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**DEVELOPMENT OF A CRACK MEASUREMENT
SYSTEM FOR CANDU PRESSURE TUBE BURST TESTING**

by

Reena Sahney, B. Sc.

**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 Aerospace Engineering
Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering
Carleton University**

Ottawa, Ontario

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**"DEVELOPMENT OF A CRACK MEASUREMENT
SYSTEM FOR CANDU PRESSURE TUBE BURST TESTING"**

submitted by Reena Sahney

in partial fulfillment of the requirements for
the degree of Master of Engineering

Thesis Supervisor

Chair, Department of Mechanical & Aerospace Engineering

*Ottawa-Carleton Institute for
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Abstract

A project to develop an automated crack measurement system for CANDU pressure tube burst testing was undertaken. After a survey of three different non-destructive testing techniques (Alternating Current Potential Drop (ACPD), localized Direct Current Potential Drop (DCPD) and Alternating Current Field Measurement (ACFM)), it was determined that the localized Direct Current Potential Drop Technique was the most suitable for this application.

An extensive study was undertaken to understand the behaviour of the localized DCPD method when used to measure flaws in pressure tube material. This consisted of testing artificial flaws (saw cuts) made in a flat plate of zirconium alloy similar to pressure tube material. These results were used to carry out preliminary work towards calibrating the system for this application.

The design of an automated positioning frame was also investigated to meet the specific requirements of Atomic Energy of Canada Limited's Chalk River Laboratories. This design, which is radiation resistant, facilitates the use of remote manipulators since all testing is carried out in test cells built to handle irradiated material.

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List of Symbols

a	Crack Depth
a_c	Critical Crack Depth
at%	Atomic Percent
$2c$	Surface Crack Length
d_i	Inside Diameter
d_o	Outside Diameter
f	Frequency of Alternating Current
K	Stress Intensity Factor
K_C	Fracture Toughness
K_I	Stress Intensity Factor Under Mode I Loading
K_{IC}	Plane Strain Fracture Toughness
K_{IH}	Threshold Stress Intensity
l	Length
P	Pressure
Q	Crack Shape Factor for Stress Intensity Calculation
r_y	Crack Tip Plastic Zone Size
S	Standard Deviation
S_e	Standard Error
t	Thickness
V_C	Voltage Across Crack Face
V_{CI}	Stable Crack Growth Velocity
V_o	(Upstream) Voltage Across Reference Surface, Remote From Flawed Region
V_p	Pick Up or Induced Voltage
V_r	Voltage Across Reference Surface
V_s	(Saddle) Voltage When Probe is Bisected by Crack
V^*	Normalized Potential Drop
wt%	Weight Percent
$\bar{x}$	Mean
α -phase	Phase of Zr-2.5Nb alloy
β -phase	Phase of Zr-2.5Nb alloy
Δ_r	Spacing Between Reference Probe Contacts
Δ_c	Spacing Between Probe Contacts Straddling Crack
σ	Electrical Conductivity
σ_h	Hoop Stress
σ_y	Yield Stress
μ_r	Relative Magnetic Permeability of Material
μ_o	Magnetic Permeability of Free Space (4×10^{-7} H/m)

1 Introduction

1.0 General

Pressure tubes containing fuel and primary coolant in CANDU (CANadian Deuterium Uranium) nuclear reactors have experienced Delayed Hydride Cracking (DHC) which has resulted in several pressure tube failures [1, 2]. In an effort to gain a better understanding of the cracking mechanism involved, and assure the integrity of in-service pressure tubes, Atomic Energy of Canada Limited (AECL) has implemented a pressure tube burst testing program at the Chalk River and Whiteshell Laboratories.

The testing program at Chalk River is part of an extensive program to study DHC. The program involves the growth of DHC induced flaws from a small starter notch machined into previously irradiated pressure tubes. The testing is carried out at temperatures up to 300°C (although the majority of the tests are carried out at 250°C) and a pressure of 10 MPa until the pressure tube fails [3]. Data from the experimental program should lead to methods of prolonging pressure tube life (these are discussed further in Chapter 2), further improving reactor safety, economics, and ensuring an adequate margin of safety for existing components.

To accommodate crack growth data acquisition during burst testing of irradiated pressure tubes, an automated system for crack detection and measurement is required. It was proposed to use an electrical potential drop system. While potential drop techniques are well established for materials such as offshore structural steels, their application to the study of DHC in zirconium alloys has been limited. In light of this, a test program to evaluate two potential drop systems for zirconium - 2.5 wt% niobium alloy (henceforth

referred to as Zr-2.5Nb) pressure tube material was undertaken. The two potential drop systems that were tested for suitability are an alternating current potential drop (ACPD) system and a localized direct current potential drop (DCPD) system. A third system, a non-contacting variation of the ACPD technique, known as the Alternating Current Field Measurement (ACFM) method was also analyzed.

An automated positioning frame and data acquisition system has also been investigated for this application.

1.1 History of the Canadian Nuclear Program

The first milestone in the history of the Canadian nuclear program was the success of the Zero Energy Experimental Pile (ZEEP) when a sustained nuclear reaction was achieved by Dr. L. Kowarski in Chalk River, Ontario on September 5, 1945. The design and construction of the National Research Experimental Reactor (NRX), also in Chalk River, was the next step in the development of nuclear technology for power generation. This was an important stage that would profoundly affect the direction of the Canadian nuclear program. During an experiment on December 12, 1952, an operator error led to an uncontrolled power surge in the NRX reactor. There were no injuries; however, serious damage to the installation had occurred in addition to contamination of the reactor building before the unit was brought under control. The following 14 months of decontamination, redesigning, and repairing of NRX shifted the focus of the Canadian nuclear program towards a safer reactor system—laying the groundwork for one of the safest reactor designs in the world [4].

The first Canadian nuclear power plant, the Nuclear Power Demonstration Plant (NPD), was brought on line in Rolphton, Ontario on June 4, 1962. Although it was a small unit (25 MWe), NPD contributed to Ontario Hydro's power network and served as an international training center for over 25 years. The NPD was important in that it proved the soundness and feasibility of the CANDU reactor concept. NPD further acted as a

training facility and test bed for various design concepts. The performance of the NPD reactor, and the discovery of large uranium deposits in the Canadian shield, made nuclear power more attractive to Canadians over time. This has led to the 22 commercial nuclear power reactors operating in Canada today. A brief summary of the Canadian Nuclear Program appears in Appendix A (Table 1).

The CANDU system has evolved since the initial NPD design. Improvements have been made in numerous areas including fuel design, emergency shutdown systems, and fuel channel design. Specifically, there have been major developments in CANDU pressure tube design which are pertinent to the work presented in this thesis—these are discussed further in Chapter 2. It is this continuous refinement which has led to internationally renowned CANDU safety and reliability. In fact, the Point Lepreau Generating Station in New Brunswick ranked first (worldwide) for performance in the one year time period ending in September 1991—sustaining its number one ranking for lifetime performance [5]. Also, at the end of March 1990, four of the top five reactors worldwide, in terms of performance, were CANDU units [6].

1.2 The Necessity for Non-Destructive Testing Techniques

With the advent of fracture mechanics analysis in the last twenty years, the concept of crack tolerant components has become feasible and an integral part of the design and servicing process for complex structures. Acknowledging the presence of cracks in mechanical components naturally leads to the need for analysis, detailed examination of cracks, measurement of crack growth characteristics, and techniques to study this accurately.

Often the cracks under consideration are too small to be observed with the unaided eye. This has led to the development of numerous crack measurement techniques such as ink staining, acoustic emission, photography, strain gage, elastic compliance gage, and potential drop methods. Potential drop methods will be described in Chapter 3.

1.3 Objectives

An integral part of the AECL pressure tube test program at Chalk River Laboratories (CRL) is the collection of detailed crack growth data. This includes accurate measurement of crack depth along the length of the crack so that a crack shape profile may be determined at various stages of the test. To do this, an automated probe will be developed to continuously scan and take measurements of the crack region. These measurements can then be converted to actual depth data with the aid of calibration curves. Thus, the objective of this work is to test and begin calibrating a potential drop technique and develop a radiation resistant (and manipulator compatible) probe positioning frame.

2 Cracking in CANDU Pressure Tubes

2.0 The CANDU Reactor Design

The success of CANDU reactors can be attributed to several unique design features. These features have led CANDU units to have an excellent lifetime performance record and be more economical when compared to other reactor designs. In a nuclear power station, as in conventional power plants, steam driven turbines are used for power generation. However, in a reactor, the steam is heated by the means of a nuclear reaction wherein uranium atoms (i.e., nuclei) are split—emitting heat and atomic particles, including neutrons. These neutrons are expelled at high speeds and must be slowed down by a "moderator" so that they may collide with other uranium nuclei, thereby sustaining a chain reaction.

One unique feature of the CANDU reactor design is the use of natural uranium for fuel, instead of the enriched uranium fuels used in other reactors. There are several advantages in using natural uranium since the fuel itself requires less processing compared to using enriched uranium fuel. This leads to a significant reduction in fuel fabrication costs. The use of natural uranium also leads to fundamentally different reactor design characteristics—such as on-power fueling, the choice of moderator, and the choice of reactor core materials.

CANDU reactors utilize heavy water (D_2O) as a moderator, as opposed to a light water or a graphite moderator which may be used in other reactors. Having chosen natural uranium as a fuel, heavy water has one important advantage as a moderator: it absorbs fewer neutrons, as compared to light water and graphite. The smaller neutron capture cross

section allows the nuclear chain reaction to be maintained since fewer neutrons are absorbed in non-nuclear reactions—making natural uranium a viable option for reactor fuel. Economically heavy water also presents an advantage since the cost of producing and upgrading it is significantly lower than the cost of enriching uranium for fuel over the lifetime of the reactor. Further, most of the water is recoverable and can be recycled. In the CANDU design, heavy water is also used as the primary heat transport medium.

The use of natural uranium, and the resulting requirement for reactor components with a small neutron capture cross section, also dictates the choice of zirconium alloys for most reactor vessel parts. Zirconium alloys meet criteria such as strength and corrosion characteristics required for structural materials in a water environment at high temperatures while ensuring that a sufficient supply of neutrons is available to sustain the fission reaction.

Each reactor unit contains between 380 to 480 pressure tubes arranged in a regular lattice. Since exact numbers vary from unit to unit specific design data appears in Appendix A (Table A2). Figures 2.1 and 2.2 show the CANDU reactor layout and pressure tubes. Pressure tubes in the most recent reactors are about 6.3 m long having an inside diameter of 103 mm with a wall thickness of 4.2 mm. Each pressure tube is fabricated from cold worked Zr-2.5Nb and contains twelve or thirteen fuel bundles as well as the heavy water coolant. Each fuel bundle is further composed of fuel elements, in Zircaloy sheaths, held together by Zircaloy end plates (Zircaloy is a term which refers to the group of zirconium-tin alloys often used for reactor applications). The fuel elements are the reactor fuel in the form of ceramic uranium oxide pellets.

The pressure tubes themselves are contained within a calandria tube, also of zirconium alloy construction. The pressure tubes are connected to the calandria vessel by mechanically rolled joints used in conjunction with stainless steel end fittings (this connection is discussed in more detail in Section 2.3.1). A rolled joint is also used to

connect the calandria tubes to the stainless steel end shield. A nine millimeter radial space is maintained between the pressure tube and calandria tube walls with circular springs, known as garter springs, which are constructed of either Inconel-X750 (a nickel-cobalt superalloy) or a zirconium, niobium and copper alloy. This gas filled space contains carbon dioxide and oxygen ($0.5\% < O_2 < 5\%$) as part of a leak detection system [2]. Leaks in the system are detected by any increase in humidity in the annulus. The oxygen is added to the system in order to maintain a normal oxidation rate to prevent gaseous hydrogen ingress. The gas filled space also serves to minimize heat loss from the primary coolant to the lower temperature moderator during normal operation. The calandria vessel also contains the heavy water moderator.

2.1 Theoretical Concepts

2.1.1 Leak-Before-Break Design Philosophy

The "leak-before-break" design is one way of introducing an added degree of safety into structures such as pressure vessels and pipelines. This concept dictates the design of pressure vessels on the premise that if a crack develops in a vessel, the vessel will leak before it fails (i.e. the critical crack length for unstable failure is greater than the vessel wall thickness). If this condition is met, the pressure vessel will leak, permitting crack detection and pressure reduction, before the vessel fails in an unstable manner. This is used as part of the 'defense in depth' philosophy and as a fitness for purpose criterion for CANDU pressure tubes. In fact, the most serious pressure tube failure (occurring in Pickering Unit 2 in 1988) was an unstable rupture because the pressure tube did not meet the leak-before-break criterion.

2.1.2 Fracture Toughness Concepts

Linear elastic fracture mechanics (LEFM) concepts can be used to make predictions regarding rates of crack propagation, critical crack lengths, and therefore component life.

