
45	18	5	6	4	0	0
50	22	2	8	1	0	0

Supplier's Risk: # of plates rejected meeting criterion
14 plates meet criterion

	% Locations Rejecting					
Test Level	0	0< ≤15	15< ≤45	45< ≤75	75< <100	100
25	14	0	0	0	0	0
30	9	2	3	0	0	0
35	5	4	3	1	1	0
40	3	0	5	3	2	1
45	3	0	1	5	3	2
50	3	0	0	3	3	5

higher than the AASHTO specifications. If the original purpose of the AASHTO specifications is to ensure that no locations averages fall below 15 ft-lbs, the test levels from the direct procedure correlate well. If AASHTO requires 25 ft-lbs to ensure a toughness of 15 ft-lbs, it is reasonable to believe that a test level of 40 ft-lbs is required to ensure a toughness of 25 ft-lbs at all locations.

It is important to recall the philosophy behind the direct procedure as used in this report. The test levels are set in an attempt to balance user's and supplier's risk. In some cases such as the 70 °F, 15 ft-lbs criterion test level, both risks are low. And in others such as the 40 °F, 25 ft-lbs criterion test level, both risks are high. The problem of both user's and supplier's risks being high is one which can be solved by increasing the sample size or decreasing the variability. These are the

Table 4.20 Summary of Test Levels from Direct Procedure (ft-lbs)

	A572 Grade 50	A588
15 ft-lbs Criterion		
40 degrees F	30	30
70 degrees F	15	25
25 ft-lbs Criterion		
40 degrees F	40	45
70 degrees F	40	40

only two ways to simultaneously lower both risks unless the performance criterion is lowered or the toughness of the plates is increased. The risks are lower for the 15 ft-lbs criterion than for the 25 ft-lbs criterion.

4.5 Comparison of Procedures

A comparison of the test levels resulting from the distribution based and direct procedure is shown in Table 4.21.

Table 4.21 Test Level Comparison (ft-lbs)

	Distribution Based Procedure	Direct Procedure
A572 Grade 50		
15 ft-lbs Criterion		
40 degrees F	30	30
70 degrees F	30	15
25 ft-lbs Criterion		
40 degrees F	50	40
70 degrees F	45	40
A588		
15 ft-lbs Criterion		
40 degrees F	40	30
70 degrees F	30	25
25 ft-lbs Criterion		
40 degrees F	65	45
70 degrees F	50	40

In all cases, the test levels from the distribution based procedure are greater than or equal to the test levels from the direct procedure. There is a simple explanation for this consistent differences between the test levels. The distribution based procedure developed test levels which considered only the user's risk. Supplier's risk never entered into the direct procedure. On the other hand, the direct procedure did consider supplier's risk equally along with user's risk.

In lieu of the differing philosophies behind the two procedures, the resulting test levels from the two procedures are consistent. The test levels resulting from the distribution based procedure are on average 5-10 ft-lbs higher than those of the direct procedure. If the direct procedure were undertaken with the idea of minimizing user's risk regardless of supplier's risk, it is conceivable to have test levels which match those of the distribution based procedure.

The 15 ft-lbs difference between the test levels from the two procedures for A572 Grade 50 steel at 70 °F for the 15 ft-lbs criterion is due to the continuous nature of the distribution based procedure. In the direct method it was possible to see that none of the plates failed the criterion and a test level could be set at 15 ft-lbs. This is not possible for a continuous distribution which in effect assumes that there will always be 5% of the location averages below the criterion level.

4.6 Summary

Chapter 4 has attempted to develop test levels for A572 Grade 50 and A588 steel plates at the 40 and 70 degree test temperatures. The data from the AISI survey SU27 were used to both develop the test limits and to evaluate them. The purpose of the test levels was to accept or reject plates based on a goal of a performance criterion. Test levels were developed which attempted to accept all plates which met the criterion and reject all plates which did not meet the criterion using a sample of the test results taken from a single location in the plate.

Two procedures were used to develop the test levels, a distribution based procedure and a direct procedure. The resulting test levels were not equal. The direct procedure led to lower test levels in general. It is recommended that the results of the direct procedure be used as the test levels with the exception of the test level for A572 Grade 50 steel at 70 °F which will be raised from 15 to 25 ft-lbs. Test results from the distribution based procedure are impractically high and will lead to supplier's risks that are much too large. The test results from the direct procedure are slightly larger than the AASHTO requirements for the 15 ft-lbs criterion and much larger for the 25 ft-lbs criterion.

Appendix E includes tables which illustrate the types of plates which may be incorrectly accepted or rejected using the recommended test levels. Table 4.22 was produced to give a feel for what the actual results might be if a single test location were used as the location from which the sample specimens were taken. The table was developed from the eight tables in Appendix E and shows the user's and supplier's risk for each plate for each possible test location. All test locations are included in the table for the sake of completeness and comparison although it is clear that not all of the test locations are suitable for taking specimens (locations 3,4, and 5 for instance).

The user's and supplier's risk which is included in Table 4.22 is actually the resulting outcome of what would happen if the recommended test limits were used at a location. The user's risk is the percentage of the plates not meeting the criterion which would be accepted at a particular location and the supplier's risk is the percentage of the plates meeting the criterion which would be rejected at the location. For instance, if location 2 is used as the location from which specimens are taken for A588 steel at 70°F for the 25 ft-lbs performance criterion, 50% (3 of 6) of the plates which did not meet the criterion are accepted and 2% (1 of 41) of the plates which did meet the criterion are not accepted.

The user's and supplier's risks are comparable for the 15 ft-lbs criterion with the possible exception of the 100% user's risk for the A588, 70°F test level. But this is the development which had only one plate not meeting the criterion and that plate is either accepted or rejected.

