MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Services des thèses canadiennes

Ottawa, Canada
K1A 0N4

CANADIAN THESES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

**THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED**

THÈSES CANADIENNES

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

**LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE**

EFFECTS OF WELD UNDERCUTTING ON THE FATIGUE LIFE

OF PLATE "T"-WELDED SPECIMENS

Stewart A. Bain

*A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the
Degree of Master of Engineering*

Department of Mechanical and Aeronautical Engineering

Carleton University

Ottawa, Ontario

Canada

August 1986

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-33429-0

The undersigned hereby recommend to the Faculty of Graduate Studies and Research, acceptance of the thesis: "Effects of Weld Undercutting on the Fatigue Life of Plate "T"-Welded Specimens", submitted by Stewart A. Bain, in partial fulfillment of the requirements for the degree of Master of Engineering.

Thesis Supervisor

Chairman, Department of Mechanical
and Aeronautical Engineering

To my mother, father, sister and Joe

"Thanks Pal"

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank the following people for their guidance and support throughout the preparation of this thesis:

- Professor R. Bell
- Grant O'Connor

Special thanks to Dianna R. Yorke for the use of her kitchen table and for her loving support.

ABSTRACT

This thesis reports on the effects of weld undercutting on the fatigue life of plate "T"-welded specimens, subjected to three-point bending, with considerations of crack shape and crack initiation/propagation.

A description of the facility used in testing the seven "T"-welded specimens, with varying severities of weld undercuts, is included. The AC potential-drop technique is used for crack growth monitoring. Comparisons of experimental results of crack growth with published and computer predicted results are presented.

Test results show that the percentage reduction in life due to varying severities of weld undercuts ranges from 14.48% to 81.91%.

TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGEMENTS	i
ABSTRACT	ii
LIST OF TABLES	v
LIST OF FIGURES	viii
NOMENCLATURE	xi
 CHAPTER 1 INTRODUCTION	 1
1.0 INTRODUCTION	1
1.1 OBJECTIVES	5
 CHAPTER 2 LITERATURE BACKGROUND AND THEORY	 7
2.0 INTRODUCTION	7
2.1 PRINCIPLES OF LINEAR ELASTIC FRACTURE MECHANICS...	8
2.1.1 EQUATIONS OF FRACTURE MECHANICS	9
2.2 CRACK SHAPE DEVELOPMENT	12
2.3 CRACK GROWTH MONITORING	13
2.4 LIFE PREDICTION BY COMPUTER PROGRAM	15
2.5 BACKGROUND LITERATURE OF PREVIOUS RESEARCH	20
 CHAPTER 3 TESTING APPARATUS AND PROCEDURE	 35
3.0 INTRODUCTION	35
3.1 ASSEMBLY OF TEST FACILITY	35
3.2 DATA ACQUISITION SYSTEM	36
3.2.1 ACPD MEASUREMENTS	37
3.3 MATERIALS AND WELDING SPECIFICATIONS	39
3.4 TEST PROCEDURE	40
3.4.1 PREPARATION OF SPECIMENS FOR FATIGUE TESTING	 40
3.4.2 CRACK GROWTH MONITORING	41
3.4.3 ANALYSIS OF CRACK GROWTH DATA	43

TABLE OF CONTENTS (cont'd.)

	<u>Page</u>
CHAPTER 4 RESULTS AND DISCUSSION	56
4.0 INTRODUCTION	56
4.1 CRACK GROWTH CONSIDERATIONS	56
4.2 CORRELATION OF CRACK DEPTH DATA	59
4.3 CRACK SHAPE DEVELOPMENT	61
4.4 COMPARISON OF DATA WITH LIFE PREDICTION BY COMPUTER PROGRAM	63
4.5 CONSIDERATIONS FOR FUTURE RESEARCH	65
 CHAPTER 5 CONCLUSIONS	 109
REFERENCES	111
 APPENDIX A	
 APPENDIX B	

LIST OF TABLES

<u>TABLE NO.</u>	<u>DESCRIPTION</u>	<u>Page</u>
3.1	CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES	44
4.1	UNDERCUT GEOMETRY OF TESTED SPECIMENS	67
4.2	MEASURED ENDURANCE AND CRACK INITIATION LIVES	67
4.2a	MEASURED CRACK INITIATION PUBLISHED RESULTS	68
4.3	PERCENTAGE REDUCTION IN ENDURANCE LIFE DUE TO UNDERCUT SEVERITY	68
4.4	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (145.0 kC)	69
4.5	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (245.0 kC)	69
4.6	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (275.0 kC)	70
4.7	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (290.0 kC)	70
4.8	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (300.0 kC)	71
4.9	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN AC05Z (305.0 kC)	71
4.10	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC03Z (130.0 kC)	72
4.11	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC03Z (200.0 kC)	72
4.12	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC03Z (215.0 kC)	73
4.13	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC03Z (225.0 kC)	73
4.14	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC03Z (257.0 kC)	74

LIST OF TABLES (cont'd.)

<u>TABLE NO.</u>	<u>DESCRIPTION</u>	<u>Page</u>
4.15	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN CCO8Z (83.0 kc)	74
4.16	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN CCO8Z (165.0 kc)	75
4.17	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN CCO8Z (190.0 kc)	75
4.18	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN CCO8Z (200.0 kc)	76
4.19	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN CCO8Z (207.5 kc)	76
4.20	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (50.0 kc)	77
4.21	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (85.0 kc)	77
4.22	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (105.0 kc)	78
4.23	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (112.5 kc)	78
4.24	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (120.0 kc)	79
4.25	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DCO4Z (134.6 kc)	79
4.26	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BCO7Y (290.0 kc)	80
4.27	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BCO7Y (560.0 kc)	80
4.28	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BCO7Y (670.0 kc)	81
4.29	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BCO7Y (720.0 kc)	81

LIST OF TABLES (cont'd.)

<u>TABLE NO.</u>	<u>DESCRIPTION</u>	<u>Page</u>
4.30	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC07Y (733.0 kC)	82
4.31	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN BC07Y (755.0 kC)	82
4.32	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DC10Y (85.0 kC)	83
4.33	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DC10Y (200.0 kC)	83
4.34	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DC10Y (280.0 kC)	84
4.35	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMAN DC10Y (305.0 kC)	84
4.36	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DC10Y (322.0 kC)	85
4.37	RESULTS FROM BEACHMARKS COMPARED WITH DOVER PREDICTIONS: SPECIMEN DC10Y (343.0 kC)	85
4.38	NUMBER OF INITIATED CRACKS IN TESTED T-JOINTS	86
4.39	EXPERIMENTAL VALUES OF SHAPE FACTOR EXPONENTIAL TERM "k" FOR TESTED SPECIMENS (BASED ON CRACK DEPTH, a)	86
4.40	EXPERIMENTAL VALUES OF SHAPE FACTOR EXPONENTIAL TERM "k" FOR TESTED SPECIMENS (BASED ON CRACK DEPTH, a + MEAN UNDERCUT DEPTH)	87
4.41	COMPARISON OF EXPERIMENTAL PROPAGATION LIFE WITH PREDICTIONS BY COMPUTER PROGRAM FOR TWO CRACK GROWTH MODELS	88

LIST OF FIGURES

<u>FIGURE NO.</u>	<u>TITLE</u>	<u>Page</u>
1.1	TUBULAR JOINT SHOWING "HOT SPOT" REGION TO BE SIMULATED	5
1.2	T-WELDED JOINT AND LOADING MODE	6
2.1	CRACK NOMENCLATURE	25
2.2	IDEAL STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT IN A UNIFORM AC POTENTIAL FIELD	26
2.3	TWO REGION PARIS GROWTH LAW OPTION	27
2.4	STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=15$ mm	28
2.5	STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=28$ mm	28
2.6	STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=53$ mm	29
2.7	STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=78$ mm	29
2.8	STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=103$ mm	30
2.9	WELD UNDERCUT NOMENCLATURE	31
2.10	WELD PROFILE AND WELD RUN ORDER	32
2.11	EFFECT OF THE IMPROVED WELD PROFILE AND SHOT PEENING ON THE FATIGUE LIFE RESISTANCE OF FILLET WELD	33
2.12	PROCEDURE FOR GRINDING WELD TOE	34
3.1	TEST FACILITY FOR 3-POINT BENDING TESTS AT CARLETON UNIVERSITY, OTTAWA	45
3.2	MTS 406 AND 436 CONTROL UNITS	46
3.3	MTS 464 DATA DISPLAY BOARD	47

LIST OF FIGURES (cont'd.)

<u>FIGURE NO.</u>	<u>TITLE</u>	<u>Page</u>
3.4	UNIT INSPECTION CRACK MICRO-GAUGE	48
3.5	KEITHLEY MODEL 706 SCANNER	49
3.6	FLOW OF DATA FOR ACPD MEASUREMENTS OF CRACK GROWTH	50
3.7	IDEAL STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT IN UNIFORM AC POTENTIAL FIELD	51
3.8	ASSUMED STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT ON A T-JOINT SPECIMEN	51
3.9	CRACK GROWTH MEASUREMENT FROM BOTTOM OF UNDERCUT	52
3.10	CODING SYSTEM FOR IDENTIFICATION OF UNDERCUT SPECIMENS	53
3.11	LOCATION OF STRAIN GAUGES ON TEST SPECIMENS	54
3.12	TYPICAL BEACHMARKS OF TEST SPECIMEN	55
4.1	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$ mm, 200 MPa	89
4.2	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$ mm, 150 MPa	90
4.3	STRESS-LIFE CURVES FOR CRACK PROPAGATION	91
4.4	STRESS-LIFE CURVES FOR ENDURANCE LIFE	92
4.5	COMPARISON OF ACTUAL CRACK DEPTH TO ACPD MEASUREMENTS .	93
4.6	ASPECT RATIO a/c VERSUS CRACK DEPTH a	94
4.7	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN AC05Z	95
4.8	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN BC03Z	96

LIST OF FIGURES (cont'd.)

<u>FIGURE NO.</u>	<u>TITLE</u>	<u>Page</u>
4.9	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN CC08Z	97
4.10	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN DC04Z	98
4.11	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN ACO6Y	99
4.12	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN BC07Y	100
4.13	FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa, EXPERIMENTAL AND PREDICTED RESULTS; SPECIMEN DC10Y	101
4.14	Da/Dn VERSUS DELTA K FOR SPECIMEN BC03Z	102
4.15	Da/Dn VERSUS DELTA K FOR SPECIMEN DC04Z	103
4.16	Da/Dn VERSUS DELTA K FOR SPECIMEN AC05Z	104
4.17	Da/Dn VERSUS DELTA K FOR SPECIMEN AC06Y	105
4.18	Da/Dn VERSUS DELTA K FOR SPECIMEN BC07Y	106
4.19	Da/Dn VERSUS DELTA K FOR SPECIMEN CC08Z	107
4.20	Da/Dn VERSUS DELTA K FOR SPECIMEN DC10Y	108
A1	TYPICAL WELDING SPECIFICATIONS FOR UNDERCUT SPECIMENS	
B1	CALIBRATION CURVE FOR ACPD CRACK DEPTH MEASUREMENTS	

NOMENCLATURE

- a - crack depth
- B - plate semi-thickness
- c - crack length
- C, m - material constants for crack propagation equation (1.1)
- Δ - probe pair spacing
- K - shape factor exponential term
- K - stress intensity factor
- N - number of cycles
- R - stress ratio ($\sigma_{\max}/\sigma_{\min}$)
- σ - stress
- t - plate thickness (=2B)
- Y - geometry factor for stress intensity factors

CHAPTER 1 - INTRODUCTION

1.0 - INTRODUCTION

The search for energy reserves in Canada and abroad has lead oil companies to numerous remote areas of the world. Most of these new energy reserves lie under major bodies of water. The need for sound offshore installations is of vital concern for the successful exploration and retrieval of these energy resources. One of the major concerns, when considering offshore drilling, should be the determination of an expected safe operating life (fatigue life) of the drilling structure based on the integrity of the welded construction. The type of fatigue damage that may be expected to occur in offshore installations is fatigue crack growth. These large offshore structures are commonly constructed from tubular steel members which extend down to the ocean floor. The weld toe of a steel connection is known to be a large stress concentration and is commonly referred to as the "hot spot" region of stress. Welded connections generally contain small initial defects at the weld toe which, in combination with high local stress concentrations, lead to fatigue crack initiation early in the life of the joint (VOSIKOVSKY, BELL, BURNS and MOHAUPT 1985).

The cyclic loading effect required for fatigue crack initiation and propagation is provided by high winds and the continual pounding of waves on the structure while it remains at sea. These large structures are not usually designed to allow for parts to be replaced once cracks are found. Thus,

importance, in the design stage, is placed on considering the length of time the structure can operate safely knowing these cracks do exist in the welded connections.