This concept is often used since it is relatively simple while still giving reasonable results. The theory of LEFM, as implied by its name, is based on applying the theories of elasticity to components containing cracks or defects. This also includes assumptions within the theory of elasticity limited to small displacements and the general linear relationship of stress and strain. The basic equations of the LEFM theory are of the form:

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + \dots \quad (2.1)$$

where:

- σ_{ij} = Local stresses at a point near a crack tip
- K = Stress Intensity Factor
- r, θ = Cylindrical coordinates of the point with respect to the crack tip
- $f_{ij}(\theta)$ = Geometry dependent correction factor

Considering Equation (2.1) along with Figure 2.3, it can be seen that the stress at any point is a function of the distance from the crack tip giving a singularity such that as $r \rightarrow 0$, $\sigma_{ij} \rightarrow \infty$. This is not physically possible since all materials have a yield stress and a region of plastically deformed material, a plastic zone of radius r_p , which would be formed around the crack tip. Despite this, as long as the size of the plastic zone at the crack tip is small (in relation to the crack length and component geometry), the assumption of linear elastic behavior and the use of this model is valid.

The stress intensity factor (SIF) mentioned in Equation (2.1) has units of $\text{MPa}\sqrt{\text{m}}$ or $\text{ksi}\sqrt{\text{in}}$ and is a function of the nominal applied stress, crack length, specimen geometry, and crack geometry. The idea of a SIF, represented by the symbol K , can essentially be used to quantify a stress field in the vicinity of a crack tip. That is:

$$K = f(g)\sigma\sqrt{\pi a} \quad (2.2)$$

where:

K	=	Stress Intensity Factor
σ	=	Stress applied to the component remote from the crack tip (<i>not</i> local stress)
$f(g)$	=	Correction factor dependent on specimen and crack geometry
a	=	Crack length

While K values for numerous loading conditions and crack geometries have been published, the parameter may be determined experimentally. The value of K can be defined for three different modes of loading: opening, sliding and tearing (Figure 2.4). Most engineering problems are Mode I loading—also applicable to DHC in pressure tubes.

An important concept when working with stress intensity factors is the distinction between plane strain and plane stress conditions. For example, in a very thin component, the stress through the thickness cannot vary appreciably. Further, since the stress at a free surface must be equal to zero, stress in the z direction through the entire body is effectively zero, resulting in a biaxial state of stress (see Figure 2.5). In other words, the value of stress in the z direction is negligible when compared to stress values in the x and y directions. This situation is termed a plane stress situation. In a thick component, the material is constrained in the z -direction (only allowing strain in two directions) resulting in a plane strain condition. In a body subjected to plane strain conditions, while stress may develop in the z direction, maximum constraint conditions exist and the size of the plastic zone at the crack tip is smaller than in a plane stress state. Thus, it is important to take into consideration the state of stress when using the concept of stress intensity factors.

In making use of LEFM concepts, several critical values may be defined. For a given material, flaw geometry, and applied load once the stress intensity factor reaches a critical value, K_C , unstable fracture occurs. This limiting value, K_C , is referred to as the fracture toughness of a material and is partially a function of the component thickness to the point of maximum constraint. Once maximum constraint conditions exist, the plane strain fracture toughness, K_{IC} , is defined. Thus the point of maximum constraint is defined when further increasing component thickness will no longer affect its fracture toughness value. In

effect, stress intensity and its limiting value of fracture toughness may be likened to applied stress and its limiting value of yield stress. For a more comprehensive treatment of fracture toughness concepts the reader should refer to a text such as Bannantine, Comer, and Handrock [7].

2.1.3 Microstructural Concepts

On a microscopic scale, different metals have different physical structures. This organization of a material at the atomic level is important since it controls the macroscopic properties of the material. Two common types of structures are body centered cubic (bcc) and hexagonal close packed (hcp) shown in Figures 2.6 and 2.7 respectively. These structures are defined on the basis of a unit cell, the structure of which is repeated throughout the material. The unit cell parameters and terminology associated with each type of structure are also illustrated in Figures 2.6 and 2.7.

Most metals deform predominantly by a mechanism where one plane of atoms slides over an adjacent plane, this is termed slip or plastic shear. This type of deformation occurs even when compressive or tensile stresses are applied since both may be resolved into shear stresses. Since slip occurs along certain crystal planes and directions more readily than others, the importance of the atomic packing is obvious. The direction along which slip occurs most readily in a crystal is the direction along which the highest density of atoms occurs. This can be explained by the fact that movement between atomic sites with the closest spacing would require the least energy, and therefore, would occur the most easily (i.e., moving a smaller distance requires less energy than moving a larger distance). Likewise, slip occurs on planes that have wide interplanar spacings, and therefore, high planar densities. The combination of a slip plane and slip direction is referred to as a slip system. For example, the hcp structure has fewer slip systems than the bcc structure since the due to the nature of the atomic packing [8]. This can be seen in Figures 2.6 and 2.7 where the bcc structure has more planes with closely packed atoms than the hcp structure.

Theoretically, any material is a perfect repeating pattern of unit cells; however, this does not hold true in reality. Often an extra atom (interstitial) or a row of atoms (dislocation), is added, or is missing from the lattice. This results in discontinuities in the material structure. Some examples of this appear in Figures 2.8, 2.9 and 2.10. Experimentally, it has been determined that the slip mechanism discussed earlier is not solely responsible for deformation in materials. It is in fact a combination of slip and dislocation movement within the material which governs its mechanical properties such as ductility. These atomic level distortions are of importance as they "move" through the structure when a material is subjected to stress.

There are two important types of dislocations. The first is termed an edge dislocation and is illustrated in Figure 2.9. A second type, shown in Figure 2.10, is known as a screw dislocation. In describing these dislocations, a slip vector is defined as the displacement distance for atoms around the dislocation. As can be seen in Figures 2.9 and 2.10, for an edge dislocation the slip vector is at right angles to the dislocation line while in a screw dislocation the slip vector is parallel to the dislocation line [8].

The deformation of a material through slip (dislocation movement) requires less energy than pure shear, since fewer atoms move at any given time. This mechanism is illustrated in Figures 2.11. Often, the process is interrupted splitting the dislocation in two and the resulting discontinuities are termed partial dislocations. The presence of point defects, such as impurities or solute atoms, in the material can inhibit the movement of dislocations (i.e., movement of the dislocation through slip requires more energy) and result in higher strength (and lower ductility) for the material. In a similar manner, a high density of dislocations in a material does not allow for free movement of the defects because they tend to get "tangled"; this also results in a loss of ductility and decrease in fracture toughness. This explains the increase in the yield strength of a material during coldworking since imposing large stresses on a component introduces dislocations into a material. The reader is referred to Reed-Hill [9] for a comprehensive explanation of these concepts.

2.2 Zirconium Alloys

While several aspects of pressure tube design have been modified since the early NPD reactor, one of the more significant points to note is the change in pressure tube material. The NPD, Douglas Point, and Pickering Units #1 and #2 all used pressure tubing fabricated from this Zircaloy-2 (Pickering Units #1 and #2 have since been retubed with Zr-2.5Nb). Zircaloy-2 is a zirconium alloy with 1.5 wt% tin, 0.2 wt% iron, 0.1 wt% chromium, and 0.5 wt% nickel content. This material is no longer used and CANDU reactor pressure tubes are now fabricated from Zr-2.5Nb alloy [2].

The new alloy was first introduced in 1958 at a conference in Geneva by Russian researchers and has several advantages over Zircaloy-2. The higher strength of Zr-2.5Nb alloy allows for a 20% reduction in wall thickness which is advantageous as it results in improved neutron economy. That is, fewer neutrons are absorbed by reactor vessel materials resulting in a greater number of neutrons being available for maintaining the reaction.

The two alloys also have significantly different corrosion characteristics. Zirconium alloys are known to interact with water to form a zirconium oxide film and hydrogen as reaction products. In the CANDU reactors, where heavy water is used, deuterium and zirconium deuteride are formed as reaction products instead of hydrogen and zirconium hydride. However, the effects of the zirconium deuteride and zirconium hydride on the mechanical properties of the Zr-2.5Nb alloy are indistinguishable from each other [10]. For the purposes of this thesis, the terminology will be used interchangeably. A portion of the deuterium produced by this reaction is absorbed by the zirconium alloy. This absorption is generally expressed as a percentage and is affected by the pressure tube temperature, water chemistry, alloy composition, and to some degree neutron irradiation. Since any deuterium absorbed in excess of the solid solubility limit is likely to lead to a loss of ductility and delayed hydride cracking (this failure mechanism is discussed in

Section 2.4), the corrosion and deuterium pickup characteristics of pressure tube material are critical.

Studies carried out by Urbanic et. al. in 1987 and 1991 [10, 11] led to several conclusions regarding corrosion and deuterium pickup rates of Zircaloy-2 and the Zr-2.5Nb alloy. Most importantly, it was found that corrosion and deuterium rates (quantified by measuring the oxide thickness) of Zr-2.5Nb are significantly better (i.e. lower) than Zircaloy-2 under typical reactor conditions. For example, after 3500 effective full power days under such conditions, the corrosion of Zr-2.5Nb was one third of that for Zircaloy-2 and the deuterium uptake was approximately 3% of that for Zircaloy-2. Secondly, the (theoretical) percent deuterium uptake in Zircaloy-2 increases with oxide thickness (to a maximum at approximately 30 μm of oxide) with higher percentages being reached in higher neutron fluences (i.e., greater cumulative exposure to neutron irradiation) [10]. A consequence of this property is that the NPD reactor was decommissioned in 1988 on the basis that crack detection before failure could no longer be guaranteed. The NPD tubes, fabricated from Zircaloy-2, had experienced a significant loss in ductility due to extensive deuterium pickup and irradiation effects [12]. In light of the above, it is clear that the use of Zr-2.5Nb is more desirable than Zircaloy-2 for pressure tubes.

The current compositional specifications and typical data for the Zr-2.5Nb alloy appear in Appendix A (Table A3). Data regarding the tensile properties of this alloy also appears in Appendix A (Table A4).

2.3 Pressure Tubes

2.3.1 Current Production Methods

Since the mechanical properties of a material are controlled by its microstructure, current pressure tube production methods and the resulting microstructure are of importance. The current fabrication process appears in Figure 2.12 and is discussed below.

Cylindrical ingots of the Zr-2.5Nb alloy are used. Each one weighing approximately 5500 kg and having a total impurity content less than 1 at%. Common impurities of importance include elements such as chlorine, iron and carbon. A small sample is taken for chemical analysis for every 1000 kg of the material. The ingots are then machined to remove surface defects prior to ultrasonic inspection. Following pre-heating to 1250 K, each ingot is forged into about thirty round bars which are then machined into hollow billets. The hollow billets are beta quenched at 1290 K to ensure a uniform microstructure before further ultrasonic inspection. The billets are then clad in steel and copper to reduce oxidation, heated to 1120 K, and extruded into tubes. The copper and steel cladding is dissolved by immersing the tubes in nitric acid. The tubes are then slowly cold drawn in two passes (each pass results in a 12 to 15% reduction in area). The inside is then finished before the outside is ground to give a 4.2 mm wall thickness.

The tubes are also subjected to a room temperature hydrostatic test at 27.6 MPa for 30 s; this produces a transverse stress of 331 MPa in the tube. During the test, if there is a pressure drop of more than 1 MPa (i.e., leakage occurs), the tube is rejected. The tubes are stress relieved for 24 h at 675 K and straightened before a final ultrasonic inspection.

The last part of the fabrication process is the installation of the pressure tubes in the reactor vessel. In this process, the tubes are attached to the stainless steel end fittings using a mechanically rolled joint. The tool used to do this is known as a five-roll tube-expander (Figure 2.13). The joining process results in several changes in the pressure tube properties. The rolling process, which forces tubing material into grooves in the fitting, results in a reduction of the wall thickness of approximately 12%. The tube is extruded in the axial direction—away from the center of the rolled area. Although the joints produced in this manner perform well, it is important to note that the pressure tube is plastically deformed and if the roll tube expander is positioned incorrectly, excessive deformation of the tube may compromise the integrity of the joint and/or the pressure tube by introducing excessive residual stresses [13]. Figure 2.14 illustrates the nature of the stress field when

joints are over-extended. Failures resulting from this problem are discussed in Section 2.6.

2.3.2 Effect of Fabrication Process on Microstructure

The pressure tube fabrication process results in a highly structured dual phase material containing an α -phase, which has a hexagonal closed packed arrangement (hcp), and a β -phase, which has a body centered cubic arrangement (bcc).