The user's and supplier's risks are not equal for both 70°F developments and the A572, 40°F development using the 25 ft-lbs criterion. These were the test levels which should ideally be between 40 and 45 ft-lbs but they were set at 40 ft-lbs for the 70°F developments and 45 for the A572, 40°F development. The imbalance

Table 4.22 User's and Supplier's Plate Risk by Location, % Plates Accepted and Rejected Incorrectly

Location	1	2	3	4	5	6	7	8	9	10
A572 Grade 50 Steel										
40 °F, 15 ft-lbs Criterion, 30 ft-lbs Test Level										
User	29	14	43	14	71	0	43	14	43	0
Supplier	40	43	23	35	38	35	43	53	38	28
40 °F, 25 ft-lbs Criterion, 40 ft-lbs Test Level										
User	21	18	36	15	33	18	18	12	18	9
Supplier	43	29	36	43	36	29	36	36	29	14
70 °F, 15 ft-lbs Criterion, 25 ft-lbs Test Level										
User	0	0	0	0	0	0	0	0	0	0
Supplier	54	15	8	8	8	15	23	35	15	8
70 °F, 25 ft-lbs Criterion, 40 ft-lbs Test Level										
User	31	31	69	38	62	69	31	31	31	31
Supplier	12	24	15	12	15	26	9	26	9	12
A588 Steel										
40 °F, 15 ft-lbs Criterion, 30 ft-lbs Test Level										
User	0	17	33	0	50	33	33	0	0	17
Supplier	10	5	5	7	12	12	12	7	12	7
40 °F, 25 ft-lbs Criterion, 45 ft-lbs Test Level										
User	0	14	21	14	36	14	0	21	0	7
Supplier	24	12	12	27	9	18	21	15	24	9
70 °F, 15 ft-lbs Criterion, 25 ft-lbs Test Level										
User	100	100	0	0	0	100	0	0	100	0
Supplier	4	0	0	0	2	7	0	2	4	0
70 °F, 25 ft-lbs Criterion, 40 ft-lbs Test Level										
User	33	50	50	50	33	33	33	17	0	33
Supplier	7	2	2	7	2	5	0	5	7	5

in the risks reflects this fact. The 70°F test levels should be raised a little and the A572, 40°F test level should be lowered a little to balance the risks.

It should be noted that while Chapter 3 showed that notch toughness does vary statistically between locations in many of the plates of survey SU27, Table 4.30 does not show any one location to produce risks that are much different than the others. The table does not show any one location to be an especially good location to test at or any one location to be an exceptionally bad location to test at with regard to user's and supplier's risk. Thus it seems that while location does have an effect on fracture toughness in about half of the plates, the effect is not consistent with respect to location throughout the database.

CHAPTER 5
SUMMARY

The results and conclusions of this thesis were arrived at through the use of the American Iron and Steel Institute survey SU27 of 1984. The data were investigated in an attempt to study notch toughness variability and to develop a rational procedure from which required test levels can be set.

With regards to testing at a single location to qualify a plate and the effect of location on notch toughness in general, it was found that there is a significant difference in notch toughness between locations in some of the plates. The unbiased analysis of variance approach showed that the location from where specimens were taken did effect the notch toughness, with significance levels less than 0.05 in from 54 to 61% of the plates depending on the test temperature.

It was found that location significance is not necessarily analogous to variability. The significance level from the analysis of variance helps answer the question of whether or not average notch toughness varies between locations given the amount of scatter within each location. But because analysis of variance depends on the relationship between the scatter between locations and within locations, it does not give a true reading of the variability.

It was found that other factors such as length, width, and thickness can have an effect on location significance. Of the additional parameters which were studied, grade and rolling mill had the greatest influence on the location effect. In general, A588 steel showed more variation in notch toughness and location significance than A572 Grade 50 steel although A588 is also generally tougher. The location significance can change drastically depending on the rolling mill which produced a plate. It was shown that the five plates from rolling mill 8, two A572 Grade 50 plates and three A588 plates, showed a consistent and large location effect regardless of grade. The other factors did not effect the database in as consistent or noticeable a manner as grade and rolling mill.

Because location was found to have an effect in more than half of the plates in the survey, the questions concerning the performance level which is actually necessary and those concerning the development of a rational method to set test levels became very important. It is initially clear, due to location effect and variability, that if only one location is to be sampled when qualifying plates, a test level is necessary which is higher than the required performance criterion.

A rational method based on a continuous, normal distribution taken from the database resulted in test levels that are higher than those in the current AASHTO specifications. Test levels required for a minimum location average of 15 ft-lbs at the 95% confidence level range from 30 to 40 ft-lbs and test levels required for a minimum location average of 25 ft-lbs at the 95% confidence level range from 45 to 60 ft-lbs. The AASHTO specifications, on the other hand, require from 25 to 30 ft-lbs depending on the grade and thickness.

A second, direct procedure resulted in test levels which fall between the AASHTO specification requirements and those of the distribution based procedure. Test levels range from 25 to 30 ft-lbs for a minimum location average of 15 ft-lbs and from 40 to 45 ft-lbs for a minimum location average of 25 ft- lbs. This direct procedure resulted in test levels lower than the distribution based procedure because it took into consideration both user's and supplier's risk while the distribution based procedure considered only user's risk.

Thus, it was seen that a variety of test levels can be specified depending on the rationale behind the procedures used to set them. The distribution based procedure is an objective one but has limitations because it assumes the distribution to be continuous to a notch toughness of zero when many of the plates do not have notch toughnesses below the performance criteria. It also does not consider supplier's risk in its development. The direct method, although somewhat subjective, provides the fairest results to both the user and supplier but in some cases, both risks are high. In both procedures, test levels would be lowered to values which are closer to the performance criteria by increasing the sample size and by lowering the variability in the plates.

If the purpose of the AASHTO requirements is to avoid location averages which are less than 15 ft-lbs, they are effective for the plates of the survey. At 70 °F, only one of the 94 plates has a location average less than 15 ft-lbs so a test level of 25 ft-lbs is sufficient. At 40 °F, 13 of the 94 plates have at least one location average below 15 ft- lbs. Seventy four of the 121 locations tested in these 13 plates will cause them to be rejected at a test level of 25 ft-lbs.

It is clear that the AASHTO specifications do not ensure location averages less than 25 ft-lbs. If the necessary performance criteria is 25 ft-lbs, the test levels must be increased to account for the variability present and the location significance.

APPENDIX A
Plate Descriptions

ID #	Grade	Rolling Mill	Heat	Length (in)	Width (in)	Thickness (in)
1	A572	1	1	360	65	2.75
2	A572	1	1	360	65	2.75
3	A572	1	2	386	88	2.00
4	A572	1	2	290	88	1.88
5	A572	1	3	330	85	2.00
6	A572	1	4	696	56	1.75
7	A572	1	5	639	56	1.75
8	A572	1	5	639	56	1.75
9	A572	1	6	696	56	1.75
10	A572	1	7	318	90	2.00
11	A572	1	8	180	104	3.00
12	A572	1	9	264	48	2.00
13	A572	2	1	372	66	2.25
14	A572	2	2	360	66	2.13
15	A572	2	2	313	98	2.75
16	A572	2	3	105	82	1.97
17	A572	2	4	120	96	2.50
18	A572	2	5	290	80	1.63
19	A572	2	6	215	54	1.50
20	A572	2	7	314	49	1.75
21	A572	2	8	360	90	2.00
22	A572	2	9	313	74	3.00
23	A572	3	1	296	84	1.38
24	A572	3	1	229	84	1.75
25	A572	3	2	299	84	1.38
26	A572	3	2	308	84	1.50
27	A572	3	3	319	84	1.50
28	A572	3	4	215	84	1.75
29	A572	3	5	250	84	2.00
30	A572	3	5	198	84	2.50
31	A572	3	6	211	84	2.00
32	A572	3	7	212	84	2.50

Plate Descriptions (cont.)