Previous design approaches considered that the crack initiation period would occupy most of the life of the structure and therefore the use of Stress-Life (S-N) curves for design would be appropriate (DEPARTMENT OF ENERGY, U.K., 1978, SNEDDEN, et. al. June, 1981, DET NORSKE VERITAS, 1975, AMERICAN PETROLEUM INSTITUTE, 1981). The applicability of S-N curves may become questionable in light of the degree of conservatism that may be inherent to this philosophy of design (VOSIKOVSKÝ, et. al. 1985). The S-N approach does not provide insight into the parameters which affect the fatigue problem nor does it allow for extrapolation beyond previous fatigue experience. More directly, the problem involved with designing offshore structures based on the S-N approach is that it cannot be applied to structures that contain cracks.

Fatigue life of these structures is dominated by the crack propagation period as opposed to the crack initiation period, therefore use of "Linear Elastic Fracture Mechanics" (LEFM) may be used to obtain estimates on the expected fatigue life. LEFM models based on fatigue crack growth, with various assumptions regarding initial crack size and shape, have been previously developed (BERGE and ENGESVIK 1981, BERGE 1984, SMITH and HURWORTH 1984, HUDAK, BURNSIDE and CHAN 1984). Initial flaws that exist at the weld toe propagate around the tubular connection and become more pronounced until they reach a critical size resulting in the failure of the structure. In tubular joints the

cracks propagate more rapidly along the weld rather than in the depth direction thus requiring a complex three-dimensional stress analysis (LEWINSON 1984).

By studying stress fields, at crack tips in elastic bodies, it has been found that the stress intensity factor "K" may be used to characterize the stress field for a given structural geometry, containing a crack, under a given loading condition.

More importantly, for fatigue life design, the growth rate of a crack at a weld toe may be described using the stress intensity factor "K". The relationship between crack growth per cycle of loading, da/dN , and the stress intensity range, ΔK due to the range in stress per cycle and crack shape, is given by the Paris law (PARIS 1960):

$$da/dN = C\Delta K^m \quad (1.1)$$

where C and m are material constants.

Once the relationship between the stress intensity range, stress range and crack shape is known (refer Section 2.1.1), the Paris law equation may be used to estimate the fatigue life of any structure. The value of stress intensity for many different crack geometries may be obtained using various analytical techniques including the finite element method (BELL and KIRKHOPE March, 1983, BELL and KIRKHOPE December, 1983, BELL and KIRKHOPE 1984, BELL 1985, VOSEIKOVSKY, et. al. 1985).

The quality of a weld becomes a key factor in the fatigue life analysis of a structure when initial crack depths are to be considered for the evaluation of stress intensity factors. The depth of a weld undercut caused during the welding process may influence the integrity of the welded joint. Undercuts in welded joints may be classified by various flaws which result during the welding process (PETERSHAGEN 1983). This thesis is concerned with the geometry of weld undercuts and their effect on the fatigue life of welded structures.

The undercut itself may be described as a groove caused by the welding process along the weld toe in the parent metal or in the weld metal already deposited during a previous run. The end result in this former case may be considered as an initial flaw or crack of considerable size in the connection. The Department of Energy (U.K.) has proposed fatigue design procedures for steel welded joints in offshore structures (SNEDDEN, et. al. May, 1981). The standard test for maximum allowable notch or groove in a welded joint has been the classical "dime" test. However, the "dime" test does not consider the effects of varying depths of undercuts within the "accepted" range specified by the test (refer Section 2.5).

As mentioned earlier, typical offshore installations are constructed with tubular steel members. Laboratory testing of tubular sections is typically awkward and extremely costly. Therefore the "hot spot" region of stress in a tubular connection, as circled in Figure 1.1, may be simulated by the T-shape welded joint as shown in Figure 1.2 (VOSIKOVSKY, et. al. 1985,

BIGONNET, LIEURADE and PICOUE 1984). The experimentation performed for this thesis involved only plate T-shape connections, as shown in Figure 1.2, for the study of the effect of weld undercutting on fatigue life.

This thesis will consider the effects of varying weld undercut depths and geometries on the fatigue life of plate T-welded specimens subjected to three point bending. The fatigue crack initiation and propagation will be monitored by the AC potential drop (ACPD) measurement system and empirical relations (VOSIKOVSKY, et. al. 1985) will be presented to describe crack shape development throughout the fatigue life of the test specimens.

1.1 OBJECTIVES

The objectives of this thesis are:

1. Construction and commissioning of a three point bending test facility at Carleton University.
2. Development of an AC potential drop measurement system using a personal computer (IBM-PC) for data acquisition.
3. Observation of the effects of weld undercutting on crack detection and crack shape development.
4. Investigation of the effects of weld undercutting on the fatigue life of plate T-welded specimens.
5. Comparison of the experimental life data with predicted results.

FIGURE 1.1 - TUBULAR JOINT SHOWING "HOT SPOT" REGION TO BE SIMULATED

FIGURE 1.2 - T-WELDED JOINT AND LOADING MODE
(All dimensions in mm)

CHAPTER 2 - LITERATURE BACKGROUND AND THEORY

2.0 INTRODUCTION

With the study of crack propagation, in any structure, the need arises for an analytical design approach which deals specifically with crack growth and crack shape development. Present design, in the area of offshore structures, is based largely on stress-life (S-N) predictions (BRISTOLL 1978). This method of design may be supplemented by linear elastic fracture mechanics (LEFM) which deals specifically with crack depth and crack growth due to varying stress intensity factors throughout the fatigue life of the loaded structure (BRISTOLL 1978, CROOKER 1978). While it is unlikely that linear elastic fracture mechanics will replace the stress life approach to design of offshore structures in the foreseeable future, nevertheless, the study of crack growth and crack shape development will reveal important information regarding the behaviour of a cracked structure and the effects of various parameters such as crack depth, weld toe radius, number of cracks, etc., on the overall behaviour of the structure.

This chapter will present the basics of linear elastic fracture mechanics and its subsequent applicability to structural fatigue design. Included will be a discussion on stress intensity factors as applied to the LEFM design technique. Consequently a discussion of analytical crack growth and crack shape development during fatigue life will be included in this chapter as

background to crack growth monitoring using the AC potential drop (ACPD) technique, which will be discussed in detail in Section 2.3.

This chapter will also present a discussion of computerized life prediction systems, a brief summary of previous topics of research which relate to linear elastic fracture mechanics as applied to fatigue life analysis, and current standards accepted by the United Kingdom's Department of Energy on stress-life curves.

2.1 PRINCIPLES OF LINEAR ELASTIC FRACTURE MECHANICS

The use of linear elastic fracture mechanics offers analytical insight into structural fatigue design by dealing directly with cracks that exist and eventually propagate during the life of a loaded structure, whereas stress-life curves are applicable exclusively to completely sound structures (i.e., void of cracks). The United Kingdom's Department of Energy (D.O.E.) has used fracture mechanics to modify the new stress life curves which take into consideration the effects of joint thickness, environment, stress relief, variable amplitude loading and weld improvement (SNEDDEN, et. al. May, 1981). The details of the D.O.E. findings in the area of weld improvement will be discussed in Section 2.5.

The basic assumptions made in any linear elastic fracture mechanics analysis concerns (BRISTOLL 1978):

1. the presence of a crack-like defect,
2. the location at which fatigue crack growth begins,
3. the direction of the fatigue crack growth,
4. the level of mean stress,
5. the effect of geometry of a joint including the weld profile,
(SNEDDEN, et. al. May, 1981),
6. the state of stress (i.e., three and four point bending, etc.).

In making these assumptions, for offshore structural analysis, use is made of previous field experience and structural component testing experience.

2.1.1 Equations of Fracture Mechanics

The stress environment at a crack tip is described by the stress intensity factor, K . For two different geometries of the same material the stress distribution at the crack tips will be the same if their stress intensity factors are equal.

This argument may be extended to state that the fatigue crack propagation in the two geometries, subjected to variations in stress $\Delta\sigma$, will be the same if the variation in the stress intensity factor, ΔK , is the same for both geometries. Therefore, relationships between the crack propagation rate and ΔK obtained from standard small scale laboratory specimens can be used to predict crack propagation in large fatigue loaded structures.

The rate of propagation of a fatigue crack may be determined from the relationship proposed by (PARIS 1960):

$$\frac{da}{dN} = C(\Delta K)^m \quad (2.1)$$

where: da/dN is the crack growth rate

ΔK is the range in the stress intensity factor

C and m are material properties.

(typical units da/dN = metres/cycle, ΔK = MPa $\sqrt{m}$).

Usually ΔK is related to the stress range, $\Delta\sigma$, and crack depth, a , by:

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \quad (2.2)$$

where Y is a function of crack length and specimen geometry. Extensive deviations of Y specifically applied to welded joints are presented by MADDIX (1975) and BELL (1985).

The life of a structure or component can be predicted by integration of equation (2.1) as:

$$\int_0^N dN = \frac{1}{\pi^{m/2} C \Delta\sigma^m} \int_{a_i}^{a_f} \frac{da}{Y^m a^{m/2}} \quad (2.3)$$

where a_i and a_f are the initial and final crack depths respectively.

From equation (2.3) it is important to note that once the variation of ΔK with crack depth, a , is known it is possible to predict the life of the component.

Other crack growth laws that may be used as alternatives to the Paris equation (2.1) are:

(i) The Forman Law

$$da/dN = C \frac{\Delta K^m}{(1-R)K_c - \Delta K} \quad (2.4)$$

where R is the stress ratio $\sigma_{\min}/\sigma_{\max}$, and K_c is the fracture toughness of the material.

(ii) The Collipriest Law

$$da/dN = C(\Delta K_{th} K_c)^{m/2} \cdot \exp \left[\ln \left(\frac{K_c}{\Delta K_{th}} \right)^{m/2} \text{ARCTANH} \right]$$

$$\left[\frac{\ln \left[\Delta K^2 \left\{ (1-R)K_c \Delta K_{th} \right\} \right]}{\ln \left[(1-R)K_c / \Delta K_{th} \right]} \right] \quad (2.5)$$

It has been noted experimentally by VOSIKOVSKY, et. al. (1985) that the stress ratio, R , demonstrates an affect on crack propagation. Typical values of C and m , used by Vosikovsky, given by THORPE, SCOTT, RANCE and SYLVESTER (1982) are:

Low R $R \leq 0.2$

$$m = 3.27$$

$$C = 3.26 \times 10^{-12}$$

High R $R \geq 0.5$

$$m = 3.0$$

$$C = 1.0 \times 10^{-11}$$

2.2 CRACK SHAPE DEVELOPMENT

The growth of a single semi-elliptical crack may be predicted by integration of the Paris equation (2.1) on a cycle by cycle basis, in the depth direction, to obtain the change in crack depth, a , and in the surface direction, to obtain the change in crack length, c (Figure 2.1). Based on these values of a and c a new elliptical crack shape may be analysed. This procedure of crack shape development analysis is referred to by VOSIKOVSKY, et. al. (1985) as the single crack (SC) analysis technique. Moreover, during experimental testing of plate T-welded joints, VOSIKOVSKY, et. al. (1985) observed a multinucleation of cracks along the length of the weld. The number of cracks initiated was observed to be a function of stress range and plate

thickness. Upon initiation these cracks have an initial depth/length, a/c , aspect ratio of 1.0 and as they grow the aspect ratio decreases until eventually the cracks coalesce to form a straight fronted crack.

From results obtained experimentally, VOSIKOVSKY, et. al. (1985) developed a semi-empirical relationship to model the change in aspect ratio as the depth of the crack, a , increased during fatigue loading:

$$a/c = \exp^{-ka} \quad (2.6)$$

where k describes the variation of the mean aspect ratio, a/c , with crack depth, a .

The value of k in equation (2.6) is obtained by fitting least square regression lines to $\ln a/c$ versus a plots for a given set of experimental data points. Equation (2.6) may be used to describe the development of the new aspect ratio. VOSIKOVSKY, et. al. (1985) observed that when the aspect ratio reaches a value of 0.2 and below the crack may be considered straight fronted. The analysis of the straight fronted crack case only requires a two-dimensional stress intensity factor solution whereas the multiple crack case requires a three-dimensional analysis (BELL 1985).

2.3 CRACK GROWTH MONITORING

Perhaps the most important factor involved in a fracture mechanics analysis of fatigue life is the need for accurate measurement of crack growth.

The Unit Inspection Crack Micro-Gauge obtains crack depth measurements based on the AC potential drop (ACPD) method developed by DOVER (1981).

The alternating current is applied to the metal body by two contacts at the ends of the test specimen (Figure 2.2). Two pairs of exploratory contacts, or probe pairs, are placed along streamlines within the uniform field, ABCD, to record two voltages. Voltage drop V_0 , measured by a probe pair not spanning the crack, is a function of the probe pair spacing, Δ , only, while voltage drop V_1 , measured by a probe pair straddling the crack, refers to a path length $(\Delta + 2a)$ to give:

$$\frac{V_0}{\Delta} = \frac{V_1}{\Delta + 2a}$$

or
$$a = \left(\frac{V_1}{V_0} - 1 \right) \frac{\Delta}{2} \quad (2.7)$$

Thus by taking two voltage drop measurements within the uniform field and knowing the probe pair spacing, Δ , it is possible to determine the crack depth at any point along the weld toe. The solution to equation (2.7) is referred to by DOVER (1981) as the one-dimensional solution.

The details of the AC potential drop method will be discussed further in Section 3.2.1.