The final pressure tube microstructure is controlled by the fabrication process. The α -grains, containing approximately 1 at% Nb in solution, are shaped like elongated platelets separated by the β -phase [14]. At the extrusion temperature of 817°C (1090 K) the grain structure of Zr-2.5Nb consists of approximately 80% β -phase and 20% α -phase. Following the extrusion process, the zirconium in the β -phase begins to transform to the α -phase by growing along the elongated α -phase grain boundaries [15]. The resulting α -grain dimensions in the extruded tubes are typically 10 μm long (longitudinally), 1 μm wide (in the transverse direction) and 0.5 μm thick (radially) within a network of meta-stable β -phase containing 18-20 wt% Nb (and approximately 1.5 at% Fe in high-Fe tubes) [14]. Cheadle et. al. [1] state that the grains can be as large as 20 μm long, 2 μm wide, and 0.4 μm thick. As a result of the β -phase transforming to α -phase, the remaining β -phase becomes enriched in niobium (the α -phase has approximately 1% Nb solubility) leading to a slight loss of ductility.

The extrusion process leaves a microstructure that varies along the length of the pressure tube. Specifically, the α -grain diameter varies from 0.3 μm at the "back" to 0.5 μm at the "front" end of the extrusion. The smaller grain structure can be attributed to faster cooling of the "back" end of the billet during extrusion. The "front" end of the billet leaves the extrusion chamber first and "back" end leaves the chamber last. The "back" end of the pressure tube is stronger as a result of this uneven cooling. Also, the majority of the α -grain basal planes are aligned such that their normals lie in the circumferential direction.

Upon stress relieving, the pressure tube microstructure is unchanged, but the high density of dislocations, introduced during the cold drawing process, is greatly reduced. Initially, the dislocation density is close to $16 \times 10^{14} \text{m}^{-2}$ [1]. Typically, the resulting dislocation densities are about $4 \times 10^{14} \text{m}^{-2}$ for a-type (i.e., are located on the basal planes of the hcp unit cells) and $1 \times 10^{14} \text{m}^{-2}$ for c-type (i.e., are parallel to the c-direction of the hcp unit cell) [14]. By comparison, in well annealed crystals the dislocation density is approximately 10^{10}m^{-2} to 10^{12}m^{-2} , but with careful treatment this can be reduced to as low as 10^6m^{-2} [16]. Stress relieving at a temperature less than 610°C will cause the Zr in the meta-stable β -phase to completely transform to an α -phase structure over time. This leads to an equilibrium structure of α -Zr and β -Nb and some loss in ductility.

2.4 Delayed Hydride Cracking

2.4.1 The Mechanism

Metals which form brittle compounds with hydrogen (hydrides) are susceptible to failure by the mechanism known as Delayed Hydride Cracking (DHC) [17]. This phenomena has been observed in both hcp metals, such as zirconium and titanium, and bcc metals, such as niobium and vanadium.

The DHC mechanism is a cyclic process where hydrogen diffuses to a region of high tensile stress (or along a temperature gradient) and precipitates as brittle hydride platelets once its solubility limit is exceeded. This is primarily to relieve strain in the matrix by the volume expansion that accompanies hydride precipitation [18]. In pressure tubes, the hydrides are precipitated with their platelet normals parallel to the largest stress (which is the hoop stress) and are referred to as radial hydrides. If the stress in the region is sufficient, and the critical condition for hydride fracture is achieved, a crack initiates and propagates in a brittle manner by means of hydride fracture. This sequence is then repeated over time resulting in crack growth through small increments. The possibility for DHC to occur is the process of reactor shutdown. This situation presents the combination of

pressure tubes subjected to cooling under stress as well as a decrease in hydrogen solubility due to a temperature drop. A simplified diagram of this process appears in Figure 2.15 [19].

There are several factors that are important in contributing to the failure of pressure tubes through DHC. Most importantly, a source of hydrogen must be present. In reactor pressure tubes, there are two sources: the zirconium alloy itself, containing circumferential hydrides from the fabrication process, and the heavy water coolant.

The sources of hydrogen themselves are also affected by the reactor environment. For example, recent work by Ding and Northwood [20], as well as Ramasubramaniam et. al. [21], indicates that the lithium concentration (used for pH control) in the coolant affects the corrosion rate of the pressure tube. Testing has shown that accelerated corrosion occurs once a critical lithium concentration has been exceeded for a given set of conditions. For example, this concentration is thought to be 1.2 to 4.8 g LiOH/l H₂O for a 300°C (573 K) pressurized lithiated H₂O environment. Results indicate that the microstructure of the oxide layer changes as the lithium concentration is varied. This is further supported by the findings of Laursen and Leslie [22] which indicate that the oxide layer has significant hydrogen permeability at temperatures on the order of reactor operating temperatures. So the DHC mechanism is indirectly affected by coolant chemistry since lithium concentrations affect the rate of hydrogen production through the oxidation of the pressure tube.

Applied stress also plays a significant role in the DHC process since it is the driving mechanism for the diffusion, re-precipitation, and cracking of hydrides in regions of high stress. A region of high stress can be a result of several factors including a crack tip, stress concentration due to component geometry, a flaw, or in the case of pressure tubes, an incorrect rolling procedure during installation. While the size of a flaw can vary, its seriousness is dependent on the stress distribution in the component.

Time is also an important factor in the DHC mechanism since crack propagation is an intermittent process. The initiation of the crack is the least understood portion of the DHC

process. The period of crack growth however, is controlled by the rate of hydrogen diffusion up a stress gradient followed by the nucleation and growth of hydrides; this is clearly time dependent. Other contributing factors to DHC are temperature and pressure since the formation of hydrides is strongly affected by the solubility and diffusivity of hydrogen in the metal matrix. Coleman et. al. [23] state that the pressure tube microstructure also affects the diffusivity of hydrogen. Hydrogen diffuses faster in the β -phase than in the α -phase; therefore, as the meta-stable β -phase decomposes, hydrogen diffusivity is reduced since the β -phase no longer provides a continuous diffusion "path".

One of the more important aspects of hydride formation is the orientation of the platelets. Due to the fabrication process, circumferential hydrides already exist in the material; however, they appear to have little or no effect on the cracking characteristics of the material in low concentrations. Concern arises when the precipitation of hydrides occurs in the radial direction. It is well known that pressure tubes with radial hydrides, as opposed to circumferential hydrides, are more susceptible to DHC [24]. In addition to this Chow et. al. [14] found that material with radial hydrides displays a ductile-brittle transition temperature which may move into the reactor operating (temperature) range, depending on the proportion of radial hydrides present. The problem of radial hydrides is further compounded by fabrication history based on the findings of Cheadle et. al. [17]. They state that hydrides tend to re-precipitate parallel to the basal planes of hcp cells; as mentioned earlier, the fabrication process results in the majority of basal planes oriented radially. Cheadle et. al. go on to state that cracks have a greater tendency to form normal to basal plane normals (i.e., in the radial direction).

The DHC mechanism is a complex process which is sensitive to numerous different variables including hydrogen concentration, temperature, stress field, and hydrogen diffusivity.

2.4.2 Stress Intensity Factors Characteristic of DHC

The general effects of various factors on the DHC mechanism may be quantified using the concept of stress intensity factors and fracture toughness. Referring to Figure 2.16 it can be seen that the crack tip region is characterized by three stages. Stage I occurs below a threshold value (K_{IH}) below which the crack will not propagate. A second stage is defined where crack velocity is essentially independent of the stress intensity factor. The third stage, above which the crack propagates in an unstable manner, is defined by the region above a critical stress intensity value (K_{IC}) [19].

K_{IH} has been experimentally determined to be 5-10 MPa $\sqrt{m}$ while typical values of K_C have been determined to be as low as 40 or 50 MPa $\sqrt{m}$ (at reactor operating temperatures) [19]. The value of critical crack length (i.e., the maximum crack length below which the crack will not cause an unstable failure of the pressure tube), at a hoop stress of 120 MPa, has been experimentally found to vary between 60-120 mm. A simple critical flaw size calculation for a typical pressure tube was carried out in Appendix B using the largest operating internal pressure of 11.1 MPa (Darlington) [15]. A hoop stress of 136 MPa was calculated and, based on a critical fracture toughness of 40 MPa $\sqrt{m}$ (a conservative value), a critical crack length of 21.9 mm was calculated. The results are significantly lower than those obtained by Chow and Simpson [24]. This could be due to the conservative K_C value used in the calculations (for example, using a K_C value of 60 MPa $\sqrt{m}$ results in a critical crack length of approximately 50 mm). It should be noted that measurements based on Compact Tension (CT) specimens underestimate the real critical crack length.

2.5 Reactor Operating Environment

2.5.1 Water Chemistry, Temperature and Pressure

The pressure tubes within the reactor are exposed to several different damage mechanisms. The inside of the pressure tube is subject to wear from the movement of fuel

bundles along the pressure tube during refueling operations. Also, heavy water coolant is pumped through the pressure tube—further exposing the channel to internal pressure and a certain degree of chemical attack. The pH of the coolant is maintained within a range of 10.2 to 10.8 using either LiOH or LiOD. The coolant also contains dissolved hydrogen in proportions of 3 to 10 cm³ D₂/kg D₂O. This hydrogen is added in order to suppress the radiolytic production of oxygen (Zr-2.5Nb is very sensitive to oxidizing environments) such that oxygen levels are maintained at a level less than 5 µg O₂/kg D₂O. Typical coolant pressures and temperatures appear in Table 1 of Appendix A [2].

2.5.2 Radiation and its Effects

Neutron irradiation, aside from having a synergistic effect with the DHC mechanism [25], affects several properties of zirconium alloy including plastic deformation and fracture toughness. It is thought that radiation effects are sensitive to minor factors (there are no major microstructural differences between various pressure tubes) such as texture, grain shape, and dislocation density of the material [25, 26]. In the reactor, the pressure tubes are typically exposed to an average neutron flux of 10¹⁸ n m⁻² s⁻¹ [26].

While there appears to be lower and upper limits, the fracture toughness of Zr-2.5Nb decreases with an increasing neutron fluence. This effect has been observed to saturate after a fluence rate of approximately 3 × 10²⁵ n m⁻² is reached. Thus, the largest decrease in toughness is likely to occur within the first year of service [14]. This is only a general trend since there is a large degree of scatter in fracture toughness data; Chow et. al. [14] were unable to identify the reason for the large degree of scatter. Although, like other metals, the fracture toughness of irradiated zirconium alloy increased with an increase in test temperature, it was also concluded that the 50°C temperature variation along the pressure tube (from the coolant inlet to the coolant outlet) did not contribute significantly to the change in fracture toughness. This data is based on specimens subjected to up to 15 years of reactor operation, and therefore the hydrogen uptake, and its effect on fracture

toughness must be considered in conjunction with the radiation effects.

On a microstructural level, irradiation has several effects on pressure tube material. It has been found that neutron irradiation produces small (< 15 nm diameter) a-type dislocations in the microstructure. The a-type dislocation density however, reaches saturation after a fluence of approximately $2 \times 10^{25} \text{ nm}^{-2}$. Observations also show a decrease in the density of c-type dislocations, although in reality, they split into partial dislocations. Another effect of irradiation is the precipitation of Nb from the supersaturated solution into the α -phase, at sub-grain boundaries, and α - β interfaces. Irradiation also results in the depletion of iron from the β -phase, dispersing it through the material. Both of these effects are fluence controlled since neither of them is observed in portions of the pressure tube shielded from radiation. Furthermore, both of these phenomena result in a reduction in ductility since the precipitates would inhibit the movement of dislocations within the material [14].

A precipitation of Nb particles within the α -phase has also been observed. There is also an enrichment of Nb in the β -phase of the material, but this is a change towards an equilibrium structure rather than the result of neutron fluence since the profile of Nb enrichment does not match that of fluence variation across the pressure tube. That is, the effect is the decomposition of the meta-stable 20-40 at% Nb enriched β -Zr towards the more stable 85 at% Nb β -phase. This decomposition to a more stable structure is suppressed by the neutron irradiation, and is only seen in the first two years of reactor operation.

Thus, the decrease in fracture toughness of Zr-2.5Nb alloy correlates with the fluence induced increase in dislocation density, the formation of β -Nb precipitates in α -grains, and the dispersal of Fe from the β -phase. The decrease in fracture toughness, after irradiation, has also been observed to be dependent on the chlorine and phosphide content of the ingot used to fabricate pressure tubes [27, 28]. However, the concentration of these two impurities may be lowered through quadruple melting during the fabrication process.

Observation of pressure tubes in the reactor have shown growth in the axial direction over time. In-reactor growth is expansion of the component during the operation of the reactor but not due to any obvious mechanical stress. It has been concluded that this pressure tube "growth" is partly a radiation induced effect. Creep is also thought to be a factor. However, the effects of creep and radiation are considered to be separate but additive, with creep playing a more significant role at higher temperatures.

The pressure tube "growth" is in fact a positive longitudinal strain in the pressure tube with a corresponding negative strain in the transverse direction (i.e., the volume of the pressure tube does not change) [26]. Lattice parameter measurements have shown that the α -phase lattice expands and reaches a saturation level after fluences of approximately $1-2 \times 10^{25} \text{ n m}^{-2}$. This expansion is primarily an elongation in the a-direction with shrinkage occurring in the c-direction. Since the pressure tube is highly textured, these changes on the atomic level are visible on a macroscopic level as pressure tube growth. Also, there is also some indication of void induced swelling (i.e. an increase in volume due to the agglomeration of point defects or vacancies); however, this mechanism does not account for all of the growth that has been observed [29].