ID #	Grade	Rolling Mill	Heat	Length (in)	Width (in)	Thickness (in)
33	A572	4	1	240	96	4.00
34	A572	4	2	240	96	3.00
35	A572	4	3	240	96	2.00
36	A572	4	4	240	96	2.00
37	A572	4	5	437	59	1.00
38	A572	4	6	766	96	3.25
39	A572	5	1	252	70	1.50
40	A572	5	2	192	96	1.50
41	A572	5	3	288	72	1.75
42	A572	6	1	147	114	1.75
43	A572	6	1	147	111	1.75
44	A572	6	2	240	48	2.50
45	A572	7	1	240	96	2.50
46	A572	8	1	358	51	4.00
47	A572	8	1	369	51	4.00
48	A588	1	1	742	62	2.00
49	A588	1	1	484	115	1.88
50	A588	1	2	392	82	1.50
51	A588	1	2	470	83	1.50
52	A588	1	3	780	69	1.00
53	A588	1	3	380	54	1.75
54	A588	1	4	480	96	1.00
55	A588	1	4	735	79	0.75
56	A588	1	5	612	93	0.75
57	A588	1	6	498	96	1.00
58	A588	1	7	294	90	4.00
59	A588	1	8	458	42	0.75
60	A588	2	1	360	60	1.00
61	A588	2	2	150	64	3.00
62	A588	2	2	367	68	2.00
63	A588	2	3	120	60	1.50
64	A588	2	4	411	68	2.25

Plate Descriptions (cont.)

ID #	Grade	Rolling Mill	Heat	Length (in)	Width (in)	Thickness (in)
65	A588	2	5	276	65	0.81
66	A588	2	6	180	67	1.75
67	A588	2	7	480	96	1.63
68	A588	2	8	242	60	3.13
69	A588	2	9	180	48	2.13
70	A588	3	1	348	96	0.38
71	A588	3	2	288	81	2.00
72	A588	3	2	223	84	2.50
73	A588	3	3	225	84	1.00
74	A588	3	4	210	84	1.00
75	A588	3	5	237	84	1.50
76	A588	3	5	254	84	1.25
77	A588	3	6	237	84	1.50
78	A588	3	7	224	84	2.50
79	A588	3	8	212	84	1.25
80	A588	5	1	360	48	1.00
81	A588	5	2	360	60	1.00
82	A588	5	2	480	69	1.25
83	A588	5	2	240	60	2.00
84	A588	5	2	240	60	2.50
85	A588	5	3	240	69	1.50
86	A588	5	4	240	60	2.50
87	A588	7	1	425	72	2.50
88	A588	7	1	520	72	2.50
89	A588	7	2	520	72	1.50
90	A588	7	3	480	84	1.25
91	A588	7	4	-	-	0.75
92	A588	8	1	592	63	2.95
93	A588	8	1	542	63	2.25
94	A588	8	2	877	61	1.44

APPENDIX B

B.1 Plate Toughness Characteristics (ft-lbs), 0 °F

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
1	13	16	8
2	12	20	7
3	15	26	10
4	15	26	7
5	14	22	10
6	12	19	7
7	15	21	9
8	18	24	11
9	13	17	9
10	16	24	12
11	13	19	9
12	21	34	18
13	26	41	12
14	19	35	10
15	22	34	8
16	23	28	19
17	21	35	12
18	37	48	23
19	26	34	11
20	19	23	12
21	20	34	8
22	24	34	12
23	17	26	10
24	18	29	8
25	14	24	7
26	16	26	6
27	28	42	12
28	11	15	5
29	19	39	10
30	18	32	6
31	23	34	10
32	17	38	9

B.1 Plate Toughness Characteristics (ft-lbs), 0 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
33	15	21	9
34	37	49	27
35	34	40	30
36	56	77	47
37	28	40	19
38	42	70	22
39	57	71	35
40	18	27	11
41	17	23	10
42	23	27	20
43	15	18	13
44	19	32	10
45	13	24	6
46	22	45	9
47	20	44	7
48	42	112	11
49	29	77	8
50	63	92	37
51	66	97	7
52	52	109	9
53	113	165	57
54	85	110	60
55	96	118	53
56	42	91	13
57	35	54	15
58	33	45	17
59	62	110	24
60	32	42	24
61	15	34	4
62	26	80	5
63	44	81	14
64	52	69	29

B.1 Plate Toughness Characteristics (ft-lbs) 0 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
65	83	134	15
66	46	76	13
67	19	38	11
68	48	72	28
69	37	71	11
70	41	55	22
71	11	21	5
72	11	23	5
73	23	31	8
74	23	34	11
75	30	52	10
76	33	53	18
77	24	39	13
78	23	58	15
79	14	42	4
80	48	85	25
81	20	31	10
82	36	69	18
83	40	55	30
84	57	79	34
85	26	41	11
86	47	53	32
87	30	53	5
88	28	42	5
89	10	19	5
90	90	116	48
91	41	128	15
92	27	51	11
93	35	53	16
94	49	62	34

B.2 Plate Toughness Characteristics (ft-lbs), 40 °F

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
1	26	37	15
2	27	45	17
3	28	36	18
4	36	45	25
5	26	33	20
6	28	41	19
7	28	35	19
8	34	47	21
9	32	44	21
10	42	59	17
11	27	38	21
12	34	45	25
13	44	56	31
14	43	51	36
15	40	51	27
16	43	51	32
17	46	59	20
18	65	87	51
19	38	45	27
20	32	46	22
21	45	61	32
22	49	70	22
23	28	36	19
24	27	41	16
25	24	33	20
26	23	35	16
27	40	52	20
28	16	20	12
29	28	35	17
30	29	47	12
31	35	51	22
32	29	59	14