2.4 LIFE PREDICTION BY COMPUTER PROGRAM

As mentioned in Section 2.1.1, fatigue crack propagation can be described by a growth law such as the Paris law (equation 2.1). The computer program, available at Carleton University, described herein, is based on the cycle by cycle integration shown in equation (2.3) and the growth laws are integrated using a Runge-Kutta numerical integration procedure (BELL 1985).

The computer program requires the following initial input and has the capabilities listed below:

1. Initial Input

- initial crack depth a
- initial crack length c
- plate thickness
- plate half width
- weld angle (30° , 45° or 70°)
- final crack depth
- weld toe stress range
- stress ratio
- material toughness K_{IC}
- fatigue crack propagation threshold K_{th}
- material growth law constants, C and m for the a direction
- material growth law constants, C and m for the c direction
- loading (tension, 4-point and 3-point bending).

2. Growth Law Selection

The program is capable of predicting fatigue crack growth according to the growth laws described in Section 2.1.1 and also using a growth law based on the Paris law with two regions. With this option it is possible to select a value of stress intensity factor, K , after which the Paris law follows a different shape as shown in Figure 2.3. This effect has been indicated by experimental results (VOSIKOVSKY 1980).

3. Stress Intensity Factor Evaluation

The program can evaluate stress intensity factor, K , for straight fronted or semi-elliptical weld toe cracks according to the following relationships:

A - Straight Fronted Cracks

(i) Gurney and Johnston Equation (GURNEY and JOHNSTON 1979).

This empirical equation was obtained from finite element analysis for non-load carrying fillet welds for welded joints with a wide range of weld sizes and plate thicknesses. The finite element analysis was carried out using a very large number of two-dimensional constant strain triangular elements to model the joint.

(ii) Phase I - 2-Dimensional Expressions

(BELL and KIRKHOPE 1984)

These empirical expressions were obtained from the two-dimensional finite element results presented by BELL and KIRKHOPE (1984). The finite element analyses were performed using the collapsed isoparametric element which imposes the $1/\sqrt{r}$ stress singularity in the crack tip region, where r refers to crack tip radius.

B - Semi-Elliptical Surface Cracks

The stress intensity factor for a semi-elliptical surface crack can be evaluated using one of the following empirical relationships.

(i) Newman and Raju Equations

(NEWMAN and RAJU 1981)

These empirical equations present an empirical stress intensity equation for a surface crack as a function of parametric angle, crack depth, crack length, plate thickness and plate width for tension and bending loads. The equation was developed from stress intensity factors obtained from three-dimensional finite element analyses using singularity elements at the crack tip region of the model.

(ii) Phase II Empirical Expressions

(BELL 1985)

Using this option the stress intensity factor of a crack at the weld toe of a plate "T" joint loaded in tension, 4-point or 3-point bending may be evaluated using the empirical equation described by BELL (1985).

(iii) Irwin's Equation

(IRWIN 1962)

The stress intensity factor solution for an elliptical crack embedded in a plate of infinite depth and surface is also included in the program. This equation is:

$$K_I(\phi) = \frac{\sigma_0}{Q} \sqrt{\frac{\pi a}{c}} \cdot (a^2 \sin^2 \phi + c^2 \cos^2 \phi)^{1/4} \quad (2.8)$$

where Q is the elliptical integral of the second kind and σ_0 is a uniform tensile stress.

4. Loading Conditions

A provision has been made in the program to permit constant or variable amplitude loading. The variable amplitude loading is performed using a block loading approach. It should be noted that the variable amplitude loading option has not been thoroughly tested.

5. Cycle Increment and Initiation Cycles

The crack growth is calculated in the a and c direction on a cycle by cycle basis. This option allows the user to specify the cycle interval at which crack growth will be printed. Also it is possible to specify a value of initiation cycles at which the program commences to calculate crack growth.

6. Material or Prescribed Crack Shape Development

This option allows the user to specify the development of the crack shape during the growth calculations. If natural crack growth development is chosen the increase in crack length in the a and c directions is calculated by integration of the growth equation using the values of material parameters for the a and c values of crack length as the minor and major axes of the ellipse respectively. This procedure models the behaviour of a single elliptical crack as mentioned in Section 2.2.

If the prescribed crack shape development is chosen then the crack shape develops according to an imposed relationship as shown by equation (2.6). This prescribed crack shape development is assumed to describe the growth and coalescence of multiple weld toe cracks. For all predictions when the aspect ratio reached a value of 0.2, the crack was assumed to be straight-fronted and the procedure outlined for straight-fronted cracks is followed.

7. Changing from 3-D to 2-D Crack Growth

There is also included in the program, the option of setting a value of aspect ratio a/c , at which the crack growth switches from 3-D to 2-D. From this point onward all load cycles for the calculation of ΔK are performed using one of the 2-D relationships for stress intensity factor.

2.5 BACKGROUND LITERATURE OF PREVIOUS RESEARCH

This section will present a brief discussion on several pertinent areas of research previously conducted with consideration of linear elastic fracture mechanics, weld undercutting and weld improvement techniques, and crack propagation in welded joints.

DOVER and HOLDBROOK (1975) performed out-of-plane bending tests on tubular welded connections to measure the stress distribution and fatigue strength of specimens under random type loading conditions. Experimental results were compared with finite element analysis with a view to estimate the fatigue life of T-joints using fracture mechanics in the design approach. The conclusion of the research affirmed that fracture mechanics would be an extremely useful tool in future fatigue life analysis.

HUDAK, BURNSIDE and CHAN (1984) conducted research on corrosion fatigue crack growth in welded tubular joints. In the subsequent report an improved fracture mechanics model was presented for fatigue crack growth in welded tubular joints. The resulting crack growth rate equation was designed to represent accumulated data over a wide range of crack growth rates (da/dN) and stress intensity factor range (ΔK) values, thereby allowing the mathematical model to be applied in a low growth rate high cycle fatigue region. This three-component model shows the fatigue crack growth resistance of the test material in three crack growth regions:

1. crack initiation
2. crack propagation
3. fast fracture.

The effect of plate thickness on the fatigue strength of plate T-welded joints has been researched by GURNEY (1979), BERGE and ENGESVIK (1981), BERGE (1984) and VOSIKOVSKY, et. al. (1985). It has been concluded that the fatigue strength of a specimen decreases with increasing plate thickness. In simple terms the explanation is that the rate of fatigue crack growth is predominantly a function of the crack depth, a , while the stresses acting on the crack are inversely proportional to the ratio of crack depth to plate semi-thickness (a/B). Consequently the stresses acting on the crack for a given crack depth are larger in thicker plates than for the same size crack in a thinner plate resulting in an increased rate of crack growth from decreasing fatigue strength. Additionally it has been shown that the stress concentration factor at the weld toe increases as plate thickness increases as shown in Figures 2.4 to 2.8 (BELL and KIRKHOPE 1984).

TSAI and TSAI (1984) researched the significance of weld undercut in the design of fillet welded T-joints. It was observed that the significance of the undercut is reflected in the loss of cross-sectional area at the weld toe. The subsequent report noted that high stress concentrations are expected due to an undercut of small tip radius (r) (Figure 2.9) while a large tip radius may act to reduce the acuity of the notch and relax the stress concen-

tration. At a 90° load angle the highest stress appears at the lower weld toe, thus, an undercut at the upper toe would not affect the integrity of the weld.

BIGONNET, LIEURADE and PICOUE (1984) researched methods of improving the fatigue resistance of welded joints in high strength steels (HSS). An improved weld procedure was devised to ensure optimum quality of the welded joints regarding fatigue resistance. The characteristics of this weld, presented in Figure 2.10, are summarized by three points:

1. Geometrically, the overall shape of the weld presents as smooth a shape as possible around the toe (Figure 2.10) in order to improve the stress distribution at the weld toe and decrease the global stress concentration factor.
2. Practically, the weld toe run is performed just after the root runs (Figure 2.10). This allows an accurate position of the weld toe; the run is laid down on the plate without the necessity of following previous runs. Experience has shown that this welding procedure leads to a better weld toe and that risks of geometrical defects are notably reduced.
3. Metallurgically, the toe run is softened by heat treatments from the filling runs, since the toe is not the last one. Furthermore, the tensile residual stresses usually encountered at the weld toe are relieved. (BIGONNET, et. al. 1984).

Following the new welding technique the test specimens are shot-peened to induce compression residual stresses along the weld toe.

Figure 2.11 shows the fatigue results obtained by BIGONNET, et. al. (1984) with the improved weld procedure, in as welded condition, compared with results by LEEUWEN, DE BACK and VAESSEN (1981) and BOOTH (1978) respectively on ~~4~~-shape (40 mm) joints using a conventional welding procedure. Additionally, the fatigue lives obtained with shot-peened specimens are given in Figure 2.11 and compared with the as welded conditions.

The improved results obtained with the improved weld profile were attributed to the lower global and local stress concentration and the lower residual stresses in the weld toe region. Shot-peening was observed as a "global" improvement technique which not only improves the weld toe but the overall weld. This is of importance because on an actual structure, the initiation sites of cracks in tubular connections may not be at the weld toe only but in the entire welded region.

The guidelines, SNEDDEN, et. al. May, 1981 (Department of Energy U.K., 1978), consider that control of weld profile alone has only a small beneficial effect on fatigue strength. However the guidelines acknowledge that large improvements in fatigue life can be obtained by local grinding of the weld toe to remove toe defects. The reason for this is that these defects are often so sharp that they are effectively small cracks and their removal introduces a crack initiation period into the fatigue life; thus the total life of the

joint is substantially increased. The guidelines require that in order to ensure that the defects are removed, it is essential for the grinding to penetrate the surface of the plate, as shown in Figure 2.12. The maximum depth of an undercut should not exceed 0.25 mm by AWS regulations. The grinding procedure results in a factor on life of approximately two for joints tested in air, but this benefit is not demonstrated for unprotected joints tested in sea water. The basis of this procedure results from tests on a variety of simple joints which are summarized by BOOTH (1978) and GURNEY (1979). MULLEN and MERWIN (1982) also published results which showed improvements in life that were obtained on "T" specimen tests by weld toe grinding which was much higher than those suggested above (i.e., factors on life range from 3 to 11).

The new U.K. Department of Energy guidelines encourage weld improvement but do not permit any benefit to be claimed for this procedure except in circumstances such as in the latter stages of design where a particular joint is found to be critical. Additional work is now underway in the various offshore test programs on the overall effect of weld profile on fatigue life.

FIGURE 2.1 - CRACK NOMENCLATURE

FIGURE 2.2 - IDEAL STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT
IN A UNIFORM AC POTENTIAL FIELD

FIGURE 2.3 - TWO REGION PARIS GROWTH LAW OPTION

FIGURE 2.4 - STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_X IN Y DIRECTION WELD ANGLE 45° $t = 15$ mm

FIGURE 2.5 - STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_X IN Y DIRECTION WELD ANGLE 45° $t = 28$ mm

FIGURE 2.6 - STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_X IN Y DIRECTION WELD ANGLE 45° $t=55$ mm

FIGURE 2.7 - STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION OF σ_X IN Y DIRECTION WELD ANGLE 45° $t=78$ mm

FIGURE 2.8.- STRESS CONCENTRATION FACTOR AT WELD TOE VARIATION
OF σ_x IN Y DIRECTION WELD ANGLE 45° $t=103$ mm

FIGURE 2.9 - WELD UNDERCUT NOMENCLATURE

FIGURE 2.11 - EFFECT OF THE IMPROVED WELD PROFILE AND SHOT PEENING ON THE FATIGUE LIFE RESISTANCE OF FILLET WELD

Grinding a weld toe tangentially to the plate surface, as at A, will produce little improvement in strength. Grinding must extend below the plate surface, as at B, in order to remove toe defects.

FIGURE 2.12 - PROCEDURE FOR GRINDING WELD TOE

CHAPTER 3 - TESTING APPARATUS AND PROCEDURE

3.0 INTRODUCTION

In order to perform thorough fatigue testing of plate T-welded specimens, subjected to three point bending, a complete test facility was constructed at Carleton University. This chapter describes briefly the framework used to support an MTS 100 kN electrohydraulic testing system, the electronic hardware used for maintaining crack growth, the materials and welding specifications of the plate T-specimen, the test procedure involved in performing three-point bending tests and the analysis of data required for such tests.

3.1 ASSEMBLY OF TEST FACILITY

The framework used to support the 100 kN MTS electrohydraulic testing system is shown in Figure 3.1. The overall framework and three-point bending supports are similar to those available at Energy, Mines and Resources Canada. The details of the design were prepared by SOTILLE (1984) to allow for safe support of the electrohydraulic system under full load conditions. The three-point bend crossbeams are fitted with adjustable mounting bolts to allow for balancing of unwanted bending loads. The T-specimens are described in Section 3.4.1.