While research in this area is still relatively new, several other observations and theories have been put forth to explain in reactor growth. Parker et. al. [26] state that major metallurgical factors that affect the irradiation growth phenomena are grain shape, texture, and dislocation density. They also observed, in agreement with Holt et. al. [30], that irradiation growth could be divided into three separate stages:

- I: To a fluence of approximately 10^{24} n m^{-2} . This region may be related to stress relief. It appears as a strain offset of $+2 \times 10^{-4}$ in the longitudinal direction, and the negative of that, in the transverse direction [14].

The magnitude of this offset does not appear to be dependent on the microstructure (i.e., it is a consequence of temperature and flux dependent equilibrium). These strain levels agree with theoretical estimates of strain due to saturation of irradiation damage. Holt et. al. [30] observed that this effect appears to decrease with temperature.

- II: A region of low growth due to a balance between recovery and growth processes. Shrinkage occurs due to recovery from internal stresses (caused by fabrication, difference in stress relieving, irradiation temperatures, and grain interactions during growth). The growth occurs from the movement of dislocations. This "movement" is due to the applied stress and because it introduces point defects into the material.
- III: After a fluence of 10^{25} nm^{-2} a significant increase in growth rate is observed; however, this phenomena is not understood well. It appears to be strongly dependent on the fabrication history of the pressure tube.

More research is needed for a better understanding of irradiation growth.

Recently, microstructural variations in the circumferential direction have also been found in pressure tubes. Inspections have revealed that the dislocation density is not uniform, and depending on the nature of dislocation distribution, this will cause the pressure tubes to "bow" out sideways during service. It was found that if the dislocation density maximum and minimum were oriented at 0° and 180° (relative to the top of the tube) respectively, the pressure tubes were prone to bowing. If however, the maximum and minimum dislocation densities are oriented at the 270° and 90° position, the phenomena can be used to counter the problem of pressure tube sagging in the vertical plane.

2.6 Pressure Tube Failures

To date, there have been two types of pressure tube failures. The first type of failure is that exhibited by the rupture of a pressure tube at the Pickering NGS "A" Unit 2 on August 1, 1983 which did not meet the "leak before break" criterion. Another set of pressure tube failures have exhibited the expected "leak-before-break" behaviour. Each time the reactor was safely brought off line to replace the leaking pressure tubes. These cases are discussed in detail below.

2.6.1 Pickering Unit #2 Pressure Tube Rupture

The failed pressure tube at Pickering Unit 2 was fabricated from Zircaloy-2 and a detailed analysis of the failed specimen led to several conclusions. The succession of events leading up to the fast fracture were determined to be as follows [31]:

- i) The solubility limit of hydrogen in the alloy was surpassed as hydrogen was picked up from the coolant and leak detection system gas.
- ii) A displaced garter spring allowed the pressure tube to sag and contact the calandria tube. This resulted in a large thermal gradient in the pressure tube wall.
- iii) The pressure tube contacting the calandria tube resulted in a cold region where the temperature was well below the solubility limit of hydrogen in the metal. This resulted in hydride precipitation and the formation of a blister. The continuous removal of hydrogen from solution resulted in it continually diffusing to the region, repeating the cycle. Thus, a large stress concentration was introduced—initiating a defect.
- iv) The defect led to the propagation of a crack through the mechanism of DHC and ultimate failure.

Subsequent investigations arising from this failure have led to two major conclusions.

- I) the fast fracture of a pressure tube does not pose a threat to public or worker safety.
- II) all pressure tubes since have been fabricated from Zr-2.5Nb alloy which has a significantly lower hydrogen pickup rate and is not susceptible to similar modes of failure—even if the pressure tube wall contacts the calandria tube [26].

This failure has led to a program to locate, and reposition, garter springs in existing reactors to minimize the possibility of pressure tubes contacting the calandria tubes.

2.6.2 Failures Meeting the "Leak-Before-Break" Criteria

The second set of failures displayed the expected "leak-before-break" phenomena. As of December 1985, 23 Zr-2.5Nb pressure tubes had been removed from CANDU reactors

because of leaks. Other pressure tubes with large cracks have been found with a total of 74 tubes removed; the breakdown is as follows [32, 33]:

- 17 tubes replaced in Pickering Unit #3 in 1974.
- 52 tubes replaced in Pickering Unit #4 in 1975.
- 3 tubes replaced in Bruce Unit #2 in 1982.
- 1 tube replaced in Pickering Unit #3 in 1985.
- 1 tube replaced in Bruce Unit #2 in 1986.

With the exception of the 1986 Bruce Unit #2 failure, the longest cracks were found to be 15-20 mm long and just inboard of the rolled joints, near the ends of the pressure tubes. Just inboard of the rolled joints is where the tube is most heavily deformed to achieve a good seal between the end fitting and the pressure tube. It was also found that the innermost contact point of the rollers used to form the joint was often the crack initiation point. While some of these cracks had actually propagated through the wall, it was found that some of them had been stopped a quarter of the way through the wall thickness. It was quite obvious however, that the cracks had grown in cycles since crack surfaces showed distinct banding or striations, depending on the amount of oxidation that had taken place. The least oxidized of the crack surfaces showed definite signs of crack propagation by DHC.

The DHC hypothesis was proven by the presence of radial hydrides in the same plane as the cracks (the normal orientation of the hydrides in cold worked Zr-2.5Nb for pressure tubes is circumferential). With the exception of the Bruce Unit #2 failure in 1986, all cracks propagated in a stable manner; that is, they did not lead to fast fracture.

The factors and sequence of events leading to the formation and propagation of these cracks (specifically Pickering #3) has also been determined and described by Cheadle et. al. in 1984 and 1985 [31, 32]. The events leading to crack propagation were determined to be as follows:

- i) The end joints were rolled with the tool placed approximately 0.5 inches too far into the tube resulting in very high strains and tensile stresses just ahead of the rollers. (Figures 2.18 and 2.19)
- ii) Upon reactor startup, these joints were heated and all hydrides originally present were taken into solution as hydrogen which then migrated to the regions of high tensile stresses caused by the incorrect rolling tool position.
- iii) Upon reactor shutdown, the joints cooled, the hydrogen re-precipitated as radial zirconium hydrides which are brittle at room temperature. Due to the high residual tensile stresses present, these hydrides cracked.
- iv) The crack propagated every time this cycle was repeated (i.e., every time the reactor was brought on and off line) [13].

The study by Dunn et. al. [13] also made several significant conclusions. It was found that while the reactor was in operation, the pressure tubes were stress relieved such that the residual stresses dropped to about 345 MPa. Further, the inlet joints are more susceptible to cracking, then the outlet joints, since the inlets are cooler and there is less stress relief at lower temperatures. This stress relieving action arrested the growth of some of the smaller cracks while the larger cracks continued to propagate with each cool-down. Cheadle et. al. [17] state that any temperature cooler than approximately 137°C (410 K) will result in crack propagation.

A correlation was also found with the fabrication process. A larger number of cracks were discovered at the "back" ends of the pressure tube extrusions (the "back" ends have a finer grain structure and higher strength, and are therefore more susceptible to DHC). Dunn et. al. [13] also state that only some pressure tubes have cracked since several criteria must be met before a crack is initiated.

The Bruce Unit #2 failure differed somewhat from previous pressure tube failures. The pressure tube did meet the expected leak-before-break criteria and was brought off line safely. However, during an effort to locate the crack through acoustic emission techniques, the pressure tube ruptured at a pressure of 8.4 MPa at 45°C. The crack originated from a flap of material and had a final axial length of 3.7 m. Examination revealed that the pressure tube contained a fabrication defect in the form of a lamination

which intersected the inside surface of the pressure tube. This defect was preferentially corroded during service and a crack developed. It is thought that the crack continued to propagate due to stresses from oxide wedging until sufficient quantities of hydrogen were available for crack propagation to continue via the DHC mechanism. The cracking then changed direction from the plane of the lamination to the radial direction as it was in mixed-mode loading. In the region of the rolled joint, the crack grew toward the inside surface of the tube due to the compressive stresses and in the bulk of the lamination the existence of tensile stresses drove the crack towards the outside surface of the tube. The crack actually penetrated the pressure tube wall in one location. The crack length was limited at one end due to the compressive stresses at the rolled joint and at the other end by a lack of hydrogen for DHC [33].

In response to this failure several actions were taken. These included modifying reactor operation procedures in an attempt to reduce the possibility of pressure tube rupture after leak detection. Additional inspections for lamination flaws were incorporated into pressure tube fabrication procedures. In-reactor inspections were also carried out on pressure tubes thought to be susceptible to this type of fabrication flaw [33].

2.6.3 The Seriousness of Pressure Tube Failures

The CANDU design is based on an overriding philosophy to minimize any danger to staff or to the public. To date, this philosophy has been proven to work both in the case of leaking tubes and in the case of pressure tube failure through fast fracture.

Where the tube did fail by fast fracture in-service, there was a major loss of electricity production as the reactor had to be shutdown immediately but there was never any danger to the public or plant staff. The reactor then remained shutdown for five years for retubing. Reactor operating history has proven that while pressure tube failures are not desirable, they do not pose any danger to plant staff or the public.

Long term performance of pressure tubes (i.e., meeting their design life) is also a concern. In the original CANDU design, the expected life of pressure tubes was 30 years. This target may be optimistic for several reasons. First, in the original design, Zircaloy-2 was used to fabricate tubing which was found to be very susceptible to hydrogen pickup and therefore DHC. Since then, all new pressure tubes have been fabricated from Zr-2.5Nb alloy which is less susceptible, but not immune, to corrosion under service conditions.

A second reason the expected design life will not be met is that design allowances for thermal and elastic expansion were in the range of 25 mm; however, the pressure tubes have had a plastic expansion rate of 4 to 5 mm per reactor year at 80% full power [30]. This expansion is due to irradiation and creep; as a result, the pressure tubes will exceed dimensional tolerances well before the end of their design life. This may necessitate retubing of a reactor several times during the course of its operating life. Once again, these problems do not pose a risk to workers or the public, but they do affect the economic viability of nuclear power generation.

Figure 2.1 Layout of a CANDU Reactor Vessel [4]

Figure 2.2 Illustration of Pressure Tube Used in CANDU Reactor [33]

The pressure tubes are fabricated from Zr-2.5Nb and are contained within the calandria tube. CANDU pressure tubes contain the primary (heavy water) coolant and reactor fuel.

Figure 2.3 Theoretical and Actual Stress Distribution at Crack Tip [7]

The dashed line indicates the theoretical stress distribution at the crack tip. Since there is a limit to the strength of a material, σ_y , the actual stress distribution is indicated by the solid line. Distance from the crack tip is defined by the cylindrical coordinates r and θ .

Figure 2.4 Three Modes of Crack Loading Leading to Crack Propagation [7]

There are three different types of loading that will cause crack propagation:

I: Opening

II: Sliding

III: Tearing

The most common type of loading leading to crack propagation is Mode I.

Figure 2.5 Illustration of Plane Strain and Plane Stress States [7]

For Plane Stress (a) $\sigma_z = \tau_{zx} = \tau_{zy} = 0$; $\epsilon_z \neq 0$ (Thin Body)

For Plane Strain (b) $\sigma_z = \nu(\sigma_x + \sigma_y)$; $\epsilon_z = 0$ (Thick Body)

Figure 2.6 Two Representations of Body Centered Cubic Structure [8]

Two different representations of the body centered cubic structure are presented. The distance "a" defines a characteristic unit cell parameter for the body centered cubic structure.

Figure 2.7 Two Representations of the Hexagonal Close Packed Structure [8]

The distances "a" and "c" define the unit cell parameters characteristic of the hexagonal close packed structure. The top and bottom of the unit cell are referred to as basal planes in this structure.

Figure 2.8 Illustration of Point Defects in the Atomic Structure of a Material [8]

(a) Vacancy (b) Di-vacancy (two missing atoms) (c) Ion-pair vacancy
(d) Interstitialcy (e) Displaced ion.

Figure 2.9 Illustration of an Edge Dislocation [8]

The parameter "a" is characteristic of the unit cell structure. The "b" vector is termed the slip vector and indicates the displacement distance of atoms around the dislocation.

Figure 2.10 Illustration of a Screw Dislocation [8]

The "b" vector is termed the slip vector. It is an indication of the displacement distance of atoms around the dislocation.

Figure 2.11 Mechanism of Dislocation Movement Through Slip [8]

In this model only a few atoms at a time are moved from their low energy positions. Therefore, less stress is required to produce slip than if all of the atoms were to move at once. The slip vector, " b ", is a measure of how far atoms are displaced during slip.