B.2 Plate Toughness Characteristics (ft-lbs), 40 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
33	27	37	19
34	48	67	32
35	42	47	37
36	78	91	68
37	41	54	25
38	54	69	22
39	76	85	65
40	27	37	23
41	29	37	25
42	31	36	28
43	19	23	13
44	29	40	20
45	41	89	14
46	35	61	13
47	31	55	13
48	64	103	28
49	52	84	29
50	99	167	51
51	100	132	53
52	92	163	38
53	182	240	89
54	104	124	93
55	124	162	87
56	74	114	31
57	61	95	28
58	57	78	35
59	105	154	33
60	46	54	36
61	25	38	16
62	46	88	26
63	74	102	40
64	90	123	65

B.2 Plate Toughness Characteristics (ft-lbs), 40 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
65	133	207	46
66	84	105	53
67	26	34	17
68	58	75	45
69	52	89	31
70	51	58	36
71	21	35	13
72	21	41	8
73	40	51	32
74	42	90	14
75	48	63	26
76	53	85	31
77	39	46	22
78	38	58	15
79	25	41	9
80	68	91	40
81	31	44	18
82	53	82	29
83	59	64	55
84	68	80	57
85	36	66	22
86	78	91	60
87	40	65	16
88	26	64	7
89	13	23	5
90	139	191	89
91	65	90	46
92	45	80	16
93	58	79	33
94	76	96	55

B.3 Plate Toughness Characteristics (ft-lbs), 70 °F

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
1	39	48	25
2	44	91	17
3	41	53	23
4	52	70	37
5	42	54	32
6	48	65	34
7	40	53	24
8	47	58	37
9	60	78	48
10	65	87	43
11	44	58	29
12	58	70	42
13	65	81	54
14	57	92	22
15	65	88	36
16	58	77	45
17	64	78	35
18	90	111	76
19	55	72	41
20	45	54	39
21	66	74	59
22	77	93	65
23	38	52	24
24	41	52	28
25	30	43	18
26	35	52	25
27	55	73	36
28	21	25	16
29	44	66	22
30	38	51	18
31	51	80	39
32	33	63	16

B.3 Plate Toughness Characteristics (ft-lbs), 70 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
33	37	56	24
34	58	79	43
35	49	56	43
36	93	103	85
37	58	74	45
38	88	101	80
39	98	111	84
40	45	77	30
41	44	53	35
42	43	48	40
43	27	31	22
44	37	49	30
45	60	93	35
46	48	76	31
47	46	75	21
48	92	130	55
49	87	115	47
50	143	207	108
51	143	191	78
52	123	195	71
53	210	240	132
54	120	135	110
55	139	181	96
56	116	145	84
57	102	126	74
58	80	107	38
59	138	183	53
60	64	77	53
61	42	66	16
62	60	95	27
63	92	114	33
64	108	186	75

B.3 Plate Toughness Characteristics (ft-lbs), 70 °F (cont.)

Plt #	Average Toughness	Maximum Loc. Avg.	Minimum Loc. Avg.
65	179	256	104
66	113	131	71
67	38	47	30
68	68	91	49
69	80	113	32
70	56	61	51
71	30	45	22
72	36	69	23
73	54	71	45
74	58	95	21
75	63	86	32
76	65	94	51
77	51	71	30
78	55	82	35
79	35	56	24
80	117	143	82
81	47	57	33
82	71	92	48
83	82	95	77
84	85	107	67
85	55	67	39
86	91	106	79
87	76	174	49
88	55	87	25
89	25	54	11
90	166	237	116
91	89	122	64
92	63	85	33
93	75	91	52
94	93	109	78

Appendix C

C.1 ANOVA Results: Plate Significance Levels

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
1	0.097	0.869	0.098	0.036
2	0	0.242	0.401	0
3	0	0.055	0.187	0.033
4	0	0.015	0.141	0.056
5	0.524	0.744	0.553	0.265
6	0	0.078	0.134	0
7	0.008	0.495	0.313	0.103
8	0.035	0.559	0.119	0.103
9	0.009	0.562	0.191	0.009
10	0.001	0.751	0.003	.001
11	0.034	0.524	0.493	0.185
12	0.119	0.382	0.110	0.336
13	0.008	0.083	0.329	0.037
14	0.095	0.278	0.963	0
15	0	0.019	0.349	0.069
16	0.114	0.952	0.294	0.094
17	0	0.075	0.002	0.021
18	0.002	0.364	0.076	0.075
19	0	0.031	0.452	0.005
20	0.049	0.170	0.023	0.244
21	0.087	0.118	0.215	0.860
22	0.501	0.719	0.097	0.202
23	0.001	0.045	0.008	0.093
24	0	0.005	0.001	0.006
25	0	0.045	0.018	0.005
26	0	0.016	0.001	0.001
27	0	0.013	0.001	0.025
28	0.001	0.192	0.110	0.409
29	0	0.007	0.308	0.005
30	0	0.008	0	0.004
31	0	0.035	0.185	0.019
32	0	0.001	0	0.001

C.1 ANOVA Results: Plate Significance Levels (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
33	0	0.020	0	0
34	0	0	0	0
35	0	0.027	0.002	0.117
36	0	0.005	0.029	0.229
37	0.027	0.419	0.042	0.368
38	0	0.001	0	0.063
39	0.001	0.066	0.259	0.259
40	0	0.086	0.036	0.002
41	0.010	0.105	0.101	0.583
42	0.079	0.085	0.086	0.245
43	0.113	0.586	0.046	0.196
44	0.001	0.108	0.263	0.071
45	0.044	0.121	0.027	0.001
46	0	0	0	0
47	0	0	0	0
48	0	0.007	0.005	0
49	0	0	0.046	0.001
50	0.091	0.752	0.023	0.010
51	0	0.013	0.001	0.003
52	0	0.010	0.001	0
53	0	0.206	0	0
54	0	0.040	0.001	0.008
55	0	0.003	0	0
56	0	0	0	0.087
57	0	0.052	0.019	0.027
58	0	0.151	0	0
59	0	0.025	0	0
60	0.006	0.385	0.142	0.051
61	0	0	0.363	0
62	0	0	0	0.001
63	0	0.001	0.002	0
64	0	0.150	0.006	0.033