The electronic equipment available to the test facility includes: an MTS Control Unit for the load and displacement of the MTS hydraulic piston, an

MTS 464 Data Display unit, a Unit Inspection Crack Micro-Gauge, a Keithley scanner, and a IBM PC. The Control Unit, (Figure 3.2) used for the MTS hydraulic piston, allows for adjustment of load and displacement values through two independent transducers. The values of load and displacement associated with the test specimen may be monitored by any one of six input/output channels on the MTS 464 Data Display unit (Figure 3.3). The Unit Inspection Crack Micro-Gauge (Figure 3.4), as mentioned in Section 2.3, applies an AC current to the test specimen and uses probe pairs, located along the weld toe, to measure voltage drop values used for monitoring of crack growth. Further details involved with this procedure are discussed in Section 3.2.1. The Keithley scanner (Figure 3.5) is used to isolate voltage drop readings across the probe pairs by opening and closing individual channels, connected separately to each probe pair, for adjustable, preset intervals of time. The IBM PC is used for acquiring and recording of ACPD data, and the subsequent analysis of fatigue test data as discussed in Sections 3.2 and 3.4.3 respectively.

3.2 DATA ACQUISITION SYSTEM

The data acquisition system available to the test facility at Carleton University is comprised of the electronic equipment described in Section 3.1. The general arrangement of equipment for data flow, for acquiring ACPD measurements of crack growth, is shown in Figure 3.6. As individual channels, connected to probe pairs along the weld toe, are sequentially opened by the

Keithley scanner, voltage drop values within the AC field are measured by the Unit Inspection Crack Micro-Gauge. From this Micro-Gauge the voltage drop readings are passed through an input/output channel of the MTS 464 Data Display Unit. The data is then transferred to the IBM PC for recording and future analysis (refer Section 3.4.3) via an RS232 communications port on the Data Display unit.

3.2.1 ACPD Measurements

The AC potential drop method, as discussed in Section 2.3, may be described by considering an alternating current (AC), applied to a metal body, and carried in a thin layer "skin" of the metal surface. This "skin" effect results in the effective section of the specimen actually carrying the current being quite small. This translates into a typical mild structural steel requiring a current of less than one ampere to produce a measurable surface voltage, as compared with an equivalent DC system which would require a current of much higher amperage (50-100 amps).

In an attempt to take advantage of this "skin" effect, for accurate crack depth measurements, it is necessary to investigate how the electric field is distributed over the surface of the test specimen. Figure 3.7 demonstrates the use of the four point contact system as a large metal body having a long surface crack, of depth a , along the weld toe. Two contacts are used to introduce the current at each end of the body while two exploratory contacts spaced

a distance, Δ , apart are used to examine the field in various regions. The accuracy of this crack depth measurement depends upon the ability of the Unit Inspection Crack Micro-Gauge to measure the true voltage drop between the probe pair. The Crack Micro-Gauge is the first instrument designed to operate on this basis. Most of the early applications (DOVER 1981) have been in situations where the cracks were surface breaking, semi-elliptical, fatigue induced, with low aspect ratios (i.e., $a/c < 0.1$). For this type of crack the potential field can be easily arranged so that equation (2.7) applies.

If we consider again the physical arrangement of contacts and streamlines (Figure 3.7), ideally the current connections should be placed across the crack so that the current flow is perpendicular to the plane of the crack. If measurements are taken in the uniform field region ABCD then the crack depth prediction will be accurate. Outside this region the applicability, and hence the accuracy of equation 2.7 is more suspect to question. The AC field associated with a plate T-welded specimen may be described by Figure 3.8. The characteristics of this field description are discussed in Section 3.4.2.

In the tests described herein each T-welded specimen has nineteen probe pairs, straddling the crack measuring V_1 , evenly spaced along the weld toe. Hence, probe pairs, not spanning the crack measuring V_0 , were located at evenly spaced intervals directly behind the nineteen probe pairs in a direction away from the weld toe. The probe pair spacing, Δ , is maintained by a jig set to 10 mm, for all probe pairs. The crack growth measurements were

interpreted as depth increments using the bottom of the undercut as an initial reference point as shown in Figure 3.9.

3.3 MATERIALS AND WELDING SPECIFICATIONS

The chemical composition and mechanical properties of the steel plates used in the fabrication of the T specimens tested are shown in Table 3.1. The plates, manufactured to Lloyd's LT60 specification, were made from the same heat and are normalized.

The geometry and dimensions of the T-welded specimens are shown in Figure 1.2. The full penetrating manual welds were performed in the vertical up position, using E7018 electrodes of 3.2 mm diameter with an average heat input of 1.3 kJ/mm/min. The specimens were preheated to room temperature and exposed to an interpass heat of 230°C. No restraint was applied during the welding process. The undercut was performed on one side only during the final pass. The welding was performed by AMCA International, Kanata and a typical welding specification is shown in Figure A1.

The depth and severity of the undercuts increases from class "A" to class "D". Seven specimens were tested, four at a stress range at the weld toe of 200 MPa and three at 150 MPa. The coding system used to identify the specimens is shown in Figure 3.10. The class of the undercuts relates to a range of depths, as shown in the figure. Class "A" relates to an average undercut depth of 0.3 mm, class "B" to 0.65 mm, class "C" to 0.90 mm and class "D" to 1.55 mm deep.

3.4 TEST PROCEDURE

The procedure carried out in the testing of plate T-welded specimens, subjected to three-point bending, may be categorized into three stages:

1. preparation of T-specimens for fatigue tests
2. crack growth monitoring
3. analysis of crack growth data.

These three stages are described in the following three sections.

3.4.1 Preparation of Specimens for Fatigue Testing

The first step in the preparation of T-welded specimens for fatigue testing is to determine the shape of the weld undercut. For the type 1 undercut PETERSHAGEN (1983) suggests silicon rubber offprints of the weld profile. This technique allows for the offprint to be cut into sections allowing for a detailed analysis of the undercut geometry (refer Figure 2.9) along the weld toe. Once the silicon offprint is divided into sections coincident with the nineteen ACPD probe pairs (refer Section 3.2.1), measurements of undercut depth and root radius are recorded. Additionally, each test specimen is ground on the opposite weld toe to ensure that cracking takes place on the instrumented weld toe.

The ACPD probe pairs (19 across the weld undercut and 3 not across the weld undercut) are then spot welded along the weld profile (refer Section

3.2.1). As the Unit Inspection Crack Micro-Gauge measures voltage drop values of millivolt amplitude, the wiring used to connect the probe pairs to the Keithley scanner is heavily shielded to reduce noise in the ACPD measurements.

Strain gauges are applied to each specimen (Figure 3.11) to ensure that the loading is axial and applied symmetrically to the specimen. Any uneven bending loads can be removed by adjustment of the support edges.

3.4.2 Crack Growth Monitoring

The eight T-specimens tested are loaded in three-point bending with a maximum bending stress range at the weld toe of either 200 MPa or 150 MPa. The stress ratio ($\sigma_{\max}/\sigma_{\min}$) is maintained at 0.05 for all tests. The loading is applied sinusoidally, at constant amplitude, with a frequency of 10 Hz. These loading conditions are maintained by the MTS Control Unit (refer Section 3.1).

The crack growth is monitored using the ACPD method (refer Sections 2.3 and 3.2.1). Crack depth measurements are usually taken every ten thousand cycles while the T-specimen is loaded statically at half of the maximum stress. Crack depth measurements are recorded more frequently as the crack depth approaches the half thickness of the plate (13.0 mm).

Beachmarks (Figure 3.12) are formed when the crack depth is approximately 1.5 mm, 5.0 mm, 9.0 mm, 11.0 mm, and 13.0 mm deep. The first beachmark, at 1.5 mm deep, is formed by applying ink to the crack opening along the weld

profile. This ink stain indicates the number of cracks initiated and the aspect ratio (a/c ; refer Section 2.2) of these initial cracks. All subsequent beachmarks are formed by reducing the maximum stress by fifty per cent and doubling the frequency, for a period of time, long enough to allow for a small crack extension (say 0.1 mm). It is important to note that the number of cycles required to form the beachmarks is not included in the fatigue life of the T-specimen.

It was found through experimentation that the DOVER (1981) one-dimensional solution for crack depths (equation 2.7) is not accurate in determining actual crack depths (refer Section 4.2), however, a revised form of equation 2.7 was found to be accurate in determining changes in crack depth. The revised Dover equation merely uses the initial depth of the undercut as the zero or starting point of all changes in crack depth as:

$$\Delta a = f \left[\left(\frac{V_1}{V_0} \right)_a - \left(\frac{V_1}{V_0} \right)_0 \right] \quad (3.1)$$

where $(V_1/V_0)_a$ corresponds to ACPD measurements at a crack depth, a , and $(V_1/V_0)_0$ corresponds to the initial ACPD measurements of the weld under-cut alone.

The relationship between Δa , and ACPD measurements is found using a calibration curve as shown in Figure B1. Once the condition of failure (refer Section 3.4.3) has been satisfied the specimen is broken open. Actual values of crack depth are measured, using a hand held micrometer, and plotted against

recorded differences in ACPD measurements, as shown by the figure. These plots are then used for subsequent tests to predict increments in crack depth, from the bottom of the undercut, based on the difference between ACPD measurements taken at a crack depth, a , and the initial ACPD measurements of the weld undercut;

$$\left[\left(\frac{V_1}{V_0} \right)_a - \left(\frac{V_1}{V_0} \right)_0 \right]$$

3.4.3 Analysis of Crack Growth Data

The condition for failure of each tested specimen is defined as the point at which the crack depth reaches half the specimen thickness in depth. The term "endurance life" is used to describe this condition ($a > t/2$; t = plate thickness). Once the specimen reaches its endurance limit it is broken apart and the beachmarks are measured and used as reference points for a linear interpolation of crack growth, using ACPD results as described in Section 3.4.2. Measurements of crack depth a and crack length c are used to analyse crack shape development (refer Section 2.2). Stress intensity factors are evaluated by the computer program described in Section 2.4 and crack growth rates (da/dN) are evaluated using a seven point incremental interpolation technique (ASTM, E647). The results of such analyses are given in Section 4.5.

Table 3.1 - Chemical Composition and
Mechanical Properties

<u>Chemical Composition</u>	
C	0.12
Mn	1.39
Si	0.29
S	0.01
P	0.017
Al	0.027
Ni	0.15
Cr	0.17
Mo	0.01
Cu	0.15
Ti	NONE
V	0.053
Nb	0.041
N	NONE
<u>Mechanical Properties:</u>	
Yield Strength (MPa)	405
UTS (MPa)	513
Elongation (5)	29

FIGURE 3.1 - TEST FACILITY FOR 3-POINT BENDING TESTS AT CARLETON
UNIVERSITY, OTTAWA

MODEL 406.II CONTROLLER

MODEL 436.IIC CONTROL UNIT

FIGURE 3.2 - MTS 406 AND 436 CONTROL UNITS

FIGURE 3.3 - MTS 464 DATA DISPLAY BOARD

FIGURE 3.4 - UNIT INSPECTION CRACK MICRO-GAUGE

FIGURE 3.5 - KEITHLEY MODEL 706 SCANNER

FIGURE 3.6 - FLOW OF DATA FOR ACPD MEAUREMENTS OF CRACK GROWTH

FIGURE 3.7 - IDEAL STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT
 FIGURE 3.8 - ASSUMED STREAMLINE ARRANGEMENT FOR CRACK DEPTH MEASUREMENT ON A T-JOINT SPECIMEN

FIGURE 3.9 - CRACK GROWTH MEASUREMENT FROM BOTTOM OF UNDERCUT

<u>A</u>	<u>C</u>	<u>06</u>	<u>Y</u>
CLASS OF UNDERCUT	SPECIMEN THICKNESS	TEST NUMBER	STRESS RANGE
"A" ~ 0.3 mm deep	C = 26.0 mm		Y - 150 MPa
"B" ~ 0.65 mm deep			Z - 200 MPa
"C" ~ 0.90 mm deep			
"D" ~ 1.55 mm deep			

FIGURE 3.10 - CODING SYSTEM FOR IDENTIFICATION OF UNDERCUT SPECIMENS

FIGURE 3.11 - LOCATION OF STRAIN GAUGES ON TEST SPECIMENS

(All dimensions in mm)

FIGURE 3.12 - TYPICAL BEACHMARKS OF TEST SPECIMEN

CHAPTER 4 - RESULTS AND DISCUSSION

4.0 INTRODUCTION

In the analysis of data obtained from ACPD measurements of crack growth, during three-point bending tests of plate T-welded specimens, consideration is given to crack growth throughout the fatigue life, the correlation of the ACPD measurements with actual crack depth, the development of crack shape (a and c), and comparison of experimental results with computer predicted values. These topics are all presented in this chapter as well as an analysis of stress intensity factor changes (ΔK) as compared to crack growth rates (da/dN) as a consideration for future research.

4.1 CRACK GROWTH CONSIDERATIONS

The starting point in crack growth analysis is to consider undercut geometry along the weld profile. The undercut geometry for the seven T-specimens, for which data is available, is presented in Table 4.1. It should be noted that the depth of the weld undercuts in both class "D" specimens exceeds the many depths of undercuts allowed by the U.K. Department of Energy for 26 mm plates, (1.3 mm SNEDDEN, et. al. June, 1981). The measured fatigue lives of the tested specimens are summarized in Table 4.2 while published values (VOSIKOVSKY, et. al. 1985) are presented in Table 4.2a. The number of cycles

required for the first discernible crack growth (first detected crack) and for the crack growth to reach 0.5 mm, were determined from the fatigue crack growth curves shown in Figures 4.1 and 4.2. The crack depths in the figures are determined from ACPD measurements of the probe pair nearest the deepest crack. The ACPD measurements are converted to crack depths using the calibration curve obtained from beachmark data as described in Section 3.4.2.