Figure 2.12 The Fabrication Process of CANDU Pressure Tubes [34]

CANDU pressure tubes are fabricated from Zr-2.5Nb. The pressure tube fabrication process results in a highly structured dual phase material containing an α -phase, which has a hexagonal closed packed arrangement, and a β -phase, which has a body centered cubic arrangement.

Figure 2.13 Rolled Joint and Tool Used for CANDU Pressure Tube Installation [13]

A rolled joint is used to connect the pressure tube to stainless steel endfittings. To insure a good seal, the pressure tube end is plastically deformed to fit into grooves on the end fittings.

Figure 2.14 Stress Distribution in Fuel Channel Due to Improper Rolled Joint [2]

- (a) Correct and incorrect positioning of the rolling tool.
- (b) Region of high residual stresses and crack initiation.
- (c) Stress distribution for correctly and incorrectly rolled joints.

Figure 2.15 Mechanism of Delayed Hydride Cracking [19]

Once the solubility limit of hydrogen in the metal is exceeded, hydrogen migrates and precipitates to regions of high stress—such as a crack tip. Platelets precipitate with their normals perpendicular to the highest stress.

Figure 2.16 Dependence of DHC Crack Velocity on Stress Intensity Factor [17]

Note the three stages of crack growth:

Stage I: No crack growth

Stage II: Crack growth independent of SIF

Stage III: Unstable crack growth

3 Potential Drop Techniques

3.0 Introduction

Potential drop techniques can be used to measure flaws in any material that is electrically conductive. Simply, this technique involves connecting the specimen to a circuit such that a current is flowing through it, then measuring the potential field in the specimen in two separate regions. One voltage reading, V_r , is taken over an unflawed area (preferably adjacent to the crack) and a second voltage reading, V_c , is taken spanning the crack. If the field distribution is known, either through theoretical calculations or by experimental calibration, then the two voltage measurements can be related to crack depth. Further theoretical discussion is carried out individually for Alternating Current Potential Drop (ACPD) and Direct Current Potential Drop (DCPD) in Section 3.1.

Potential drop techniques have numerous applications beyond basic crack detection (see Section 3.3). They have been successfully applied to fracture problems such as velocity measurement of fast running cleavage cracks and detection of crack initiation. Other applications include determination of slow crack growth rates under sustained loading, fatigue loading, stress corrosion, hydrogen embrittlement, and creep [35]. The actual application of individual techniques however, depends on several factors including the sensitivity required and the nature of the specimen.

Potential drop techniques were used as early as 1938 by Thornton et. al. and by Tröst in 1944. However, their use became widely known only after 1957 when Barnett and Troiano at University College in London published their work with DCPD. They used a Kelvin bridge for investigating hydrogen embrittlement [36]. Although initially DCPD

methods used currents of up to 1500 A, advances in electronic technology have led to the use of much smaller currents [37]. One such advance that has allowed the use of smaller currents is the advent of ACPD. The fundamental differences, limitations, and advantages of ACPD and DCPD technologies, as well as their variations, are discussed below.

3.1 Theoretical Concepts

3.1.1 ACPD Techniques

The ACPD method makes use of the fact that when an alternating current travels through a specimen, it is not conducted across the entire cross section but instead in a skin along the specimen surface. It should be noted that the field may either be injected into the specimen through direct contact or induced in the specimen through current carrying coils mounted in the probe itself [38]. Using either method, the thickness of the current carrying skin can be determined from:

$$\delta = \frac{1}{\sqrt{\mu_r \mu_0 \pi \sigma f}} \quad (3.1)$$

where:

δ	= skin depth (m)
μ_r	= relative permeability of conductor
μ_0	= permeability of free space (4×10^{-7} H/m)
σ	= conductivity of specimen (S/m)
f	= frequency of alternating current (Hz)

From Equation 3.1, it can be seen that the current carrying skin thickness is highly material dependent. For example, it is affected by the relative permeability (μ_r) of the specimen. A higher relative permeability in a material will give a thinner current carrying skin. Physically, this would mean that a ferrous material would have a smaller skin depth than aluminum or zirconium.

The equation also takes into account the electrical conductivity (σ) of a specimen; a specimen with a higher conductivity would have a thinner current carrying skin than a

material with a lower conductivity. Likewise, a higher frequency will also result in a smaller skin depth. If skin depth is relatively small, a relationship can be developed for a simple crack of infinite length and uniform depth to give what is known as the "Thin Skin" model. Practically, a skin thickness is considered small if $\delta/\Delta < 0.1$ and $\delta/a < 0.1$ (where Δ is the probe contact spacing). Current flows down one side of the crack, up the other, and back along the surface. If the potential field is assumed to be uniform in the x and y directions, barring the effects of the crack itself, the potential difference measured between two points on the specimen surface can then be considered proportional only to the path length between those two points. This makes calibration essentially a one-dimensional problem. A theoretical plot of Potential Drop versus Position illustrates this in Figure 3.1 This gives a simple relationship between the measured voltages, V_r and V_c , and crack depth:

$$a = \frac{\Delta_r}{2} \left(\frac{V_c}{V_r} - \frac{\Delta_c}{\Delta_r} \right) \quad (3.2)$$

where:

a	= crack depth (m)
Δ_r	= spacing between reference probe contacts (m)
Δ_c	= spacing between probe contacts straddling crack (m)
V_c	= potential drop across crack face (V)
V_r	= potential drop across reference surface (V)

It is important to note that while Equation 3.2 [39] can give good results and quantifies the main properties affecting current flow within a specimen, there are numerous assumptions and restrictions inherent in the relationship:

- i) The crack depth is large when compared to the depth of the current carrying skin.

The practical limits are $\delta/\Delta < 0.1$ and $\delta/a < 0.1$. This allows the assumption that increased voltage drop is purely a result of a change in the path length the current travels and is therefore directly proportional crack depth.

- ii) The current on the surface of the specimen is uniform, and the flow of the current is perpendicular to the crack face.

A current flow which is not perpendicular to the crack face or a non-uniform current would result in a different relationship between crack depth and voltage change due to the more complex potential distribution.

- iii) The crack is long and thin (i.e., has a high aspect ratio, length/width).

In practice, the aspect ratio should be greater than 10. If Equation 3.2 is used to predict crack depth for a short crack, values would tend to be underestimated. This is due to the fact that in a short crack some of the current would travel "around" the ends of the crack.

- iv) The crack opening is sufficiently narrow.

A crack which is relatively wide can influence voltage readings; this source of error is discussed further in Section 3.2.1. An increase in crack width would also result in an increase in the path length of the current which would have to be accounted for during calibration.

- v) The probe is ideal.

The concept of an ideal probe is discussed in Section 3.2.1. A non-ideal probe leads to inductive effects which are discussed further in Section 3.2.1.

Should the potential distribution change for any reason and the above criteria are not met, Equation 3.2 is no longer valid. In such a situation, either a modified equation, a more complex theoretical model for potential distribution, or system calibration must be used to interpret data.

The "Thin Skin" theory is one extreme in which the current carrying skin is quite small relative to the specimen geometry [40]. The other extreme, a "Thick Skin" case, should also be considered. This model applies when the ratio δ/a is greater than 2 either due to the current frequency or material being used. Criteria (ii) to (v) still apply. Considering the theoretical plot of Potential Drop versus Position for a Thick Skin case, Figure 3.1, it can be seen that the voltage distribution is different than that of a Thin Skin case. Lugg [40] states the empirical relationship of crack depth and voltage drop as:

$$a = \frac{\Delta_r}{2} \left(\frac{V_c}{V_r} - \frac{\Delta_c}{\Delta_r} \right) \sqrt{\frac{V_r}{V_c}} \quad (3.3)$$

where:

- a = crack depth (m)
- Δ_r = spacing between reference probe contacts (m)
- Δ_c = spacing between probe contacts straddling crack (m)
- V_c = potential drop across crack face (V)
- V_r = potential drop across reference surface (V)

This equation gives good results with one major area of concern. Once again considering Figure 3.1, it can be seen that the V_r and V_c voltages are sharply peaked making accurate voltage measurement highly susceptible to positioning errors. In practice, this leads to large errors in crack depth predictions made with this model.

An alternative Thick Skin model developed by Lugg [40] is less sensitive to probe position:

$$a = \frac{\Delta}{2} \sqrt{\frac{V_s}{V_o} - 1} \quad (3.4)$$

where:

- a = crack depth (m)
- Δ = spacing between probe contacts (m)
- V_s = potential drop when probe straddles the crack (V)
- V_o = potential drop across reference surface, remote from flawed region. These probe positions are illustrated in Figure 3.1 (V)

Lugg cautions that while this interpretation is less sensitive to probe position, it is also less sensitive to crack depth and requires a greater region of uniform field strength. He also states that as a result of this insensitivity the model should only be used for situations where $a \gg \Delta$.

The adaptation of these models for non-ideal situations, such as sizing cracks having a small aspect ratio, is accomplished through the use of modifiers. A situation may arise where the ratio of δ/a approaches unity and neither the thick skin, or thin skin, model criteria are met. A lack of work in this area has been pointed out by Lugg and Lewis

[36, 40]. A possible solution may be to vary the current frequency and consider another regime where $\delta \gg t$ (where t is the specimen thickness). This topic appears only to have been addressed by Lewis [36] who states that in cases where $\delta \gg t$, the potential distribution may be treated in a similar manner to that of a direct current potential distribution.

3.1.2 Alternating Current Field Measurement Techniques

The Alternating Current Field Measurement (ACFM) technique is a non-contacting technique similar to the ACPD technique [41]. ACFM, developed for test conditions meeting the Thin Skin criterion by Collins et. al. [38], requires a uniform field in the specimen and directly maps components of the induced magnetic field above a specimen. Any perturbations in the magnetic field can be related to the presence of a discontinuity or flaw. There is no equivalent to the ACPD one dimensional interpretation (i.e., Equation 3.2) for ACFM; however, characteristic plots of the magnetic field combined with probe height, can be used to size cracks (this is illustrated in Figure 3.2). The ACFM method does not require any prior calibration and crack depth may be calculated from existing equations for situations where the Thin Skin criterion are met. This technique has been used successfully in field trials in the offshore oil industry and has the added advantage of not requiring any surface treatment (such as surface cleaning) or physical contact with the specimen surface.

It should be noted that ACFM calibration equations for situations other than the ideal Thin Skin case are not yet available.

3.1.3 DCPD Techniques

Like ACPD, the DCPD technique is also based on relating voltage difference to crack depth; however, DCPD systems operate differently because the injected current being used is a direct current. In a specimen, a direct current is conducted over the entire specimen

cross section—in contrast to an alternating current which is conducted through a skin along the surface. Again, the theory is based on the premise that current flow will be redirected around any flaw in the specimen, resulting in a measurable voltage change. As in the ACPD method, two readings are taken: a reading, V_c , across the crack face and a second reading, V_r , adjacent to the crack. The difference in voltage can then be calibrated to crack depth through either analytical or experimental calibration relationships. Equation 3.2 does not hold for DCPD since the current flow occurs over the entire specimen cross section. As a result, calculation of potential distribution is a three dimensional problem and more complex calibration techniques are required; these are discussed in detail in Section 3.2.

The full body conduction inherent in DCPD requires that large currents (up to 100 A) be used in order to obtain measurable voltage readings. This has many ramifications including the danger of working with large currents, specimen heating (therefore altering specimen physical properties), and the necessity for large power supplies. One technique to combat specimen heating is the use of thermally stabilized connections. A second method is to use the "reversed" DCPD technique. A reversed direct current (i.e., a non-sinusoidal alternating current) has been used by Catlin et. al. with some success [42].

A fundamentally different approach is to inject current locally—confining the potential distribution to the flawed area. This change in potential distribution allows the use of smaller currents. Costanza and Mohaupt [43] have reported using currents as low as 2.5 A with success; this is a factor of 40 lower than conventional DCPD techniques. While probe positioning becomes critical with the localized DCPD method, it does allow for increased safety and lower power requirements. A possible limitation of the localized DCPD technique is detecting crack initiation in fatigue testing. In this situation, crack initiation sites are unknown and difficult to estimate—making probe positioning a problem. The localized methods discussed by Costanza and Mohaupt, using a 5 A current, require a probe contact spacing of approximately one third of the specimen thickness.

3.2 Calibration Methods and Sources of Error

3.2.1 ACPD Calibration and Sources of Error

Calibration is the process of determining the relationship between the measured voltages and crack geometry, usually length, for a given set of test conditions and sample configuration (i.e., type of material, specimen geometry and test conditions) [44]. One of several methods may be used to do this. In simple situations (i.e., ideal Thin or Thick Skin cases), the ACPD technique does not require experimental calibration due to the simple potential distribution; mathematical models (Equations 3.2, 3.3, and 3.4) may be applied [38].

If test conditions are such that the use of the existing models is not valid, then calibration is much more complicated. Experimental calibration may be used—where voltage readings are taken for calibration notches and then applied to test data. Analytical methods may also be used to calibrate ACPD. They involve the use of techniques such as finite element or boundary element methods to predict the relationship between crack shape and potential distribution.