C.1 ANOVA Results: Plate Significance Levels (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
65	0	0.012	0	0
66	0	0.001	0.138	0.001
67	0.017	0.010	0.190	0.680
68	0	0.001	0.004	0.004
69	0	0.017	0.010	0
70	0	0	0.001	0.009
71	0.001	0.179	0.362	0.480
72	0	0.033	0.210	0.302
73	0.025	0.295	0.375	0.056
74	0	0.025	0	0
75	0	0.001	0.051	0
76	0	0.087	0.003	0.001
77	0	0.019	0.539	0.002
78	0	0.007	0.012	0.177
79	0	0	0.011	0
80	0.248	0.370	0.353	0.193
81	0.108	0.314	0.170	0.740
82	0	0.013	0.002	0.066
83	0.250	0.364	0.993	0.512
84	0	0.006	0.565	0.311
85	0	0.056	0.027	0.107
86	0.043	0.607	0.089	0.714
87	0.014	0	0	0
88	0	0.001	0	0
89	0	0.144	0.067	0
90	0.001	0.050	0.202	0.016
91	0.001	0	0.002	0.027
92	0	0.003	0.024	0.001
93	0	0.001	0.001	0.022
94	0	0.003	0.107	0

C.2 ANOVA Results: Plate F Ratios

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
1	1.72	0.48	1.98	2.59
2	4.89	1.43	1.11	13.51
3	4.55	2.34	1.59	2.65
4	4.21	3.19	1.76	2.32
5	0.91	0.65	0.89	1.37
6	4.65	2.12	1.79	6.19
7	2.73	0.97	1.27	1.95
8	2.14	0.88	1.86	1.95
9	2.68	0.88	1.57	3.57
10	3.76	0.64	4.50	5.06
11	2.15	0.93	0.97	1.59
12	1.64	1.14	1.91	1.22
13	2.74	2.08	1.24	2.59
14	1.74	1.34	0.31	6.50
15	4.73	3.02	1.20	2.19
16	1.66	0.34	1.31	2.00
17	4.12	2.14	4.92	2.94
18	3.18	1.17	2.13	2.14
19	4.13	2.70	1.03	3.96
20	2.08	1.69	3.08	1.45
21	1.77	1.86	1.50	0.50
22	0.93	0.68	1.98	1.54
23	3.76	2.45	3.63	2.01
24	11.08	3.96	5.09	3.85
25	6.36	2.46	3.06	3.99
26	9.13	3.14	5.38	9.93
27	7.60	3.30	5.01	2.85
28	3.50	1.57	1.91	1.09
29	4.83	3.69	1.28	4.00
30	6.22	3.61	5.96	4.23
31	4.68	2.62	1.59	3.02
32	11.88	5.46	13.10	5.64

C.2 ANOVA Results: Plate F Ratios (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
33	9.29	3.19	9.73	6.71
34	60.53	9.98	39.86	22.35
35	5.10	2.95	5.11	1.93
36	6.41	4.24	2.90	1.49
37	2.35	1.08	2.64	1.17
38	8.93	6.30	9.28	2.35
39	3.74	2.32	1.41	1.41
40	6.95	2.14	2.74	5.36
41	2.78	2.00	2.03	0.84
42	1.87	2.15	2.14	1.44
43	1.70	0.83	2.57	1.59
44	4.00	1.99	1.40	2.27
45	2.13	1.91	2.96	6.02
46	28.09	9.71	23.33	8.57
47	28.00	18.10	10.92	8.06
48	7.90	3.68	3.91	13.07
49	5.57	8.54	2.44	5.87
50	1.75	0.64	2.90	3.45
51	9.09	3.30	5.18	4.40
52	10.91	3.44	5.07	6.19
53	9.53	1.53	14.95	6.92
54	5.73	2.54	5.00	3.61
55	16.79	4.26	11.07	28.13
56	9.55	7.77	7.47	2.05
57	4.48	2.37	3.01	2.78
58	9.48	1.71	6.14	26.43
59	7.54	2.85	10.37	16.65
60	3.01	1.14	1.81	2.49
61	4.02	6.37	1.17	7.61
62	18.07	16.03	13.44	5.66
63	11.65	5.20	4.60	7.47
64	5.16	1.77	4.14	2.80

C.2 ANOVA Results: Plate F Ratios (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
65	13.31	3.57	19.74	7.32
66	5.95	4.99	1.77	5.64
67	2.43	3.49	1.58	0.73
68	11.10	5.97	4.38	4.41
69	10.65	3.11	3.49	6.63
70	6.04	10.10	5.55	3.53
71	3.48	1.61	1.17	0.99
72	4.28	2.67	1.51	1.29
73	2.28	1.30	1.15	2.33
74	9.51	3.01	21.57	7.27
75	5.42	4.97	2.39	8.72
76	6.97	2.05	4.34	5.82
77	4.69	3.01	0.91	4.71
78	5.81	3.74	3.31	1.62
79	9.38	9.29	3.40	6.34
80	1.32	1.17	1.20	1.60
81	1.72	1.28	1.69	0.63
82	7.86	3.53	5.18	2.32
83	1.32	1.18	0.16	0.94
84	4.13	4.08	0.86	1.29
85	4.64	2.43	2.94	1.99
86	2.14	0.81	2.12	0.67
87	2.63	21.63	7.90	23.87
88	6.62	6.04	12.91	12.54
89	4.94	1.80	2.31	6.78
90	3.69	2.51	1.57	3.32
91	3.87	7.27	5.06	2.95
92	13.82	6.00	3.56	7.41
93	13.97	6.63	6.66	3.32
94	5.71	5.17	2.08	7.66

C.3 ANOVA Results: Degrees of Freedom

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
1	89	29	29	29
2	89	29	29	29
3	89	29	29	29
4	89	29	29	29
5	89	29	29	29
6	89	29	29	29
7	89	29	29	29
8	89	29	29	29
9	89	29	29	29
10	89	29	29	29
11	89	29	29	29
12	89	29	29	29
13	89	29	29	29
14	89	29	29	29
15	89	29	29	29
16	89	29	29	29
17	89	29	29	29
18	89	29	29	29
19	89	29	29	29
20	80	26	26	26
21	89	29	29	29
22	89	29	29	29
23	89	29	29	29
24	89	29	29	29
25	89	29	29	29
26	89	29	29	29
27	89	29	29	29
28	89	29	29	29
29	89	29	29	29
30	89	29	29	29
31	89	29	29	29
32	89	29	29	29

C.3 ANOVA Results: Degrees of Freedom (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
33	80	26	26	26
34	80	26	26	26
35	80	26	26	26
36	80	26	26	26
37	80	26	26	26
38	80	26	26	26
39	80	26	26	26
40	80	26	26	26
41	80	26	26	26
42	80	26	26	26
43	80	26	26	26
44	80	26	26	26
45	80	26	26	26
46	71	23	23	23
47	71	23	23	23
48	89	29	29	29
49	89	29	29	29
50	89	29	29	29
51	89	29	29	29
52	89	29	29	29
53	89	29	29	29
54	89	29	29	29
55	89	29	29	29
56	89	29	29	29
57	89	29	29	29
58	89	29	29	29
59	89	29	29	29
60	80	26	26	26
61	89	29	29	29
62	89	29	29	29
63	89	29	29	29
64	80	26	26	26

C.3 ANOVA Results: Degrees of Freedom (cont.)