It may be observed from the data presented in Table 4.2 that, the percentage of the endurance life required for first detection of crack growth and crack growth to a depth of 0.5 mm generally decreases as the depth of the undercut increases for both stress ranges (150 MPa and 200 MPa). Specimen BC03Z is the only result inconsistent with this trend. This anomaly may be further explained by the data presented in Table 4.1. From here it may be observed that although the depth of the undercut in specimen BC03Z is greater than in specimen AC05Z, the mean undercut radius of specimen BC03Z is significantly larger than that of AC05Z. This larger radius of undercut may explain the prolonged first crack detection in specimen BC03Z. Therefore it may be observed that undercut depth should not be the sole parameter considered for crack initiation. Moreover, it should be noted that, the radius of the undercut (acuity) plays a significant role in crack initiation of weld undercut specimens and therefore has a significant effect on the total life of the welded joint.

It should be noted that, due to the minimal severity of weld undercut, the class "A" specimens are considered geometrically similar, in the weld toe region, to the specimens tested by VOSIKOVSKY, et. al. (1985). It may be observed that the percentage of endurance life required for the crack depth to reach 0.5 mm in the class "A" specimens compares favourably with published results shown in Table 4.2a.

The percentage of life reduction resulting from changes in weld undercut depth and radius is shown in Table 4.3. From these results it may be observed that, a larger percentage reduction in life occurs at the lower stress range (150 MPa) for similar increases in undercut depth and decreases in undercut geometry (i.e. increasing severity of undercut), therefore, stress range should also be considered in evaluating the effects of weld undercutting on the fatigue life of plate T-welded specimens.

In addition to crack growth considerations the results shown in Table 4.2 have been plotted on stress-life curves for comparisons with experimental results obtained by VOSIKOVSKY, et. al. (1985) in Figures 4.3 and 4.4. The number of cycles required to propagate a crack from a depth of 0.5 mm to half the thickness plate 13.0 mm at stress ranges of 150 MPa and 200 MPa are compared with published results (VOSIKOVSKY, et, al. 1985) in Figure 4.3. It is assumed here, based on published results (VOSIKOVSKY, et. al. 1985) that a crack depth of 0.5 mm is the minimum crack depth that can be detected with confidence using the ACPD technique. Therefore, propagation life is measured from a crack depth of 0.5 mm, up to half the plate thickness. It may be

observed analogously to increasing thickness effects (VOSIKOVSKY, et. al. 1985), that the number of cycles required for crack propagation decreases as the severity of the undercut increases (i.e. increasing depth or decreasing radius).

The endurance lives obtained from the undercut specimens tested have also been compared to those values obtained by VOSIKOVSKY, et. al. (1985) in Figure 4.4. Again, it may be observed that the endurance life of the undercut specimens decreases as the severity of the undercut increases (Figure 4.4).

Based on the observations presented in this section, it may be stated that, the severity of the weld undercut affects both crack initiation and crack propagation. It is postulated that, the affect on crack initiation is based on an increased stress concentration introduced at the weld toe by the increasing severity of the weld undercut (TSAI and TSAI 1984). Additionally it is postulated that, the weld undercut does not act as an initial crack as a crack initiation period exists (refer Section 4.4), however, once the cracks have been initiated the depth of the undercut is now included in the depth of the crack, hence reducing the propagation life.

4.2 CORRELATION OF CRACK DEPTH DATA

Another interesting point to consider is the comparison of actual crack depths measured from beachmark data with crack depth predictions based on Dover's equation (2.7) for ACPD measurements. Such comparisons are presented for those specimens with beachmarks clear enough to record values of

crack depth along the entire width of the specimen (i.e. all specimens except ACO6Y).

Tables 4.4 to 4.37 present actual crack depths measured from the beachmarks using a micrometer, compared with crack depth predictions using the Dover equation (2.7). Examination of the results indicates that the Dover equation is inaccurate in predicting actual crack depths. This may be due to the fact that the assumed geometry of the field induced in the T-specimen, as shown in Figure 3.8, is more varied than that of the flat plate (Figure 3.7) from which the Dover equation was derived. The right angled T-section and the 45° weld profile may cause a disturbance in the AC current flow through the surface of the test specimen so as to affect the voltage drop recorded by the Unit Inspection Crack Micro-Gauge. The Dover equation also requires an accurate value of the probe pair spacing, Δ (Figure 3.7). Despite the fact that the probe pairs are spot welded using a jig to control the spacing (refer 3.2.1), small errors in the probe spacing may still occur, however it is estimated in this work these errors are of a magnitude no greater than one per cent.

A comparison of Dover equation predictions of crack depth with actual measured beachmark data is plotted in Figure 4.5. This figure is typical of the tabulated results and demonstrates that, the Dover equation generally underpredicts actual values of crack depth, but the accuracy of this equation increases with increasing crack depth. However, it should be noted that the Dover equation does quite accurately follow the shape of the actual beachmark.

In light of the presented data it may be observed that the Dover equation, when applied to T-welded specimens, is useful in predicting general crack shape. However, it is inaccurate in predicting actual crack depths, particularly for small cracks (i.e. less than 5 mm). Regardless of the reason for the inaccuracy, be it due to disturbances in the potential field or variations in the probe spacing, it is noted that, the use of the ACPD values, as suggested by the Dover equation (2.7), is unsuitable for direct applications to undercut T-welded specimens. An alternative use of the ACPD values, based on calibration curves using beachmark measurements, as described in Section 3.4.2, is found more appropriate for application to undercut T-welded specimens for predicting changes in crack depth from the initial depth of the weld undercut.

4.3 CRACK SHAPE DEVELOPMENT

In conjunction with the consideration of crack growth, as applied to various severities of weld undercuts, attention is given to the development of crack shape during the fatigue life. Examination of the actual crack profile, indicated by the beachmarks, shows that the number of randomly distributed cracks initiated along the length of the weld toe depends on the stress range and the severity of the weld undercut (refer Table 4.38). The results demonstrate that, at the higher stress range (200 MPa) an increase in the severity of the weld undercut is associated with a decrease in the number of cracks initiated, as opposed to the situation at the lower stress range (150 MPa)

whereas, an increase in the severity of the weld undercut is associated with an increase in the number of cracks initiated. However, the number of cracks initiated, for all specimens, increases as the stress range increases.

It may be observed that an increase in stress range causes more cracks to be initiated due to added stress at the weld toe. However, considering the higher stress range only, an increase in the severity of the weld undercut causes the cracks to coalesce at an earlier stage due to an increase in the rate of crack growth. It is postulated that, at the lower stress range an increase in the severity of the weld undercut predominates an increase in the rate of crack growth to allow for more cracks to be initiated.

In order to characterize the variation of crack shape development as a function of stress range, the aspect ratios of all cracks are plotted as a function of crack depth (Figure 4.6). From this figure it is difficult to discern the effects of weld undercutting on the crack shape development because of the large scatter in the results. The purpose of presenting this figure is merely to demonstrate the exponential form of the relationship between aspect ratio, a/c , and crack depth, a , as given by equation 2.6 (VOSIKOVSKY, et. al. 1985) in Section 2.2:

$$a/c = e^{-ka}.$$

The shape factor exponential term " k " in the equation above is obtained by least square regressions of $\ln a/c$ versus $\ln a$ plots as mentioned

in Section 2.2. For the purposes of using life prediction computer programs (refer Section 2.2 and 4.4), consideration is given to the basis of evaluating "k" in relation to crack depth values. Five sets of values for "k" are evaluated and presented in Tables 4.39 and 4.40. Table 4.39 evaluates "k" based on values of crack depth, a, as measured from the base of the undercut, whereas, Table 4.40 evaluates "k" based on the value of crack depth, a, plus the depth of the undercut. From the comparisons of mean values of "k" with values used by VOSIKOVSKY, et. al. (1985), it would appear that the values of "k" evaluated based on crack depth alone are more consistent with published results than values of "k" evaluated based on crack depth plus the depth of the undercut.

Based on the above observations it appears that the depth of the weld undercut should not be included in the initial crack size when predicting propagation life by crack growth modelling computer programs (refer Section 4.4).

It may be observed (from both Table 4.39 and 4.40) that, consistent with published results (VOSIKOVSKY, et. al. 1985), the value of the shape factor exponential term "k" increases as the stress range increases. Additionally, the value of "k" increases as the severity of the undercut increases for all specimens.

4.4. COMPARISON OF DATA WITH LIFE PREDICTION COMPUTER PROGRAMS

For the purposes of predicting crack growth in weld undercut specimens, the life prediction computer program described in Section 2.4, is used.

The computer program is implemented using the growth law based on Paris law with two regions. The straight fronted crack growth (2-D) calculations of stress intensity factors use the 2-D equations of BELL and KIRKHOPE (1984), while the multiple crack model uses the 3-D equations of BELL and KIRKHOPE (1984). The prescribed crack shape development option is used. The value of shape factor exponential term "k" is selected based on results from VOSIKOVSKY, et. al. (1985) (i.e. $k = 0.58$ for $\Delta\sigma = 200$ MPa and $k = 0.27$ for $\Delta\sigma = 150$ MPa). The option to change from 3-D to 2-D crack growth is also implemented with changeover occurring at an aspect ratio, a/c , of 0.2. The initial crack depth is varied, for different classes of weld undercut, to determine the most suitable value for accurate life prediction by the computer model. For the class "A" undercut specimens, three initial crack depths are studied:

- (i) 0.5 mm, based on observations by VOSIKOVSKY, et. al. (1985)
- (ii) depth of the undercut alone, and
- (iii) depth of the undercut plus 0.5 mm.

For the remaining classes of undercut (i.e. B, C and D) two initial crack depths are studied:

- (i) depth of undercut, and
- (ii) depth of the undercut plus 0.5 mm (refer Table 4.41).

The initial crack length, c , is selected to give an initial aspect ratio of 1.0 (i.e. $a = c$). The values of C and m , for the Paris law equation (1.1), are selected based on the criterion for low stress ratio, R , (i.e., $C = 3.26 \times 10^{-12}$, $m = 3.27$), as given in Section 2.1.

The results of the life prediction computer program for the single crack and multiple crack cases are presented in Table 4.41 and compared with experimental results in Figures 4.7 to 4.13.

It may be observed that, the most suitable model for predicting crack growth, for T-weld undercut specimens, is the multiple crack model using an initial crack depth equal to the depth of the undercut (i.e. mean value of depth across the weld profile). It should be noted that the life prediction computer program considers only crack propagation and does not allow any time for crack initiation. Therefore, it is postulated (as in Section 4.2), based on comparisons with life prediction computer results, that, the weld undercut does not act as an initial crack at the weld toe, but rather, the weld undercut acts to increase the probability of crack initiation depending on the severity of the undercut and the amount of stress applied (refer Sections 4.2 and 4.3).

4.5 CONSIDERATIONS FOR FUTURE RESEARCH

Changes in the stress intensity factors (ΔK) during crack growth are plotted against crack growth rates (da/dN) for all specimens, in Figures 4.14 to 4.20.

The stress intensity factors are calculated by the same equations used by the life prediction computer programs (refer Section 4.4). The crack growth rates are calculated using the ASTM E647 seven point incremental interpolation technique as mentioned in Section 3.4.2.

It may be observed from these figures that a "jump" in data predominantly occurs when the stress intensity factor equation changes from 3-D to 2-D calculations. This discontinuity should be investigated for future applications.

The data presented here is insufficient and therefore, inconclusive for determining any relationship between crack growth rates and delta K for the weld undercut specimens tested. However, the results presented may provide reference information should future research be conducted relating to this topic.

Table 4.1 - Undercut Geometry of Tested Specimens

Specimen	Mean Depth of undercut a (mm)	Minimum undercut radius r min. (mm)	Maximum undercut radius r max. (mm)	Mean undercut radius r mean (mm)	Mean weld angle θ mean (degrees)
AC05Z	0.280	0.635	1.27	0.905	45.0
BC03Z	0.546	0.476	1.27	1.020	45.3
CC08Z	0.895	0.556	1.27	0.861	45.0
DC04Z	1.524	0.318	1.03	0.579	44.7
AC06Y	0.332	0.635	1.27	1.010	44.0
BC07Y	0.684	0.476	1.27	0.973	45.0
DC10Y	1.603	0.318	0.794	0.523	45.3

Table 4.2 - Measured Endurance and Crack Initiation Lives

Specimen	Stress Range (MPa)	Endurance $a=t/2$ (kC)	First Detected Crack (kC)	% End	a=0.5 mm (kC)	% End	No. of cycles for propagation (kC)
AC05Z	200	290.	55	19.0	95	32.8	195.
BC03Z	200	248.	60	24.2	90	36.3	158.
CC08Z	200	202.5	15	7.4	45	22.2	157.5
DC04Z	200	127.5	5	3.9	20	15.7	107.5
AC06Y	150	1830.	530	29.0	630	34.4	1200.
BC07Y	150	730.	150	17.8	180	24.7	550.
DC10Y	150	331.	5	1.5	35	10.6	296.