Regardless of the type of calibration used, the inherently small signals of the ACPD and ACFM techniques are highly susceptible to crosstalk caused by stray magnetic fields. For this reason, wires in the circuit should be shielded or carried as twisted pairs whenever possible [45, 46]. In particular, the input current leads should be led directly away from the specimen whenever possible to minimize the possibility of inducing unwanted magnetic fields in the vicinity of the specimen. If this is not possible, the wires should be carried as a twisted pair to minimize the inductive effect.

The area defined by the circuit path between the leads and specimen surface is related to the induced voltage. If the dimensions of this area are minimized the magnitude of the induced voltage will also be minimized. Figure 3.3 illustrates the area to be minimized. While a detailed proof of the relationship appears in the work of Charlesworth and Dover

[45], it is of interest to note that the ratio of V_p/V_o (where V_p is pick up or induced voltage and V_o is the measured voltage) is relatively insignificant for ferromagnetic materials. This effect is due to the higher relative permeability characteristic of such materials. The induced voltage is so small in comparison with the ohmic voltage drop in ferromagnetic materials that the induced voltage may be safely neglected [39].

One source of error, which is not readily apparent, arises from the cross section of the crack itself. A crack with depth, d , and a gap width of w , will contribute to the voltage V_c an extraneous voltage proportional to the area ($d \times w$). Mirshekar-Syahkal et. al. [47] prove this mathematically and also show that this extraneous voltage is out of phase of the signal voltage by $\frac{1}{2}\pi$. This type of error can be accounted for by using phase sensitive instrumentation.

Mirshekar-Syahkal extended the scope of this work by demonstrating that a similar phenomenon occurs with probes (see Figure 3.3). This effect may be quantified for individual probes giving subsequent voltage measurements a greater degree of repeatability.

The choice of frequency also plays a role in the amount of noise encountered during ACPD testing. The frequency of noise sources in the immediate environment should be taken into consideration to minimize interference. Furthermore, higher harmonics of these frequencies should also be avoided whenever possible as they too can distort signals in a phase locked amplifier [44]. Referring to Equation 3.1 it can be seen that a lower frequency increases the skin depth, which leads to either lower field voltages and/or the use of higher currents. At the other extreme, a frequency which is too high leads to high sensitivity to stray inductive and capacitive coupling effects. Parasitic voltages from sources such as probe loops are proportional to frequency whereas the surface voltages to be measured are actually proportional to the root of the frequency, resulting in more noise in the system at high frequencies [38]. An innovative method of minimizing system noise for ACPD testing is presented in Section 3.3.1.

The second consideration in choosing a frequency is its effect on current distribution

within the specimen. The current carrying skin depth is crucial in determining which theoretical model can be used for data interpretation; thus frequency may be used to ensure that criteria for either Thin Skin or Thick Skin models are met. In the case of commercial systems the frequency is often a predetermined value. For example, the U-7 Crack Microgauge is only capable a 6 kHz field output [48]. Values of skin depth for several materials at several common frequencies appear in Table 3.1. The wide range of skin thicknesses listed in Table 3.1 illustrates that the ACPD technique is highly influenced by the physical properties of the material to which it is applied.

Material	Frequency (kHz)	Skin Depth (mm)
Mild Steel	6	0.1
Mild Steel	0.6	0.85
Aluminum	6	1.5
Stainless Steel	0.6	20
Titanium	6	6-8
Zr-2.5Nb	6	5.1

Table 3.1 Theoretical Alternating Current Carrying Skin Thickness for Several Materials Using Typical ACPD Frequencies [36, 41, 49]

Research work is limited in the regime where neither Thick or Thin Skin models are valid (i.e., δ/Δ and δ/a are of the order of unity) [36]. This makes calibration of the ACPD technique in this regime complicated.

A potential source of error during ACPD measurements is the piezo-magnetic effect. This property changes the magnetic permeability in a sample when it is subjected to mechanical stress. This phenomenon results in a change in skin depth for the material and is therefore a concern with ACPD measurements, especially in fatigue testing. To complicate matters, this change is anisotropic. The phenomenon varies with the direction of the principle stress as well as domain magnetization and input current direction [50].

To fully understand the piezo-magnetic effect (also known as magnetostriction), the

presence and behavior of magnetic domains must be considered. Domains, although not related to composition or most other physical properties, may be considered analogous to grains in a metal. They tend to arrange themselves such that no magnetic field exists on the macroscopic level. This is essentially a minimization of what is called magneto-static energy; this is similar to the minimization of potential energy. Recognizing the existence of domains in a material, it is apparent that any distortion of the material through stress or plastic deformation will distort domain boundaries, and therefore, change the magnetic properties of a material. Conversely, the application of a magnetic field will cause small dimensional changes in a material as domain boundaries distort in an effort to minimize energy within the system.

Materials are termed as either having positive or negative magnetostriction. For example, ferritic steels and iron are classified as having positive magnetostriction. Physically this means that the application of a tensile stress will result in a decrease of the material's magnetic permeability in a direction parallel to the stress. In turn this leads to a decrease in skin depth for a given set of ACPD test conditions. Conversely, a compressive stress will result in an increase in magnetic permeability in the stress direction and a decrease in magnetic permeability normal to it. Magnetic permeability is dependent on domain structure and is therefore also affected by both elastic and plastic deformation. The phenomena of magnetostriction is an important consideration in high frequency fatigue testing of magnetic materials as the high frequencies may result in the induction of stray voltages in the specimen.

Other factors to note during calibration are temperature variations, small variations in specimen composition, and stress effects. These factors are accounted for by the use of a reference probe. When voltage data is normalized by a reference probe voltage, enhanced repeatability is observed. The method of calibration must be selected on a case-by-case basis, each situation having different requirements and limitations.

3.2.2 DCPD Calibration and Sources of Error

In the DCPD method the relationship of voltage drop to crack depth may be determined either experimentally, numerically, or analytically. Analytical methods are often best suited for situations where geometry is simple. For complex geometries, experimental calibrations often provide an easier and equally reliable method of determining the relationship between crack depth and voltage change. These techniques include: the use of an electrolytic bath, the use of conducting paper to map potential distribution, and relating data from optical techniques to potential-drop data [37, 51].

To obtain repeatable data, Wei et. al. [44] recommend that, regardless of the calibration being used, all voltage readings should be normalized so that they may be considered free of any specimen dependent effects. This is done by dividing the crack spanning voltage by a reference voltage taken on a section adjacent to the crack as follows:

$$V^* = \frac{V - V_r}{V_r} \quad (3.5)$$

where:

V^*	= normalized potential (V)
V_r	= reference voltage (V)
V	= signal voltage (V)

This procedure then results in values of potential that are entirely a function of the change in specimen resistance resulting from crack growth.

Pishva et. al. [52] used a similar approach by defining a voltage ratio parameter beta (β). The voltage parameter was calibrated against crack length in an attempt to eliminate the effects of temperature, material, and current on voltage readings (i.e., minimize the effects of the measuring equipment). The parameter is defined as:

$$\beta = \frac{(V_{on} - V_{off})_{test\ specimen}}{(V_{on} - V_{off})_{reference\ specimen}} \quad (3.6)$$

where: V_{on} = potential drop when current is on (V)
 V_{off} = potential drop when current is off (V)

Pishva et. al. expanded on work by Aker [53] by experimentally developing a calibration equation based on a/w (i.e., the area/width of a specimen) and β . The initial calibration curve was developed for nickel-based alloys at room temperature and then applied to a different alloy at high temperature (550°C). Actual crack sizes were confirmed by optical measurements.

Other techniques used to determine crack size include specimen beach marking (in fatigue testing) (Soboyejo et. al. [54]) and the use of conducting paper. The conducting paper technique has been used successfully by Hicks and Pickard [55] to determine crack lengths. The premise of the method is that current distribution is only a function of specimen profile. This allows a two dimensional representation using conducting paper. Potential is then measured for various crack lengths. This also assumes the surface crack length is a true length (i.e., no crack tunneling occurs). Ritchie et. al. [56] used the technique to determine the nature of the potential distribution in compact tension specimens for a uniform potential distribution (as opposed to a localized potential distribution).

The electrolyte-bath technique has been used with success by Burns et. al. [51] and Soboyejo et. al. [54]. This method operates on the premise that an electrolyte bath, shaped like the specimen, can accurately model the current conducting specimen. Electrodes are located at either end of the tank to simulate potential leads. The current flow in the bath is perturbed by inserting insulating material cut in the shape of a crack. Potential readings are taken using insulated probes. Once again this calibration method applies when the injected current produces a uniform potential distribution as opposed to a localized distribution.

Finite element methods have been used in an attempt to calibrate the DCPD technique since the current distribution can be modeled using Laplace's Equation. Good results have been obtained by Ritchie and Bathe [57], Aronson and Ritchie [35], and Gangloff et. al. [58] for compact tension (CT) specimens. Pishva et. al. [52] also used finite element methods to generate a voltage contour map in a CT specimen. The one drawback of the technique is that numerous stages in crack growth must be modeled to obtain calibration data. However, finite element methods can provide a relatively inexpensive tool to calibrate the DCPD technique since the need for experimental work is reduced.

Other efforts to calibrate DCPD have been analytical in nature. Johnson [59] published solutions for a plate with a symmetrical center-crack or an edge crack in 1965, followed by Gilbey and Pearson in 1966 [60]. These works were extended by Li and Wei [61] and Read and Pfluff [62], to include asymmetric center-cracks in panels. Gangloff also published work on small cracks in infinite plates. Formulas for small (semi-circular and elliptic) surface-cracks were also developed by Ikeda et. al. [63].

Recently Tada [64] has published approximate solutions for modeling surface cracks in a finite body. Tada points out that a significant back-wall effect exists if the component thickness is smaller than the surface crack length. However, Tada provides no experimental confirmation of his work. All the analytical solutions mentioned are for the case where the current distribution is uniform. Analytical methods have additional shortcomings since they do not account for changes in resistivity that could result from crack tunneling, plastic deformation at the crack tip, or temperature variations.

3.3 Applications of Potential Drop Technology

3.3.1 Applications of the ACPD Technique

One application of the ACPD technique is determining the inclination of surface cracks. Lugg et. al. [65] show that the ACPD technique operating in the Thick Skin regime can be

used quite effectively to find crack inclination to the normal of the specimen surface. This can be done by interpreting the asymmetry in the surface potential across the crack. Their work also confirms that the true Thin Skin cases are insensitive to crack inclination.

A system using fiber optics was developed by Taylor et. al. [66]. This technique has the advantage of minimizing the effect of any electro-magnetic interference in the testing area. In the Taylor apparatus, the potential drop probe (i.e., transducer) not only measures the surface potential, but also converts it to digital form, which is then transmitted through a fiber optic cable. The signal is transmitted as a series of pulses to an infra-red optical detector connected to a computer. The frequency of the pulses, which is proportional to the magnitude of the voltage measured by the transducer, is computed by the microprocessor. After nominal calibration for the given material, a calibration curve of crack depth versus pulse frequency can easily be determined before actual testing. The main advantages of a fiber optic link used in conjunction with an ACPD system are:

- i) Minimization of electro-magnetic interference.
- ii) Elimination of induced magnetic fields from current carrying wires.
- iii) Integrity of the signal is maintained during transmission.
- iv) Minimization of sparking and fire hazards.
- v) Complete electrical isolation of the system is possible.
- vi) Complete absence of ground loops.
- vii) Circuit elements are robust and have low-weight characteristics.

A further advantage to this system is its low power consumption, it can even be adapted for battery operation. This feature is particularly important in building automated systems for hazardous environments. One disadvantage however, is the need for calibration of crack depth versus frequency for each type of test piece to be used.

The ACPD technique has also been used for the measurement of stress intensity factors. Saka et. al. [67] revealed the relationship between increments of K_I and potential to be

linear; furthermore, this relationship proved to be independent of crack size under a Mode I loading condition. This technique is based on the effect of load (therefore stress) on ACPD measurements. Saka et. al. [67] carried out testing on both a ultra-high tensile strength steel (a ferromagnetic material) and an aluminum alloy (a paramagnetic material). The linear relationship between increments of K_I and potential was confirmed for both types of materials.

Conventional experimental techniques, such as methods based on photoelasticity, measurement of strain distribution using strain gages, and the method of caustics measure stress on the surface which is perpendicular to the crack front (i.e., in the vicinity of the crack tip). Using the ACPD technique, Saka measures the stress intensity factor on a face perpendicular to the crack tip as shown in Figure 3.4. Thus, measurements need not be made in a region where severe plasticity can occur.