Plt. No.	All Temps.	0 deg F	40 deg F	70 deg F
65	80	26	26	26
66	89	29	29	29
67	89	29	29	29
68	80	26	26	26
69	89	29	29	29
70	89	29	29	29
71	89	29	29	29
72	89	29	29	29
73	89	29	29	29
74	80	26	26	26
75	89	29	29	29
76	89	29	29	29
77	89	29	29	29
78	89	29	29	29
79	89	29	29	29
80	80	26	26	26
81	80	26	26	26
82	79	26	25	26
83	79	26	25	26
84	80	26	26	26
85	80	26	26	26
86	78	24	26	26
87	80	26	26	26
88	80	26	26	26
89	80	26	26	26
90	80	26	26	26
91	80	26	26	26
92	62	20	20	20
93	71	23	23	23
94	71	23	23	23

APPENDIX D

Distribution Rosters

Dist. #	A572 Grade 50	A588
1 2 3	1 - 47	48 - 94
4 5 6	1,3,5,6,7,8,9,11, 12,16,18,20,23,32, 33,34,35,36,37,39, 40,41,42,43,44	50,54,55,60,64,67, 68,70,76,77,80,81, 82,83,84,86,90,94
7	1,5,12,14,16, 21,22,42,43	50,80,81,83
8	1,2,3,4,5,6,7,8,9, 11,12,13,14,15,16, 18,19,21,22,28,29, 30,39,41,42,44	60,61,66,67,71,72, 73,75,77,80,81,83, 84,86,89,90,94
9	4,5,7,8,11,12,15,16, 18,20,21,22,23,28, 35,36,37,38,39,41, 42,43,44	56,60,67,71,72,73, 78,80,81,82,83,84, 85,86
10 11 12	1,2,3,4,5,6,7,8,9, 11,12,19,20,23,24,25, 26,29,30,31,32,33, 40,41,42,44,46,47	61,67,71,72,73,77, 78,79,81,85,87,88

APPENDIX E
User's and Supplier's Risk

E.1 A572 Grade 50, 15 ft-lbs Criterion, 70 °F

Recommended Test Level: 25 ft-lbs

47 plates meet criterion
0 plates do not meet criterion

No User's Risk

Supplier's Risk (ft-lbs)

				Location									
#	Avg.	Max.	Min.	1	2	3	4	5	6	7	8	9	10
28	20.5	25.0	15.7	18.7	20.3	19.0	19.7	18.0	21.0	23.3	24.0		15.7
32	32.5	62.7	16.0	16.7	16.0						16.0		
43	26.8	31.3	22.3								24.7	22.3	
30	38.3	51.0	18.3	18.3							23.7		
2	43.9	90.7	17.0	17.0									
3	40.7	53.3	23.3							23.3			
7	40.1	53.3	24.3	24.3									
14	56.9	91.7	22.0	22.0									
23	38.1	52.3	24.3									24.3	
25	30.2	43.0	17.7								17.7		
29	43.5	66.0	22.0							22.0			
33	37.4	55.7	24.0						24.0				
47	46.3	75.3	21.0	21.0									

34 of 47 plates accepted at all locations not included

E.2 A588, 15 ft-lbs Criterion, 70 °F

Recommended Test Level: 25 ft-lbs

46 plates meet criterion
1 plate does not meet criterion

User's Risk (ft-lbs)

				Location									
#	Avg.	Max.	Min.	1	2	3	4	5	6	7	8	9	10
89	25.1	54.3	11.3	54.3	28.7				26.0			28.7	

Supplier's Risk (ft-lbs)

				Location									
#	Avg.	Max.	Min.	1	2	3	4	5	6	7	8	9	10
71	30.1	44.7	21.7	23.3				21.7	23.0			23.0	
72	36.0	69.0	22.7						22.7		24.0		
61	42.4	66.0	15.7						15.7				
74	57.7	94.7	21.3									21.3	
79	34.6	56.0	24.0	24.0									

41 of 46 plates accepted at all locations not included

E.3 A572 Grade 50, 15 ft-lbs Criterion, 40 °F

Recommended Test Level: 30 ft-lbs
40 plates meet criterion
7 plates do not meet criterion

User's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
45	40.6	88.7	14.0	60.3	32.0			40.7		49.0	88.7		
46	34.6	60.7	13.3	31.7		60.0		60.7		35.3		33.3	
30	28.5	47.0	12.3			40.0		39.3		32.0		47.0	
47	30.6	55.3	12.7			55.3		51.3				30.3	
32	28.7	58.7	14.3			37.7	40.3	58.7					

2 of 7 plates rejected at all locations not included

Supplier's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
11	26.9	38.3	20.7	26.7	25.0	24.0	29.3	28.3		20.7	25.0	26.3	25.0
25	23.9	32.7	19.7	26.3	26.3		19.7	23.3	25.7	19.7	19.7	20.7	25.3
26	23.4	35.3	15.7	28.3	21.3	15.7		18.0	19.3	24.3	24.0	26.7	21.0
40	26.7	37.3	22.7	23.3	21.3	23.3	22.7	26.0	23.3	26.7	24.3		
5	25.7	32.7	20.0	23.3	21.3		26.7	21.0		26.0	20.0	25.0	28.3
33	26.6	37.3	19.0		26.0	24.7	25.0	26.3	19.0		28.7	21.7	
1	25.8	37.3	15.3	15.3	18.7			24.7	22.3	20.0	27.3		27.0
2	27.4	45.0	16.7	16.7	23.0	17.3	22.3	23.7			21.0		26.7
6	27.9	41.0	18.7	22.3	24.3		23.7	26.7	27.3		18.7		22.0
7	27.5	34.7	19.3	19.3	19.7		28.3		27.0	25.3	27.0		29.0
29	27.8	35.0	17.0	29.3	28.0			29.7	27.3	17.0	28.7	19.3	
44	28.8	39.7	20.3			27.7		25.7	24.0	29.7	20.3	24.0	
3	27.7	36.3	18.3	23.7	27.7		22.3			24.7	24.3	18.3	
23	28.0	35.7	19.3		28.3				22.7	24.7	19.3	23.7	27.0
24	26.9	41.0	15.7		16.7				15.7	27.3	23.7	27.3	17.0
20	32.0	45.7	22.0	27.7		29.0	26.7			28.0		22.0	
41	29.2	36.7	24.7			26.7	29.3		24.7		27.3	25.0	
9	32.1	44.0	21.3				21.3		29.7	24.7	28.3	29.7	
42	31.1	36.0	28.0	28.0	29.3						28.0	29.7	
31	35.2	51.3	22.0	28.7	28.7					28.7	22.0		
12	34.2	45.0	25.3			29.0	25.3	25.3					
8	34.3	46.7	21.3							24.7	21.3		
10	41.7	58.7	17.3							17.3		17.7	
15	40.0	51.0	27.3					27.3					28.0
27	40.1	51.7	20.0				27.3	20.0					
37	41.1	54.0	24.7						24.7				
38	54.0	69.3	22.3					22.3					
4	36.1	44.7	25.0	25.0									
17	45.5	59.0	19.7								19.7		
19	38.1	45.3	27.3	27.3									
22	49.3	70.0	21.7		21.7								