Table 4.2a - Measured Crack Initiation Published Results
(VOSIKOVSKY, et. al. 1985)

Specimen Thickness (mm)	Stress Range (MPa)	Endurance $a_f = t/2$ (kC)	a=0.5 mm		No. of cycles for propagation (kC)
			(kC)	% End	
26.0	200	336	88	26.2	248
26.0	150	1125	390	34.7	735

Table 4.3 - Percentage Reduction in Endurance Life Due
to Undercut Severity

Stress, Range (MPa)	Mean Depth of Undercut (mm)	Mean Undercut Radius (mm)	% Life Reduction
200	0.280	0.905	-
200	0.546	1.020	14.48
200	0.895	0.861	30.17
200	1.524	0.579	56.03
150	0.332	1.010	-
150	0.684	0.973	60.10
150	1.603	0.523	81.91

Table 4.4 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (145.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	1.00	0.395	60.5
2	1.00	0.530	47.0
3	1.20	0.485	59.6
4	2.00	0.450	77.5
6	0.00	0.235	100.0
7	0.00	0.280	100.0
8	0.00	0.305	100.0
9	1.00	0.410	52.0
10	1.00	0.385	61.5
11	1.20	0.600	50.0
13	2.00	0.815	59.3
14	2.00	0.880	56.0
15	1.00	0.770	23.0
16	1.50	0.430	71.3
17	0.00	0.000	0.0
19	1.00	0.000	100.0
20	0.00	0.120	100.0

Table 4.5 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (245.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	2.50	1.160	53.6
2	3.00	1.305	56.5
3	3.80	1.300	65.8
4	4.00	1.515	62.1
6	2.00	1.385	30.8
7	2.50	1.300	48.0
8	3.50	0.700	80.0
9	4.50	1.910	57.6
10	5.00	1.970	60.6
11	5.50	2.180	60.4
13	6.00	2.540	57.7
14	6.10	3.180	47.9
15	6.50	3.230	50.7
16	5.00	2.820	43.6
17	4.20	2.480	41.0
19	3.00	1.895	36.8
20	1.50	1.420	5.3

Table 4.6 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (275.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	5.00	2.450	51.0
2	6.00	2.635	56.1
3	7.00	2.950	57.9
4	7.00	3.465	50.5
6	6.50	3.545	45.5
7	6.10	2.960	51.5
8	7.90	No Value	-
9	9.00	3.065	65.9
10	9.10	No Value	-
11	9.90	3.705	62.6
13	9.90	4.735	52.2
14	9.90	5.610	43.3
15	9.90	5.355	45.9
16	8.60	4.545	47.2
17	7.00	3.985	43.1
19	5.80	3.100	46.6
20	4.00	2.450	38.8

Table 4.7 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (290.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	8.50	6.940	18.4
2	9.70	6.595	32.0
3	10.30	6.835	33.6
4	11.00	7.510	31.7
6	10.80	6.880	36.3
7	11.00	5.485	50.1
8	11.60	No Value	-
9	12.20	6.175	49.4
10	12.50	No Value	-
11	13.00	7.075	45.6
13	12.50	8.095	35.2
14	12.50	8.645	30.8
15	12.50	8.333	33.3
16	11.50	6.830	40.6
17	10.10	5.895	41.6
19	9.00	4.865	45.9
20	7.80	4.190	46.3

Table 4.8 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (300.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	13.50	11.835	12.3
2	14.00	11.175	20.2
3	14.50	10.755	25.8
4	15.00	10.345	31.0
6	15.00	9.530	36.5
7	15.00	8.690	42.1
8	15.20	6.870	54.8
9	15.50	9.455	39.0
10	15.50	No Value	-
11	16.00	10.245	36.0
13	15.50	11.045	28.7
14	15.50	11.520	25.7
15	15.50	11.400	26.5
16	14.50	9.590	33.9
17	13.80	8.985	34.9
19	13.00	8.333	35.9
20	12.00	8.230	31.4

Table 4.9 - Results from Beachmarks Compared with Dover
Predictions: Specimen AC05Z (305.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	17.00	16.460	3.2
2	17.00	15.570	8.4
3	17.00	14.815	14.8
4	18.00	12.875	12.9
6	18.00	12.480	30.7
7	18.00	No Value	-
8	18.00	No Value	-
9	18.00	11.735	34.8
10	18.00	No Value	-
11	18.00	13.225	26.5
13	18.00	13.880	22.9
14	18.00	14.440	19.8
15	18.00	14.660	18.6
16	17.00	No Value	-
17	16.00	13.160	17.9
19	15.80	No Value	-
20	15.00	13.590	9.4

Table 4.10 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC03Z (130.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.000	0.0
2	1.00	0.330	66.7
3	1.00	0.610	39.0
4	1.50	0.780	48.0
6	1.50	0.785	47.7
7	1.50	0.910	39.3
8	1.50	0.085	24.3
9	0.00	0.000	0.0
10	0.00	0.000	0.0
11	1.50	0.725	51.7
13	0.00	0.000	0.0
14	0.00	0.000	0.0
15	1.00	0.000	100.0
16	1.50	0.540	64.0
17	1.50	0.670	55.3
19	1.50	0.590	60.7
20	1.00	0.320	68.0
21	0.00	0.165	100.0
22	0.00	0.105	100.0

Table 4.11 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC03Z (200.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.765	100.0
2	2.10	1.335	36.4
3	3.00	1.950	35.0
4	4.60	2.525	45.1
6	5.00	2.850	43.0
7	5.00	2.835	43.3
8	5.00	1.500	70.0
9	4.80	1.495	68.9
10	5.00	1.285	74.3
11	4.70	2.040	56.6
13	4.80	1.345	72.0
14	5.10	1.440	71.8
15	4.50	1.440	68.0
16	5.00	1.885	62.3
17	4.70	1.985	57.8
19	4.00	1.625	59.4
20	2.00	1.170	41.5
21	0.00	0.695	100.0
22	0.00	0.330	100.0

Table 4.12 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC03Z (215.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	1.170	100.0
2	2.50	1.525	39.0
3	4.20	2.490	40.7
4	6.00	3.160	47.3
6	6.50	3.585	44.8
7	6.50	3.575	45.0
8	6.50	2.430	62.6
9	6.50	2.550	60.8
10	6.50	2.050	68.5
11	6.50	3.185	51.0
13	6.50	2.760	57.5
14	6.20	2.965	52.2
15	6.00	3.160	47.3
16	6.10	2.885	52.7
17	6.00	2.710	54.8
19	5.50	2.215	59.7
20	3.00	2.280	24.0
21	0.00	1.000	100.0
22	0.00	0.565	100.0

Table 4.13 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC03Z (225.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	1.890	100.0
2	4.10	2.435	40.6
3	5.60	3.040	45.7
4	7.10	3.785	46.7
6	8.00	4.285	46.4
7	8.00	4.410	44.9
8	8.00	3.450	56.9
9	8.00	3.250	59.4
10	8.00	3.150	60.6
11	8.00	2.425	69.7
13	8.00	3.555	55.6
14	8.10	4.035	50.2
15	8.10	4.440	45.2
16	7.90	4.510	42.9
17	7.50	4.050	46.0
19	6.30	3.030	51.9
20	3.80	2.280	40.0
21	0.00	1.515	100.0
22	0.00	0.970	100.0

Table 4.14 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC03Z (257.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
2	12.50	9.110	27.1
3	13.00	9.615	26.0
4	14.10	10.080	28.5
6	15.00	10.190	32.1
7	15.00	9.985	33.4
8	15.10	11.145	26.2
9	15.10	11.760	22.1
10	15.20	12.095	20.4
11	15.50	12.310	20.6
13	15.50	11.955	22.9
14	15.50	11.820	23.7
15	15.50	11.620	25.0
16	15.00	9.045	39.7
17	14.00	8.675	38.0
19	14.00	7.930	43.4

Table 4.15 - Results from Beachmarks Compared with Dover
Predictions: Specimen CC08Z (83.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.000	0.0
2	0.00	0.000	0.0
3	0.00	0.000	0.0
4	0.00	0.000	0.0
6	0.00	0.070	100.0
7	1.00	0.120	88.0
8	2.00	0.450	77.5
9	1.00	0.405	59.5
10	1.50	0.430	71.3
11	1.50	0.635	57.7
13	2.00	0.690	65.5
14	1.50	0.815	45.7
15	1.00	0.840	16.0
16	2.00	0.915	54.3
17	2.00	0.780	61.0
19	1.50	0.610	59.3
20	1.00	0.420	58.0
21	1.75	0.360	79.4
22	0.00	0.200	100.0

Table 4.16 - Results from Beachmarks Compared with Dover
Predictions: Specimen CC08Z (165.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.000	0.0
2	0.00	0.000	0.0
3	0.00	0.000	0.0
4	3.00	0.200	93.3
6	1.50	0.585	61.0
7	3.50	0.895	74.4
8	4.00	1.785	55.4
9	4.00	2.170	45.8
10	5.00	2.290	54.2
11	5.50	2.490	54.7
13	5.50	2.605	52.6
14	6.00	3.040	49.3
15	6.00	2.935	51.1
16	6.00	3.220	46.3
17	6.00	3.150	47.5
19	5.80	2.455	57.7
20	4.60	2.100	54.3
21	4.00	1.645	58.9
22	2.00	1.305	34.8

Table 4.17 - Results from Beachmarks Compared with Dover
Predictions: Specimen CC08Z (190.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.000	0.0
2	0.00	0.000	0.0
3	2.00	0.570	71.5
4	4.50	1.110	75.3
6	3.00	1.555	48.2
7	6.00	1.870	68.8
8	7.00	3.090	55.9
9	7.80	3.740	52.1
10	8.10	3.695	54.4
11	8.60	3.815	55.6
13	8.60	3.965	53.9
14	9.00	4.535	49.6
15	9.50	4.365	54.1
16	9.80	5.150	47.4
17	9.80	5.260	46.3
19	8.50	4.755	44.1
20	8.00	4.265	46.7
21	7.50	3.730	50.3
22	5.50	3.200	41.8

Table 4.18 - Results from Beachmarks Compared with Dover
Predictions: Specimen CC08Z (200.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.005	100.0
2	0.00	0.610	100.0
3	3.00	1.175	60.8
4	5.20	1.910	63.3
6	6.00	2.430	59.5
7	8.00	2.860	64.3
8	9.00	4.130	54.1
9	10.00	4.750	52.5
10	10.00	4.790	52.1
11	10.70	4.950	53.7
13	11.00	5.115	53.5
14	11.10	5.695	48.7
15	11.50	5.520	52.0
16	11.90	6.385	46.3
17	11.90	6.580	44.7
19	11.80	6.230	47.2
20	10.50	6.000	42.9
21	10.00	5.795	42.1
22	8.00	5.120	36.0

Table 4.19 - Results from Beachmarks Compared with Dover
Predictions: Specimen CC08Z (207.5 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.590	100.0
2	0.00	1.300	100.0
3	4.50	2.045	54.6
4	7.00	2.835	59.5
6	8.50	3.480	47.2
7	9.50	3.895	59.0
8	10.50	4.820	54.1
9	11.50	5.540	51.8
10	11.80	5.655	52.1
11	12.40	5.905	52.4
13	12.80	5.395	57.9
14	13.50	7.640	43.4
15	13.10	8.333	36.4
16	13.90	9.260	33.4
17	13.90	9.435	32.1
19	13.50	9.510	29.6
20	12.50	9.790	21.7
21	12.50	9.970	20.2
22	11.20	9.825	12.3

Table 4.20 - Results from Beachmarks Compared with Dover
Predictions: Specimen DCO4Z (50.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	1.00	0.695	30.5
2	1.00	0.960	4.0
3	1.20	0.910	24.2
4	1.00	1.100	9.1
6	1.50	1.220	18.7
7	1.00	1.080	7.4
8	1.50	0.960	36.0
9	1.50	1.105	26.3
10	1.00	1.040	3.8
11	1.50	1.010	32.7
13	1.50	1.015	32.3
14	1.00	0.885	11.5
15	1.20	0.930	22.5
16	1.50	0.890	40.7
17	1.00	0.615	38.5
19	1.00	0.410	59.0
20	0.25	0.285	12.3
21	0.00	0.180	100.0
22	0.00	0.105	100.0

Table 4.21 - Results from Beachmarks Compared with Dover
Predictions: Specimen DCO4Z (85.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	2.00	1.930	3.5
2	2.50	2.500	0.0
3	3.00	3.120	3.8
4	3.10	3.395	8.7
6	3.50	3.440	1.7
7	3.50	3.370	3.7
8	3.20	2.650	17.2
9	3.50	2.695	23.0
10	3.20	2.655	17.0
11	3.50	2.595	25.9
13	3.00	2.485	17.2
14	2.80	2.185	22.0
15	3.00	2.225	25.8
16	3.00	2.275	9.2
17	2.50	2.000	20.0
19	2.00	1.620	19.0