3.3.2 Applications of the ACFM Technique

The ACFM technique, a variation on the ACPD system, has a large advantage for sub-sea weld inspections of offshore oil platforms [68]. These platforms are particularly susceptible to cyclic loading and thus fatigue cracking. The cyclic loading of these structures is a result of environmental factors such as ocean waves and strong winds. The marine environment is conducive to producing fatigue cracks and necessitates frequent inspection of the structures. Current methods of regular inspection, such as magnetic-particle inspection and ACPD, are very time consuming for two reasons. First, the surface must be cleaned and polished to a bright-metal finish, and second, instrument set up is labor intensive and difficult in the cold marine environment below an oil rig.

In contrast, the ACFM technique requires no electrical contact with the specimen surface and can also be used through coatings (either metallic or nonmetallic). The ACFM technique is particularly good for crack detection since the character of the magnetic field is such that very large perturbations occur at the crack ends. Thus, the technique is

particularly good for sizing and detecting surface breaking cracks. Recent work supported by the UK offshore industry has produced a hand-held ACFM probe which has performed well in test trials [41]. The use of ACFM would significantly reduce cost as a result of shorter inspection times as well as improve safety since the diver does not have the added responsibility of interpreting and/or reporting results. This is a relatively new, but promising, technique.

3.3.3 Applications of the DCPD Technique

Crack detection, sizing and growth in a variety of situations are common applications of the DCPD method. Hallett and Licht [69] utilized a unique approach by using the method to detect wall thinning due to corrosion and erosion. The technique is quite simple. Measurements are taken at two different locations of an unflawed component and any difference in voltage readings is explained by a difference in wall thickness:

$$\frac{V}{V_o} = \frac{t_o}{t} \quad (3.7)$$

where:

V	=	potential drop corresponding to thickness t (V)
t	=	present thickness of specimen (m)
V_o	=	initial potential drop of sample (V)
t_o	=	initial thickness of specimen (m)

The assumption behind this equation is that material is uniformly corroded on the surface being considered; and therefore, can also be considered in terms of mass loss.

Catlin et. al. [42] successfully applied reversed DCPD technology to both static and cyclic crack-growth in high-temperature pressurized water. They reported success in using a reference probe for temperature compensation as well as the use of multiple probe pairs to accurately determine changes in crack size and shape over time.

3.4 Application of Potential Drop to Zirconium Alloys

Applications of potential drop technologies to zirconium alloys has been limited. Currently all CT testing conducted at AECL uses DCPD to measure crack length. In the past, work has been done by Hallett & Licht [69] (in addition to their work on detection of pipe wall thinning) in applying potential drop technology to zirconium alloys. Specifically, they did work on sizing cracks in CANDU (Zircaloy-2) pressure tube rolled joint assemblies. The mathematical model they used (the origins of which are not stated in the publication) consistently underestimated crack depth. They felt that the sources of error included poor electrical contact of the leads, crack face contact due to bridges, oxide, or stress induced crack closure. In doing work with crack growth in calandria tubes, they found large voltage changes when cracks grew deeper (through the wall) and smaller voltage changes as cracks grew longer.

Davies and Stearns [70] used potential drop in fracture toughness testing of Zircaloy-2 specimens (made from rings of pressure tube material). They attempted to calibrate the DCPD technique assuming a linear relationship between voltage drop and crack length. More recent work has found that this relationship is not linear. Davies and Stearns were not successful in calibration; however, they surmised that sources of error included bridging across crack face due to the presence of hydrides, and possibly plasticity effects influencing voltage readings.

Figure 3.1 ACPD Voltages Measured For a Surface-Breaking Crack [40].

- (a) Probe positions.
- (b) Voltage trace for a probe traversing a uniform depth crack with a small skin depth
- (c) Voltage trace for a finite length crack or for a large skin depth.

Figure 3.2 Magnetic Field Variation Around a Surface Breaking Crack [50].

The crack is shown at the top. Theoretical plots of the magnetic field variation in the x, y and z directions are shown in (a), (b) and (c).

Figure 3.3 Illustration of a Probe Loop Resulting in Parasitic Voltages [45].

The pickup loop, formed between the probe and specimen surface, should be minimized to reduce noise in the signal.

Figure 3.4 **Location of Stress Intensity Measurement Using ACPD [67].**
The stress intensity measurement is made on Surface A of the component—remote from any crack tip plasticity effects.

4 Experimental Equipment and Program

4.0 Introduction

The specimen characteristics, experimental equipment, and test program are described in this chapter. In developing the experimental program, it was important to subject the techniques to conditions relevant to this application. A brief explanation of the constant load pressure tube burst test procedure used at Chalk River Laboratories (CRL) is followed by a description of the experimental program.

The test program consisted of three parts. Parts I (a comparison of ACPD and localized DCPD methods) and III (a localized DCPD study) were carried out at Carleton University. Part II (ACFM testing) of the test program was carried out at Technical Software Consultants (TSC) located in Milton Keynes (England) by Mr. David Broom and at the Non-Destructive Examination (NDE) Center at University College London (UCL) in England by Dr. Martin Lugg. Testing at both sites was conducted in the presence of the author.

4.1 Pressure Tube Burst Testing

The constant load burst testing procedure at CRL requires an approximately 450 mm long section of pressure tube with a 15-20 mm long, and 1-2 mm deep, starter notch on the inside wall. The test sections have been previously irradiated since they are cut from pressure tubes taken out of service. This necessitates the use of a "hot" cell which isolates the irradiated material. All material within the "hot" cell is handled by remote manipulators.

For burst testing, the tube section is attached to an existing apparatus that facilitates heating and internal pressurization of the specimen. The pressure tube section is raised to a temperature above 290°C for three hours so that any hydrides present will dissolve. As the test section approaches test temperature, it is also pressurized to 10 MPa (1450 psi). To do this, a gas cylinder pressurizes water inside the tube section. To heat the pressure tube from the inside, as would occur in-service, a heater is placed inside tube section. Since the pressure tube is thin walled, the temperature gradient across it is negligible. Following the three hour period at 290°C, pressure is maintained while the test temperature is dropped to a value such that the solubility of limit of hydrogen in the metal is exceeded. Typically, this temperature is between 200°C and 250°C depending on the hydrogen content of the material [3]. A plot of burst test temperature and pressure versus time appears in Figure 4.1. This process results in conditions favorable for crack growth through the DHC mechanism.

In most cases, a 12 hour period is required for the crack to grow through the wall of the pressure tube section. This can be detected through a pressure drop and leakage of water from the pressure tube section. Once the crack breaks through the wall, the experiment is stopped and the apparatus dismantled. This allows the placement of a liner inside the pressure tube—sealing the leak to make pressurization possible. Without the seal, a large make-up system would be needed to maintain pressure at 10 MPa inside the tube section. The test is resumed at the previous temperature and pressure until the crack causes the pressure tube section to burst. This burst is contained by the bell jar which encloses the apparatus. An illustration of the apparatus appears in Figure 4.2.

The burst testing apparatus consists of a bell jar used for the containment of hot water and steam during burst tests. It is attached to a platform with four connecting bolts. Inside, the pressure tube section, with end caps, is also fixed to the platform. All piping/wiring for the heater and pressurization equipment is carried out of the bottom of the test section. Any wiring is carried to a separate room since computers and control boxes are placed outside the hot cell.

The nature of the burst test procedure requires that the crack measurement system must be operational in a radiation field, at temperatures up to 300°C, with intermittent exposure to steam and hot water. These requirements are discussed further in Section 4.5.

4.2 Test Specimens

Two plates and a pressure tube section were used for testing. The plates, obtained from CRL, were manufactured to produce material properties similar to real pressure tubes.

A layout of Plate #1 appears in Figure 4.3. It has the same thickness as a pressure tube, 4.2 mm, and is 650 mm × 300 mm in size. A summary of sawcut characteristics (henceforth referred to as cracks) appears in Table 4.1.

Crack #	Length (mm)	Width (mm)	Depth (mm)	Profile	
1	29.5	< 0.25	2.1	Semi-Elliptical
2	35.5	< 0.25 to 0.5	4.2	Semi-Elliptical
3	33	1.14	1	Semi-Elliptical
4	33	0.33	1	Semi-Elliptical
5	60	1.14	2.1	Ramped
6	56.5	0.33	2.1	Ramped
7	101	0.33	4.2	Ramped
8	110.5	1.14	4.2	Ramped
9	27	0.33	1	Semi-Elliptical
10	29.5	0.33	2	Semi-Elliptical
11	33	0.33	3	Semi-Elliptical
12	37	0.33	4.2	Semi-Elliptical

Table 4.1 Summary of Plate #1 Crack Characteristics

It should be noted that the sketch illustrating crack profile is *not* indicative of crack depth, only shape.

Twelve sawcuts of varying geometries were made in this plate to simulate cracks. Crack geometries were determined visually with the aid of a ruler, feeler gauges, and wire (used to determine crack depth at various points). There were two basic crack profiles used in this study: semi-elliptical and ramped. A ramped profile, illustrated in Table 4.1, is one where the crack depth increases gradually, and linearly, to its maximum.

Plate #2 is also composed of Zr-2.5Nb alloy but has a slightly larger thickness of 4.5 mm. A schematic of this plate showing crack locations appears in Figure 4.4. This plate had three sawcuts made in it to simulate cracks. A summary of crack dimensions and shapes appears in Table 4.2.

Crack #	Length (mm)	Width (mm)	Depth (mm)	Profile	
13	19	0.33	2.5	Semi-Elliptical
14	53	0.33	4.5	Semi-Elliptical
15	108	0.33	4.5	Ramped

Table 4.2 Summary of Plate #2 Crack Characteristics

Plate #2 was used primarily for ACFM testing, and limited ACPD testing, which was carried out by The NDE Center and TSC in the U.K..

A 366 mm long pressure tube section was also available to provide a mock-up for the apparatus. The pressure tube has a wall thickness of 4.2 mm with an outer diameter of 104.5 mm, a schematic of which appears in Figure 4.5. A summary of the sawcut geometries on the pressure tube section appears in Table 4.3. The branched geometry of Crack #17 resulted when two passes with a saw were used; however, misalignment led to the crack having its left side diverge into two, slightly separated, branches.

Crack #	Length (mm)	Width (mm)	Depth (mm)	Profile
16	36	0.3	4.2	Semi-Elliptical
17	41	0.1-0.6	4.2	Branched & Semi-Elliptical

Table 4.3 Summary of Tube Section Crack Characteristics

4.3 Test Equipment

4.3.1 Localized DCPD Equipment

The localized DCPD testing was done using a PC-controlled MDT Model 100 multi-channel data acquisition system produced by the MDT Company of Waterloo, Ontario. Data acquisition was accomplished using a personal computer in conjunction with the MDT 100 system and accompanying software. In order to facilitate use with a positioning frame, the software had previously been modified at Carleton University [71, 72].

Initial testing was conducted using spot-welded zirconium-wire contacts spaced 10 mm apart. A wire wrapping technique was used in order to connect the spot welded contacts to twisted shielded cable. A photograph of the fixed array appears in Figure 4.6. During testing, the 10 mm contact spacing did not provide sufficient sensitivity so the spot welded probes were removed.

The removal of the fixed array facilitated the use of a moveable (four contact) probe. The spacing between the contacts was 2 mm. As Figure 4.7 illustrates, the outer two contacts were used to input the 2.5 A direct current and the inner two were used to sample the voltage drop. The probe was constructed using spring loaded ("pogo") contacts fixed in a Plexiglas template with epoxy. The contacts were then soldered to shielded, twisted cable which was connected to the data acquisition system. The probe was then mounted on a computer controlled positioning frame. The frame consisted of a collar traveling on a

stepper-motor-driven lead screw. The probe could also be positioned manually. A schematic of typical equipment layout appears in Figure 4.8 with photographs of the probe and positioning frame appearing in Figures 4.9 and 4.10 respectively.

The software used for testing had been previously modified at Carleton University [72]. The software allowed the user to choose the size of the scan area, the number of scans of the specified area, the distance between each reading, and the number of samples averaged for each reading. It then provided a text file which recorded position and the corresponding voltage reading for each trial.

To insure good contact between the probe and test plate, fine grained sandpaper was used to remove oxide from the surface of the plate. Interference of this oxide layer with voltage readings was observed in earlier testing [72]. Also, for backside testing a permanent marker was used to mark crack start and end points in order to facilitate probe positioning, and later, the plotting of data. The significance of using this technique is discussed in Chapter 5.

High temperature testing was conducted using an equipment setup similar to that illustrated in Figure 4.8. The setup was modified simply by placing hot plates under the Zr-2.5Nb plate. The positioning frame was placed over the flawed region while the remainder of the plate was covered with foil-backed fiber glass insulation. An Omega 2168A digital thermometer was attached to the plate to allow temperature monitoring. The highest temperature possible with the equipment was 242°C. The plate was heated for one hour prior to testing to insure the system had reached equilibrium.

4.3.2 ACPD Equipment

Preliminary ACPD testing was carried out using a Unit Inspection Limited U-7 Crack Microgauge. In this case, the potential field was injected at the ends of the plate using two leads screwed to the specimen. As with the localized DCPD testing, initial testing was carried out using fixed probe contacts which proved to be unsatisfactory.