9 of 40 plates accepted at all locations not included

E.4 A588, 15 ft-lbs Criterion, 40 °F

Recommended Test Level: 30 ft-lbs

41 plates meet criterion
6 plates do not meet criterion

User's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
74	41.7	89.7	14.3		53.3	32.0		89.7	45.3	36.0			58.3
88	25.5	64.3	7.3					64.7	42.7				
71	20.9	35.3	13.3					35.3					
72	20.7	40.7	7.7			40.7							
79	24.5	41.3	9.3							41.3			

1 of 6 plates rejected at all locations not included

Supplier's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
61	25.1	38.3	16.0		18.3		20.7	24.3	21.0	21.7		16.0	22.0
67	26.3	34.0	17.0	21.7		23.3		17.0			19.3	20.7	29.3
81	30.7	44.3	17.7			27.0	28.7	17.7	23.3				
85	35.7	66.0	22.0					25.0	26.3	24.7		22.0	
78	37.7	58.0	15.0		18.7				29.7	15.0		23.0	
92	45.0	80.0	15.7	28.0					15.7				
49	51.6	84.0	28.7	28.7							29.3		
87	40.0	65.0	16.3	16.3						23.7			
82	53.4	81.7	29.3							29.3			
48	64.1	103.0	28.3									28.3	
57	60.7	95.3	27.7								27.7		
62	45.7	87.7	25.7										25.7
75	47.8	63.0	26.0					26.0					
77	38.7	46.0	21.7				21.7						

27 of 41 plates accepted at all locations not included

E.5 A572 Grade 50, 25 ft-lbs Criterion, 70 °F

Recommended Test Level: 40 ft-lbs

34 plates meet criterion
13 plates do not meet criterion

User's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
14	56.9	91.7	22.0		71.3	60.7	91.7	52.3	62.7	58.3	42.7	40.7	66.3
3	40.7	53.3	23.3	40.3	53.0	53.3		53.0	43.7				45.3
29	43.5	66.0	22.0	46.0			66.0	46.0	45.3			48.0	50.0
7	40.1	53.3	24.3		46.0	53.3	43.7	41.7			48.3		
30	38.3	51.0	18.3		47.0	51.0		46.3		50.0			45.3
47	46.3	75.3	21.0			75.3		71.0			44.7	52.3	
2	43.9	90.7	17.0			42.3			65.3	90.7		63.0	
23	38.1	52.3	24.3	40.7		41.0	48.7	52.3					
32	32.5	62.7	16.0			43.3	62.7	40.7		42.0			
33	37.4	55.7	24.0	46.7							43.3		
25	30.2	43.0	17.7			43.0							

2 of 13 plates rejected at all locations not included

Supplier's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
44	37.1	49.3	30.3		30.3		35.3	33.3	33.0	34.0	34.3	37.0	
26	35.2	52.0	25.0		25.0	25.3		33.0	28.7		32.0	37.3	28.3
40	44.7	77.3	29.7	38.3		29.7	36.3	30.7	34.0				
1	39.1	47.7	25.3	31.3	25.3	38.7			30.0	37.3			
5	42.0	54.3	32.0		39.0	34.0		38.0			32.0		
46	47.5	76.0	30.7		36.3				30.7		37.7		
41	44.0	52.7	35.3			35.3	38.3		39.3				
6	48.2	64.7	34.3		34.3			37.3			34.3		
24	40.9	52.0	28.0		30.3				28.3				28.0
8	47.4	57.7	37.3						37.3		39.7		
11	43.8	58.0	29.0							34.3			29.0
31	50.9	80.0	38.7	38.7	39.3								
45	60.4	93.3	34.7				34.7				37.7		
4	52.4	70.3	36.7	36.7									
15	64.8	87.7	36.0										36.0
17	64.0	78.0	45.0								34.7		
20	45.4	54.0	39.3									39.3	
27	55.0	72.7	36.3						36.3				
42	43.2	47.7	39.7								39.7		

15 of 34 plates accepted at all locations not included

E.6 A588, 25 ft-lbs Criterion, 70 °F

Recommended Test Level: 40 ft-lbs

41 plates meet criterion
6 plates do not meet criterion

User's Risk (ft-lbs)

				Location									
#	Avg.	Max.	Min.	1	2	3	4	5	6	7	8	9	10
74	57.7	94.7	21.3	45.0	74.7	58.7	47.0	94.7	52.7	53.7			71.7
61	42.4	66.0	15.7	48.7	51.7		43.7		64.7				66.0
72	36.0	69.0	22.7			53.7	69.0	44.3					
79	34.6	56.0	24.0							56.0	41.7		
71	30.1	44.7	21.7			44.7							
89	25.1	54.3	11.3		54.3								

Supplier's Risk (ft-lbs)

				Location									
#	Avg.	Max.	Min.	1	2	3	4	5	6	7	8	9	10
67	37.9	46.7	30.3	34.3	39.7	30.3					30.3	36.3	38.3
81	47.4	57.0	32.7	38.3							32.7		
58	80.3	107.0	37.7									37.7	
62	59.5	94.7	27.3				27.3						
63	91.5	114.3	33.0				33.0						
69	79.6	113.0	31.7	31.7									
75	63.0	85.7	32.3					32.3					
77	50.9	70.7	29.7				29.7						
78	54.7	82.0	35.3										35.3
85	54.7	66.7	39.0						39.0				
88	54.9	87.3	25.3									25.3	
92	62.5	84.7	33.3						33.3				