Table 4.22 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC04Z (105.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	3.50	4.265	24.3
2	4.20	5.070	17.2
3	5.10	5.910	13.7
4	5.60	6.460	13.3
6	6.00	6.700	10.4
7	6.00	6.715	10.6
8	5.80	5.070	12.6
9	6.00	5.160	14.0
10	6.00	5.080	15.3
11	6.00	4.895	18.4
13	5.50	4.555	17.2
14	5.00	4.015	19.7
15	5.00	4.155	16.9
16	5.00	4.450	11.0
17	4.50	4.110	8.7
19	4.00	3.385	15.4

Table 4.23 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC04Z (112.5 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	4.80	5.860	18.1
2	5.50	6.480	15.1
3	6.50	7.520	13.6
4	7.00	8.205	14.7
6	7.50	8.440	11.1
7	7.50	8.495	11.7
8	7.00	6.685	4.5
9	7.50	6.850	8.7
10	7.10	6.915	2.6
11	7.50	6.775	9.7
13	6.80	6.450	5.1
14	6.50	5.970	8.2
15	6.10	5.880	3.6
16	6.00	5.730	4.5
17	5.50	5.280	4.0
19	5.00	4.540	9.2

Table 4.24 - Results from Beachmarks Compared with Dover
Predictions: Specimen DCO4Z (120.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	6.20	7.830	20.1
2	7.00	No Value	-
3	8.00	9.410	15.0
4	8.50	2.020	76.2
6	9.10	10.205	10.8
7	9.10	10.300	11.7
8	8.90	8.385	5.8
9	9.00	8.610	4.3
10	8.90	8.505	4.4
11	9.00	8.470	5.9
13	8.20	7.975	2.7
14	8.00	7.480	6.5
15	7.90	7.385	6.5
16	7.50	7.150	4.7
17	7.00	6.705	4.2
19	6.50	5.845	10.1

Table 4.25 - Results from Beachmarks Compared with Dover
Predictions: Specimen DCO4Z (134.6 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	12.00	15.780	24.0
2	13.50	15.865	14.0
3	15.00	16.215	7.5
4	16.00	16.590	3.6
6	16.50	16.520	0.1
7	17.00	16.315	4.0
8	17.00	No Value	-
9	17.00	13.195	22.4
10	16.50	13.240	19.8
11	16.50	13.025	21.1
13	15.00	12.800	14.7
14	14.70	12.290	16.4
15	14.00	No Value	-
16	13.20	12.650	4.2
17	12.50	11.835	5.3
19	11.00	11.345	3.0

Table 4.26 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (290.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	1.00	0.260	74.0
2	0.00	0.170	100.0
3	0.00	0.185	100.0
4	0.75	0.270	64.0
6	0.00	0.410	100.0
7	2.00	0.580	71.0
8	1.00	0.685	31.5
9	1.50	0.775	48.3
10	1.75	0.930	46.9
11	2.00	0.845	57.8
13	1.75	0.580	66.9
14	1.00	0.305	69.5
15	1.00	0.230	77.0
16	1.20	0.260	78.3
17	1.00	0.285	71.5
19	0.75	0.205	72.7

Table 4.27 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (560.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	No Value	1.095	-
2	0.00	1.020	100.0
3	0.00	1.040	100.0
4	3.00	1.510	49.7
6	4.00	2.390	40.3
7	5.00	2.725	45.5
8	6.00	2.670	55.5
9	6.00	2.475	58.8
10	6.00	2.590	56.8
11	5.80	2.400	58.6
13	5.00	1.885	62.3
14	4.10	1.720	58.0
15	3.20	1.620	49.4
16	4.00	1.930	51.8
17	3.50	1.620	53.7
19	3.00	1.100	63.3

Table 4.28 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (670.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	3.00	2.440	18.7
2	4.00	2.735	31.6
3	4.00	2.910	27.3
4	6.00	3.240	46.0
6	8.00	4.035	49.6
7	8.00	4.465	44.2
8	9.50	4.635	51.2
9	9.50	4.970	47.7
10	9.50	4.800	49.5
11	9.00	4.040	55.1
13	8.80	3.260	63.0
14	9.00	3.300	63.3
15	8.00	3.080	61.5
16	8.00	3.060	61.8
17	7.100	1.920	73.0
19	5.50	1.410	74.4

Table 4.29 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (720.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	7.00	4.315	38.4
2	7.80	4.990	36.0
3	8.50	5.435	36.1
4	9.80	5.815	40.7
6	11.00	6.650	39.5
7	11.00	7.115	35.3
8	12.00	7.310	39.1
9	12.00	7.320	39.0
10	12.00	6.970	41.0
11	11.80	6.090	48.4
13	11.60	5.125	55.8
14	11.60	4.890	57.8
15	11.20	4.405	60.7
16	11.10	4.035	63.6
17	10.50	3.530	66.4
19	8.90	3.265	63.7

2

OF/DE

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table 4.30 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (733.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	8.50	5.390	36.6
2	9.50	6.285	33.8
3	10.00	6.800	32.0
4	11.00	7.060	35.8
6	12.50	7.865	37.1
7	12.50	8.455	32.4
8	13.10	9.105	30.5
9	13.00	9.195	29.3
10	13.00	9.035	30.5
11	12.90	8.440	34.6
13	12.70	7.385	41.9
14	12.70	6.595	48.1
15	12.50	5.650	54.8
16	12.20	4.640	62.0
17	11.80	4.115	65.1
19	10.20	3.810	62.6

Table 4.31 - Results from Beachmarks Compared with Dover
Predictions: Specimen BC07Y (755.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	15.00	17.420	13.9
2	15.10	16.745	9.8
3	15.10	16.320	7.5
4	16.00	15.845	1.0
6	17.00	15.570	8.4
7	17.00	15.360	9.6
8	17.60	No Value	-
9	17.50	15.040	14.1
10	18.00	No Value	-
11	17.00	14.620	14.0
13	17.00	14.150	16.8
14	17.00	13.425	21.0
15	16.80	12.525	25.4
16	16.80	10.995	34.6
17	16.50	11.030	33.2
19	15.80	11.955	24.3

Table 4.32 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (85.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	0.190	100.0
2	0.75	0.360	52.0
3	0.00	0.545	100.0
4	1.00	0.565	43.5
6	1.20	0.645	46.3
7	1.00	0.760	24.0
8	2.00	0.875	56.3
9	2.00	0.790	60.5
10	0.75	0.595	20.7
11	0.75	0.440	41.3
13	1.00	0.410	59.0
14	1.30	0.370	71.5
15	0.60	0.290	51.7
16	0.75	0.145	80.7
17	0.50	0.115	77.0
19	0.00	0.100	100.0
20	0.00	0.040	100.0
21	0.00	0.005	100.0
22	0.00	0.000	100.0

Table 4.33 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (200.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	0.00	1.075	100.0
2	2.00	1.520	24.0
3	2.70	1.890	30.0
4	3.20	1.985	38.0
6	3.50	2.120	39.4
7	3.50	2.265	35.3
8	4.10	2.470	39.8
9	4.00	2.375	40.6
10	3.00	1.980	34.0
11	3.00	1.740	42.0
13	3.00	1.815	39.5
14	3.10	1.695	45.3
15	3.00	2.075	30.8
16	1.50	1.315	12.3
17	1.00	0.975	2.5
19	0.00	0.645	100.0
20	0.00	0.515	100.0
21	0.00	0.265	100.0
22	0.00	0.000	100.0

Table 4.34 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (280.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	3.80	2.520	33.7
2	5.00	3.290	34.2
3	5.50	3.605	34.5
4	6.00	3.720	38.0
6	6.00	4.155	30.8
7	6.50	4.325	33.5
8	7.00	4.020	42.6
9	7.00	3.685	47.4
10	6.80	3.250	52.2
11	6.80	3.025	55.5
13	6.10	3.090	49.3
14	6.20	3.695	40.4
15	6.10	3.900	36.1
16	5.60	2.990	46.6
17	4.00	2.505	37.4
19	3.30	1.935	41.4
20	3.00	1.815	39.5
21	2.50	1.345	46.2
22	1.00	0.665	33.5

Table 4.35 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (305.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	5.70	3.825	32.9
2	7.00	4.710	32.7
3	7.60	5.175	31.9
4	8.00	5.255	34.3
6	8.00	5.670	29.1
7	8.50	5.905	30.5
8	9.00	5.380	40.2
9	9.00	4.820	46.4
10	8.80	4.280	51.4
11	8.80	3.995	54.6
13	8.10	4.015	50.4
14	8.00	4.735	40.8
15	8.00	5.015	37.3
16	7.50	4.105	45.3
17	5.80	3.555	38.7
19	5.00	2.910	41.8
20	4.50	2.740	39.1
21	3.80	2.160	43.2
22	2.00	1.255	37.3

Table 4.36 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (322.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	8.50	6.750	20.6
2	9.50	7.515	20.9
3	10.00	8.085	19.2
4	10.00	7.980	20.2
6	10.00	8.135	18.7
7	11.00	8.185	25.6
8	11.20	7.900	29.5
9	11.00	7.205	34.5
10	10.70	6.570	38.6
11	10.70	5.565	38.6
13	10.20	6.525	36.0
14	10.00	7.090	29.1
15	10.00	7.400	26.0
16	9.80	6.185	36.9
17	8.00	5.800	27.5
19	7.50	5.205	30.6
20	6.80	4.745	30.2
21	5.50	3.720	32.4
22	4.00	2.550	36.3

Table 4.37 - Results from Beachmarks Compared with Dover
Predictions: Specimen DC10Y (343.0 kC)

Channel	Actual Depth From Beachmarks (mm)	Dover Prediction From ACPD Values (mm)	% Difference
1	16.00	17.740	9.8
2	16.00	16.715	4.3
3	16.20	16.160	0.2
4	16.20	15.265	5.8
6	16.20	14.720	9.1
7	16.50	14.515	12.0
8	17.00	15.565	8.4
9	16.50	14.975	9.2
10	16.00	No Value	-
11	16.00	14.410	9.9
13	15.60	14.355	8.0
14	15.20	14.125	7.1
15	15.50	14.060	9.3
16	15.00	No Value	-
17	14.00	10.875	22.3
19	14.00	10.480	25.1
20	13.00	No Value	-
21	12.00	10.130	15.6
22	11.00	9.680	12.0

Table 4.38 - Number of Initiated Cracks in Tested T-Joints.

Weld Undercut (Class)	Stress Range (MPa)	
	150	200
"A"	15	27
"B"	18	25
"C"	No Value	24
"D"	20	22
No Undercut*	10	28

*VOSIKOVSKY, et. al. (1985)

Table 4.39 - Experimental Values of Shape Factor Exponential Term "k" for Tested Specimens (Based on Crack Depth, a)

Specimen	Stress Range (MPa)	Experimental k	VOSIKOVSKY, et. al. (1985) k	% Difference
AC05Z	200	0.352	-	-
BC03Z	200	0.454	-	-
CC08Z	200	0.662	-	-
DC04Z	200	0.773	-	-
Mean Value	200	0.550	0.584	5.8
AC06Y	150	0.228	-	-
BC03Y	150	0.268	-	-
DC10Y	150	0.470	-	-
Mean Value	150	0.332	0.369	16.5

Table 4.40 - Experimental Values of Shape Factor Exponential Term "k" for Tested Specimens (Based on Crack Depth, a + Mean Undercut Depth)

Specimen	Stress Range (MPa)	Experimental k	VOSIKOVSKY, et. al. (1985) k	% Difference
AC05Z	200	0.309	-	-
BC03Z	200	0.394	-	-
CC08Z	200	0.435	-	-
DC04Z	200	0.470	-	-
Mean Value	200	0.402	0.584	31.2
AC06Y	150	0.217	-	-
BC03Z	150	0.242	-	-
DC10Y	150	0.338	-	-
Mean Value	150	0.265	0.269	1.5

Table 4.41 - Comparison of Experimental Propagation Life
with Predictions by Computer Program for Two
Crack Growth Models

Specimen	Stress Range (MPa)	Initial Crack Size for Computer (mm)	Experimental Propagation Life (kC)	Predicted Propagation Life	
				Multiple Crack Model	Single Crack Model
AC05Z	200	0.500	195	0.92	3.29
		0.780*		0.82	3.18
		0.280+		1.13	3.39
BC03Z	200	1.046*	158	0.75	3.80
		0.546+		1.15	4.05
CC08Z	200	1.395*	158	0.63	3.67
		0.895+		0.89	3.80
DC04Z	200	2.024*	107.5	0.56	5.03
		1.524+		0.93	5.21

AC06Y	150	0.500	1200	0.64	1.27
		0.832*		0.52	1.22
		0.332+		0.70	1.30
BC07Y	150	1.184*	550	0.69	2.55
		0.684+		1.23	2.69
DC10Y	150	2.103*	296	1.15	4.60
		1.603+		1.42	4.53

* Denotes depth of undercut + 0.5 mm

+ Denotes depth of undercut alone

EFFECTS OF WELD UNDERCUTTING ON FATIGUE LIFE

FIGURE 4.1 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$ mm, 200 MPa

EFFECTS OF WELD UNDERCUTTING ON FATIGUE LIFE

FIGURE 4.2 - FATIGUE CRACK GROWTH: "T" SPECIMEN t=26.0 mm, 150 MPa

FIGURE 4.3 - STRESS-LIFE CURVES FOR CRACK PROPAGATION

FIGURE 4.4 - STRESS-LIFE CURVES FOR ENDURANCE LIFE

FIGURE 4.5.- COMPARISON OF ACTUAL CRACK DEPTH TO ACPD MEASUREMENTS
 FOR SPECIMEN DC10Y

CRACK SHAPE DEVELOPMENT : WELD UNDERCUT SPECIMENS

FIGURE 4.6 - ASPECT RATIO a/c VERSUS CRACK DEPTH a

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

- 4
SINGLE CRACK MODEL	MULTIPLE CRACK MODEL
1. a_i - UNDERCUT	4. a_i - UNDERCUT
2. a_i - 0.5 mm	5. a_i - 0.5 mm
3. a_i - 0.5 mm + UND	6. a_i - 0.5 mm + UND

FIGURE 4.7 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=25.0$, 200 MPa.