29 of 41 plates accepted at all locations not included

E.7 A572 Grade 50, 25 ft-lbs Criterion, 40 °F

Recommended Test Level: 40 ft-lbs

14 plates meet criterion

33 plates do not meet criterion

User's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
22	49.3	41.0	15.7	56.7		43.3	50.3	48.0	45.7	48.0	43.3	70.6	65.7
17	45.5	59.0	19.7	54.0	59.0	42.0	43.0	54.3	53.3	43.3		48.7	
38	54.0	69.3	22.3		62.0	69.3	60.7		59.7	67.3	44.0	68.0	
10	41.7	58.7	17.3	58.0	58.7	44.3		46.3			55.3		52.0
27	40.1	51.7	20.0	49.3	48.3	42.7			51.7	42.0			50.0
37	41.1	54.0	24.7	40.0	40.7	48.0	52.0	54.0					
45	40.6	88.7	14.0	60.3				40.7		49.0	88.7		
31	35.2	51.3	22.0			51.3		45.7				44.3	
2	27.4	45.0	15.3							40.0		45.0	
8	34.3	46.7	21.3	46.7	42.3								
9	32.1	44.0	21.3			44.0		42.0					
20	32.0	45.7	22.0					45.7	44.3				
30	28.5	47.0	12.3			40.0						47.0	
32	28.7	58.7	14.3				40.3	58.7					
46	34.6	60.7	13.3			60.0		60.7					
47	30.6	55.3	12.7			55.3		51.3					
6	27.9	41.0	18.7						41.0				
24	26.9	41.0	15.7			41.0							

15 of 33 plates rejected at all locations not included

Supplier's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
4	36.1	44.7	25.0	25.0	37.0		31.7	36.0		34.3	37.3	36.0	36.3
12	34.2	45.0	25.3		39.7	29.0	25.3	25.3	32.7	33.7	36.0	34.7	
19	38.1	45.3	27.3	27.3		38.7	30.7		37.0		35.0	38.7	
15	40.0	51.0	27.3			38.0	36.3	27.3		34.0			28.0
21	45.4	60.7	32.3			32.3	39.0			38.3	39.3	38.3	
13	43.6	55.7	30.7	37.7		30.7	37.3						
14	42.7	50.7	35.7		37.3				35.7	38.3			
16	42.8	51.3	32.3	36.7					36.0		32.3		
35	41.7	47.3	36.7	38.7	39.7			36.7					
34	47.7	66.7	32.0	32.0				36.7					

3 of 14 plates accepted at all locations not included

E.8 A588, 25 ft-lbs Criterion, 40 °F

Recommended Test Level: 45 ft-lbs

33 plates meet criterion
14 plates do not meet criterion

User's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
74	41.7	89.7	21.3		53.3			89.7	45.3				58.3
87	40.0	65.0	16.3			50.3	53.0		65.0		53.0		
78	37.7	58.0	15.0			58.0	50.0	57.3			50.0		
92	45.0	80.0	15.6		80.0			73.0					
77	38.7	46.0	21.7					45.7			46.0		
85	35.7	66.0	22.0			66.0							
88	25.5	64.3	7.3					64.3					

7 of 14 plates rejected at all locations not included

Supplier's Risk (ft-lbs)

#	Avg.	Max.	Min.	Location 1	2	3	4	5	6	7	8	9	10
73	39.8	51.0	31.7	31.7	38.0	32.0	35.7	38.3	39.3			41.0	
62	45.7	87.7	25.7	30.0	32.3	35.7	32.3					34.7	25.7
69	52.2	89.3	30.7	33.7	44.0				42.0	40.3	30.7		
75	47.8	63.0	26.0	41.3				26.0	41.3			41.3	44.0
58	56.8	78.3	34.7				40.7		43.0	34.7		39.3	
60	46.0	54.3	36.0			36.0	42.0		44.7	40.7			
76	53.0	85.3	30.7	30.7				40.0		32.7		31.0	
49	51.6	84.0	28.7	28.7			32.7				29.3		
57	60.7	95.3	27.7	33.0						35.0	27.7		
48	64.1	103.0	28.3						44.3			28.3	
52	92.1	163.3	38.3							42.7		38.3	
70	50.6	57.7	35.7		40.0								35.7
80	67.7	91.3	40.0			44.7	40.0						
82	53.4	81.7	29.3							29.3		39.0	
93	58.0	78.7	33.0	33.0							43.3		
56	74.3	113.7	31.0				31.0						
59	104.9	154.3	33.3				33.3						
63	73.8	101.7	39.7				39.7						
68	58.2	75.0	44.7								44.7		

14 of 33 plates accepted at all locations not included

REFERENCES

1. *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members,* American Association of State Highway and Transportation Officials, Washington, D.C., 1978.

2. Hartbower, C.E. and Sunbury, R.D., "Variability of Fracture Toughness in A514/517 Plate," Federal Highway Administration, Washington, D.C., Report FHWA-RD-76-37, December 1975.

3. Krishna, G.V. and Roberts, R., "Fracture Behavior of A36 Bridge Steels," Federal Highway Administration, Washington, D.C., Report FHWA-RD-77-156, April 1977.

4. American Iron and Steel Institute, Survey SU27, received from Bethlehem Steel Company, 1984.

5. American Iron and Steel Institute, "The Variations in Charpy V-Notch Impact Properties in Plates," Washington, D.C., unpublished draft of report on survey SU27 database, 1988.

6. American Society of Testing Materials, "Notched Bar Impact Testing of Metallic Materials", ASTM E23-72.

7. Barsom, Johm M. and Rolfe, Stanley T., *Fracture & Fatigue Control in Structures,* Prentice- Hall, Inc., Englewood Cliffs, N.J., second edition, 1987.

8. American Iron and Steel Institute, "The Variations in Charpy V-Notch Impact Properties In Steel Plates," Washington, D.C., January 1979.

VITA

David Raymond Horos was born in Sacramento, California on December 16, 1965, the son of Raymond Anthony Horos and Camille Prattini Horos. After graduating from Brother Martin High School, New Orleans, Louisiana, in 1983, he entered Louisiana State University in Baton Rouge, Louisiana. He received the degree of Bachelor of Science in Civil Engineering from Louisiana State University in May, 1987. In August, 1987, he entered the Graduate School of The University of Texas at Austin.

Permanent Address: 5316 Washingtonian Drive
Metairie, Louisiana

This thesis was typed by the author.