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

SINGLE CRACK MODEL MULTIPLE CRACK MODEL
 1. a_i - UNDERCUT 3. a_i - UNDERCUT
 2. a_i - 0.5 mm + UND 4. a_i - 0.5 mm + UND.

FIGURE 4.8 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa,

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

SINGLE CRACK MODEL MULTIPLE CRACK MODEL
 1. a_1 - UNDERCUT 3. a_1 - UNDERCUT
 2. a_1 - 0.5 mm + UND 4. a_1 - 0.5 mm + UND.

FIGURE 4.9 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa,

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

- SINGLE CRACK MODEL MULTIPLE CRACK MODEL
1. a_i - UNDERCUT 3. a_i - UNDERCUT
 2. a_i - 0.5 mm + UND 4. a_i - 0.5 mm + UND.

FIGURE 4.10 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 200 MPa.

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

SINGLE CRACK MODEL MULTIPLE CRACK MODEL

1. a_1 - UNDERCUT 4. a_1 - UNDERCUT

2. a_1 - 0.5 mm 5. a_1 - 0.5 mm

3. a_1 - 0.5 mm + UND 6. a_1 - 0.5 mm + UND

FIGURE 4.11 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa,

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

FIGURE 4.12 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa,

FATIGUE CRACK GROWTH: EXPT'L, SINGLE & MULTIPLE CRACK MODELS

SINGLE CRACK MODEL MULTIPLE CRACK MODEL
 1. a_i - UNDERCUT 3. a_i - UNDERCUT
 2. a_i - 0.5 mm + UND 4. a_i - 0.5 mm + UND.

No. of Cycles (Kcycles)

FIGURE 4.13 - FATIGUE CRACK GROWTH: "T" SPECIMEN $t=26.0$, 150 MPa,

FIGURE 4.14 - D_a/D_n VERSUS ΔK FOR SPECIMEN BCO32

FIGURE 4.15 - Da/Dn VERSUS ΔK FOR SPECIMEN DCO4Z

FIGURE 4.16 - Da/Dn VERSUS ΔK FOR SPECIMEN AC05Z

FIGURE 4.17 - D_a/D_n VERSUS DELTA K FOR SPECIMEN ACO6Y

FIGURE 4.13 - Da/Dn VERSUS ΔK FOR SPECIMEN BC07Y

FIGURE 4.19 - D_a/D_n VERSUS ΔK FOR SPECIMEN CC08Z

FIGURE 4.20 - D_a/D_n VERSUS DELTA K FOR SPECIMEN DC10Y

CHAPTER 5 - CONCLUSIONS OF WORK

Based on the information presented by this thesis, it is concluded that:

1. The experimental fatigue test rig is serviceable and sufficient for further testing purposes of plate T-welded joints subjected to three-point bending loads.
2. Also the data acquisition system used in fatigue life/crack growth monitoring is satisfactory for similar applications.
3. The ACPD crack measurement system is accurate in predicting changes in crack growth, which requires the use of a revised form of the Dover equation.
4. The radius and depth of weld undercut are both significant to life reduction.
5. The reduction in crack initiation period, due to weld undercuts, increases as the severity of the undercut increases.
6. The reduction in crack propagation life, due to weld undercuts, increases as the severity of the weld undercut increases.

7. The value of the applied stress range affects the number of cracks initiated. As the stress range increases the number of cracks initiated increases.
8. The value of the applied stress is associated with the affect of increasing weld severity on the number of cracks initiated: for the low stress range (150 MPa) the number of cracks initiated increases as the weld undercut severity increases; the high stress range (200 MPa) the number of cracks initiated decreases as the weld undercut severity increases, this is due to a balance between the predominance of increasing weld undercut severity and increasing crack growth rate.
9. The percentage of life reduction due to weld undercutting ranges from 14.48% to 81.91%.
10. The allowable depth of weld undercut, stated by AWS of 0.25 mm should be investigated further.
11. The comparison of computer predicted results with experimental results show that, the most accurate model incorporates the multiple crack model of crack development with an initial crack size equal to the depth of the undercut.

REFERENCES

- American Petroleum Institute, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms"; A.P.I. RP24, Twelfth Edition, 1981.
- R. Bell and J. Kirkhope, "The Evaluation of 3-Dimensional Stress Intensity Factors Using Finite Element Methods"; Phase II Report, D.S.S. Contract 85V80-00010, Carleton University, Ottawa, March 1983.
- Op. cit.; Phase III Report, December 1983.
- R. Bell and J. Kirkhope, "Determination of Stress Intensity Factors for Weld Toe Defects"; Final Report, D.S.S. Contract OSV82-00233, Carleton University, Ottawa, April 1984.
- R. Bell, "Determination of Stress Intensity Factors for Weld Toe Defects; Phase II Final Report, D.S.S. Contract OST84-00125, Carleton University, Ottawa, October 1985.
- S. Berge and K. Engesvik, "Effect of Plate Thickness in Fatigue of Transverse Fillet Welds"; International Conference on Steel in Marine Structures, Paper 2.5, Paris, October 1981.
- S. Berge, "Effect of Plate Thickness in Fatigue Design of Welded Structures"; Offshore Technology Conference, Paper 4829, Houston, May 1984.
- A. Bigonnet, H.P. Lieurade and L. Picouet, "Improvement of the Fatigue Life for Offshore Welded Connections"; Institut de Recherches de la Sidnergie Franaise (IRSID), France, 1984.
- G.S. Booth, "Constant Amplitude Fatigue Tests on Welded Steel Joints Performed in Air"; European Offshore Steels Research Seminar, Paper 4, Cambridge U.K., 1978.
- P. Bristoll, "A Review of the Fracture Mechanics Approach to the Problems of Design, Quality Assurance, Maintenance and Repair of Offshore Structures"; European Offshore Steels Research Seminar, Paper 24, 1978.
- T.W. Crooker, "The Role of Fracture Mechanics in Fatigue Design"; 1978.
- Department, of Energy U.K., "Offshore Installations: Guidance on Design and Construction"; HMSO: London, 1978 (Second Impression).
- Det Norske Veritas, "Rules for the Construction and Classification of Mobile Offshore Units"; 1975.

REFERENCES (cont'd.)

- W.D. Dover and S.J. Holdbrook, "Fatigue Crack Growth in Tubular Welded Connections"; Behaviour of Offshore Structures Conference, Paper 40, London, August 1979.
- W.D. Dover, "Fatigue Fracture Mechanics Analysis of Offshore Structures"; International Journal of Fatigue, Vol. 3, No. 2, pp. 52-60, April 1981.
- T.R. Gurney and G.O. Johnston, "A Revised Analysis of the Influence of Toe Defects on the Fatigue Strength of Transverse Non-Load-Carrying Fillet Welds"; Welding Research International 9-3, pp. 43-79, 1979.
- T.R. Gurney, "The Influence of Thickness on the Fatigue Strength of Welded Joints"; BOSS Conference, Paper 41, London, August 1979.
- S.J. Hudak, O.H. Burnside, and K.S. Chan, "Analysis of Corrosion Fatigue Crack Growth in Welded Tubular Joints"; Offshore Technology Conference, Paper 4771, Houston, May 1984.
- G.R. Irwin, "The Crack Extension Force for a Part-Through Crack in a Plate"; Trans. ASME, Journal of Applied Mechanics, Vol. 29, No. 4, 1962.
- J.L. Leeuwen, J. De Back, and G.H.G. Vaessen, "Constant Amplitude Tests on Welded Steel Joints Performed in Air and Sea Water"; Steel in Marine Structures, Paper 2-1, Luxembourg, 1981.
- T.H. Lewinson, "Determination of Stress Intensity Factor Equations for Life Prediction of Welds with Semi-Elliptical Weld Toe Cracks"; Thesis Submitted for Degree of Master of Engineering, Carleton University, Ottawa, August 1984.
- S.J. Maddox, "An Analysis of Fatigue Cracks in Fillet Welded Joints", International Journal of Fracture, 11(12), 1975, pp. 221-243.
- C.L. Mullen and J.E. Merwin, "Fatigue Life Improvement Factors Obtained by Weld Reinforcement and Toe Grinding"; Offshore Technology Conference, Paper OTC4240, 1982.
- J.C. Newman and I.S. Raju, "An Empirical Stress Intensity Factor Equation for a Surface Crack"; Engineering Fracture Mechanics, Vol. 15, No. 1-2, pp. 185-192, 1981.
- P.C. Paris, "The Growth of Cracks Due to Variations in Load"; Thesis Submitted for Degree of Ph.D., Lehigh University, 1960.

REFERENCES (cont'd.)

- H. Petershagen, "The Influence of Undercut on the Fatigue Strength of Welds - A Literature Survey"; Institut Fur Schiffbau der Universitat Hamburg, August 1983.
- T.J. Smith and S.J. Hurworth, "The Effect of Geometry Changes upon the Predicted Fatigue Strength of Welded Joints"; Welding Institute Report No. 224, 1984.
- N.W. Snedden, et. al., "Background to Proposed New Fatigue Design Rules for Welded Steel Joints in Offshore Structures"; Department of Energy: U.K., May 1981.
- N.W. Snedden, et. al., "Offshore Installations: Guidance on Design and Construction. Proposed New Fatigue Design Rules for Steel Welded Joints in Offshore Structures"; Department of Energy: U.K., June 1981.
- T. Sotille, "Design of Fatigue Test Frame"; Paper Submitted for Fourth Year Engineering Project, Carleton University, Ottawa, Ontario, April 1984.
- T.W. Thorpe, P.M. Scott, A. Rance and D. Sylvester, "Corrosion-Fatigue of BS4360:50D Structural Steel in Seawater"; Report AEPE Harwell -R10679, November 1982.
- C.L. Tsai and M.J. Tsai, "Significance of Weld Undercut in Design of Fillet Welded T-Joints"; Welding Journal, Vol. 63, No. 2, pp. 64-70, February 1984.
- O. Vosikovskiy, "Effect of Mechanical and Environmental Variables on Fatigue Crack Growth Rates in Steels"; Canadian Metallurgical Quarterly, Vol. 19, No. 1, pp. 87-97, 1980.
- O. Vosikovskiy, R. Bell, D.J. Burns and U.H. Mohaupt, "Fracture Mechanics Assessment of Fatigue Life of Welded Plate T-Joints, Including Thickness Effect"; Behaviour of Offshore Structures Conference, pp. 453-464, Delft, July 1985.

APPENDIX A

PROJECT NO:
SERIES NO:

2-184-126-099
1080

WELDING DATA AND QC SHEET

POWER SOURCE: Lincoln TM 400/400
WELDING PROCESS: SMAW

WELDING POSITION: 3G

ELECTRODE
IDENTIFICATION NO.: TC

PLATE
IDENTIFICATION NO.: 108D

ELECTRODE TYPE: CLA E7018
ELECTRODE DIAMETER(mm): 3.2

PLATE TYPE: LT 60
PLATE THICKNESS(mm): 25

WELDING PARAMETERS

CURRENT: 125
VOLTAGE: 21
TRAVEL SPEED(mm/min): 206
RUN OUT LENGTH(mm): 230

POLARITY: DC+
PREHEAT: RT °C
INTERPASS HEAT: 230 °C

ADDITIONAL INFORMATION

BACKGOUGE TO SOUND METAL
USE OF RESTRAINTS

YES
YES

NO
NO

STAMP "T" FOR PLATE TOP

QUALITY CONTROL HOLD POINTS

FIT-UP PRIOR TO WELDING
BACKGOUGE CHECK
FINAL INSPECTION

YES
YES
YES

NO
NO
NO

SIGNATURE

JP
JP
JP

JOINT GEOMETRY

LAYER NO.	PASS NO.	ELECTRODE DIAMETER
--------------	-------------	-----------------------

WELDING TECHNICIAN'S SIGNATURE:

WELDING SUPERVISOR'S SIGNATURE:

QC INSPECTOR'S SIGNATURE:

JP
JP
JP

DATE: 12-4-85

DATE: 12-4-85

DATE: 12-4-85

APPENDIX B

FIGURE B1 - CALIBRATION CURVE FOR ACPD CRACK DEPTH MEASUREMENTS

END

08.08.87

FIN