Two different types of moveable probes were used for ACPD testing. Figure 4.11 illustrates the two types of moveable probes. The first set of tests used a three contact probe (similar to localized DCPD probes) where one channel was used to measure the voltage drop across the crack and a second channel was used to measure a reference voltage. A Keithely 706 Switching Unit was used to facilitate multi-channel data acquisition. The second set of tests utilized a single channel and a two contact probe which was used to sample both the reference and crack voltages. This was done in an effort to minimize noise and signal degradation by minimizing cable length and instrumentation.

Data acquisition was accommodated by using a personal computer in conjunction with the Crack Microgauge Unit [46]. A typical equipment layout appears in Figure 4.8.

Limited ACPD testing was carried out at The NDE Center at University College using a U-10 Crack Microgauge. The U-10 Crack Microgauge has multi-frequency capability and incorporates recent advances in electronics technology.

4.3.3 ACFM Equipment

ACFM testing was carried out at the facilities of TSC in the presence of the author. A U-10 Crack Microgauge was used in conjunction with both hand and automated positioning of the probe. Plate #2 was used for this portion of the testing. Automatic positioning was accomplished by the use of a stepper-motor-driven lead screw mounted in a frame, similar to the one described earlier. The probe used for room temperature tests was one previously developed at TSC for "small" specimen sizes.

Limited high temperature testing was done by heating the test plate for one hour at 300°C before taking readings. The high temperature tests utilized a probe rated for temperatures up to 600°C. It is of importance that the probe used for high temperature testing was originally constructed for much larger component sizes. This point is discussed further in Chapter 5.

4.4 Test Program

The test program consisted of three major sections. Part I was a brief study comparing the ACPD and localized DCPD techniques and was carried out using the equipment available at Carleton University. Part II involved ACFM testing at the NDE Center and TSC facilities in the U.K.. Part III, a more extensive study of the localized DCPD technique only, was conducted at Carleton University .

4.4.1 Comparison of ACPD and Localized DCPD Techniques

Part I of the program involved testing both the ACPD and localized DCPD systems. Readings were taken primarily for Crack #2, on the frontside, since a method incapable of detecting a through-thickness crack would not detect a shallower crack.

Test #	Technique	Probe Type	Probe Configuration	Probe Positioning
1	ACPD	Fixed	3 Contact with Switching Unit	Fixed Array
2	Localized DCPD	Fixed	4 Contact with MDT M100 Unit	Fixed Array
3	ACPD	Moveable	3 Contact with Switching Unit	Manual
4	ACPD	Moveable	2 Contact no Switching Unit Shortened Cables	Manual
5	ACPD	Moveable	2 Contact no Switching Unit Shortened Cables	Automatic
6	Localized DCPD	Moveable	4 Contact with MDT M100 Unit	Manual
7	Localized DCPD	Moveable	4 Contact with MDT M100 Unit	Automatic
8	Localized DCPD (242°C)	Moveable	4 Contact with MDT M100 Unit	Automatic
9	DCPD (Tube Section)	Moveable	4 Contact with MDT M100 Unit	Automatic

Table 4.4 Test Program Comparing ACPD and Localized DCPD Techniques

Table 4.4 shows the test program carried out to compare the performance of the ACPD and localized DCPD techniques. This portion of the study consisted of frontside tests only. The frontside of the plate is considered to be the surface breaking side of the crack while the backside is opposite to that. For through-thickness cracks (i.e., a crack which breaks through both surfaces of the plate), the surface with the longest crack length is considered to be the frontside. Numerous trials were performed for each test configuration to ensure the repeatability of data.

ACPD testing initially involved the use of spot welded zirconium wire contacts spaced 10 mm apart. Since the initial probe configuration did not give satisfactory results, testing was continued using a moveable probe. The moveable probe was connected through existing cables to a switching unit and a computer for data acquisition. To minimize noise levels, all wiring was secured to prevent movement of the current leads. Several trials were conducted on Crack #2 but the results were not satisfactory. Thus, in an effort to reduce noise pickup, existing connections and the switching unit were by-passed. The probe was then connected directly to the U-7 Crack Microgauge through a low noise connector. High temperature tests were not conducted for ACPD since test configurations, subsequent to the first hand held probe test, were unable to detect the presence of a crack.

Initial localized DCPD testing (Test #2) used spot welded zirconium wire contacts spaced 10 mm apart. This spacing did not provide sufficient sensitivity so further testing used a moveable probe with a 2 mm contact spacing. During Tests #6 and #7 both manual and automatic probe positioning was used. Since promising results from Tests #6 and #7 were obtained, the technique was subjected to the same test at high temperature (242°C).

Finally, localized DCPD testing was also carried out on pressure tube section (Test #9). Probe placement for this test was done automatically using the positioning frame. The pressure tube test was done to ensure that potential drop measurements remained unaffected by a change in geometry—confirming that the potential distribution was localized.

4.4.2 ACFM Testing

The ACFM testing was conducted at the TSC facilities in Milton Keynes and the NDE Center in London (England). Testing was conducted at both room temperature and high temperature (300°C). A summary of the tests performed appear in Table 4.5.

Test #	Technique	Probe Type	Probe Configuration	Probe Positioning
10	ACFM	Moveable	U-10 Microgauge	Automatic
11	ACFM (300°C)	Moveable	U-10 Microgauge	Manual
12	ACPD	Moveable	2 Contact U-10 Microgauge	Manual

Table 4.5 ACFM and ACPD Testing Carried out at Technical Software Consultants and University College in London

A specialized high temperature probe was used for the 300°C testing. Time constraints did not allow for more extensive testing of either the ACFM or ACPD technique.

4.4.3 Localized DCPD Study

The third part of the test program involved a more extensive study of the localized DCPD technique. Plate #1 was used for this group of tests. Table 4.6 shows the experimental program undertaken for this portion of the work. Once again, the frontside of the plate is considered to be the surface breaking side of the crack while the backside is opposite. In the case of through-thickness cracks (i.e., a crack which breaks through both surfaces of the plate), the surface with the longest crack length is considered to be the frontside. Each configuration was tested a minimum of five times upon which standard error calculations are based.

All voltage data was plotted, along with actual crack depths, as a function of distance along the plate. Standard error (standard deviation/sample size) was also calculated and

plotted for each point. In many cases, the error values are too small to be visible on the graphs. A sample calculation of standard error appears in Appendix D.

Crack #	Type of Test:		
	Front Side	Back Side	Other
1	X	X	
2	X	X	-High Temperature
3	X	X	
4	X	X	
5	X	X	
6	X	X	
7	X	X	
8	X	X	
9	X	X	
10	X	X	
11	X	X	
12	X	X	-Boiling Water -Contact Pressure

Table 4.6 Test Program for localized DCPD Study

The objective of this part of the testing was defining the limitations of localized DCPD. Boundaries such as minimum detectable crack depth, repeatability of data and sensitivity to crack geometry needed to be determined. Also, since the crack measurement equipment is to be placed outside the pressure tube during burst testing (with the crack to be measured usually on the inside wall of the tube) both front and backside testing was necessary.

The technique was also tested under high temperature since it would be subjected to temperatures up to 300°C in-service. The nature of burst testing also required study of the effect of boiling water and steam on localized DCPD performance. These tests were carried out at room temperature and pressure due to limited equipment available for testing.

The effect of contact pressure was also studied since in previous work the effect on contact pressure on voltage readings was noted [72].

4.5 Apparatus Design

The nature of the pressure tube burst testing imposes numerous conditions on the design of the crack measurement system. Considerations arise from the previously irradiated pressure tube sections being tested. The entire experiment is conducted in a "hot" cell in order to isolate the irradiated material. Thus, any equipment to be used, including the crack measurement system, must remain operational in a radiation field. The apparatus must also be compatible with the remote manipulators.

The effect of radiation on materials must be considered during the design process. Steel exposed to radiation experiences an increase in its yield and ultimate strengths. The magnitude of this effect is dependent on several factors such as the amount of exposure to radiation, the microstructure of the steel, and temperature. However, data indicates that a fluence of at least $5 \times 10^{22} \text{nm}^{-2}$ (fast neutrons) must occur before appreciable damage occurs in steels [73]. Radiation damage in metals is usually reversible through post-irradiation treatments.

In polymeric material, damage is not reversible since radiation affects covalent bonding in the material causing chemical changes. Radiation induced changes are quite varied depending on the polymer; the eventual result of these changes is a breakdown of the material either through embrittlement or severe "softening" [74]. Thus, material selection for automated crack measurement system must lead to a radiation resistant design.

Another important design consideration is compatibility with manipulator arms. While a skilled operator can accomplish fairly complicated tasks, even the simplest operation is time consuming. There is also a limitation in the size of the components of the apparatus since small objects can be difficult to grasp. Thus, the components of the apparatus must be simple and robust in order to survive the potentially rough handling. The assembly of the apparatus itself must also be straightforward—not requiring extremely detailed work. Thus, radiation resistance and manipulator compatibility were of primary importance

beyond standard design considerations for the automated crack measurement system.

Figures 4.12 and 4.13 are schematics of the proposed design. The crack measurement system is to be compatible with the current burst test apparatus. The assembly consists of two support columns fixed to two end plates. The end plates are secured to the pressure tube section itself using flexible metal strips and an easily grasped tension latch. A lead screw extends from the bottom endplate and extends outside the bell jar (which will be modified to accommodate this). The lead screw is engaged by the stepper motor through a flexible coupling. The detachable coupling has two parts: a male end (mounted on the lead screw) and female end (mounted on the stepper motor shaft) to prevent misalignment. The probe assembly is mounted on a collar which travels along the lead screw, guided by the support columns.

The probe and moving collar appear in Figure 4.13. The probe is to be manufactured as a "cartridge" so that it may be attached to the collar after the lead screw assembly has been attached to the burst test apparatus. This is done in order to protect the fragile probe contacts. Wires connected to the probe contacts will be carried away from the probe cartridge as twisted shielded cable. The wiring will include connections for a reed switch that is to be mounted on the probe. The reed switch, in conjunction with magnets mounted on either end plate, will allow accurate positioning. The reed switch will be activated as it approaches either end plate—stopping the collar. This will prevent jamming of the collar against the end plates and provide a reference position for subsequent voltage measurements.

Some modification of the burst test apparatus is necessary. This includes cutting a hole near the top of the bell jar to allow the lead screw, and the female end of the coupling, to protrude from the assembly. The bell jar will be further modified by the addition of a motor housing. Since the motor is not rated for high temperatures, positioning it outside the bell jar containment will prevent exposure to high temperature water and steam during the burst test. The motor will be further protected by a flexible "flap" which will be placed

over the hole in the bell jar to limit, and deflect, any escaping steam. Placement of the stepper motor in the housing and engaging the coupling is to be the last step during apparatus assembly.

Alignment of the bell jar cut-out with the lead screw will be accomplished through distinct markings to be painted onto both the bell jar and pressure tube (this will also ensure alignment of the crack measurement equipment with the starter notch on the pressure tube).

The procedure for assembling the apparatus will need to be modified in order to accommodate the crack measurement system. As before, the pressure tube and equipment necessary for heating and internal pressurization will be assembled. However, once the pressure tube section has been mounted to ensure that starter notch is aligned with the markers mentioned earlier, the lead screw and supporting frame will be mounted. At that point, the probe cartridge will be inserted into the moving collar. The bell jar will then be placed over the assembly, ensuring that the top of the lead screw is protruding from the opening. The last step in the procedure would be to mount the stepper motor in its housing while ensuring the detachable coupling has been correctly engaged.

4.6 Software Design

The nature of the burst testing procedure also demands that certain features be incorporated into the software accompanying the crack measurement apparatus. Like the program used for the present project, the two basic functions of the software will be to control positioning of the probe and data acquisition. Once a calibration curve has been developed for pressure tube burst test conditions it can also be incorporated into the software. A simple chart showing the basic software structure, from the user's perspective, appears in Figure 4.14.

The probe positioning, a prime function of the software, is to be accomplished through the use of a stepper motor. Thus, the program must be capable of changing the direction of the stepper motor and determining the probe position by counting the steps. In addition, a

reference position must be established so that positioning is accurate, and consistent, over numerous tests. This will be accomplished with the aid of a reed switch mounted on the moving collar. As mentioned in Section 4.5, the switch will close (or open) as it approaches magnets mounted on either end plate; the activation of this signal can be used to stop the motor and establish a reference point upon which subsequent position measurements can be based.

The software will also be interfaced with the localized DCPD measurement system allowing it control data acquisition. The program must allow the user to choose features such as the sample size for each reading, the distance between readings, how the position and voltage data is to be recorded, and the size of the area to be scanned. Once calibration is complete, the software should be able to present raw data as well as calibrated data. Also, as with any software, while accomplishing its basic functions the software should be simple and provide the user with as much flexibility as possible.

Figure 4.1 Pressure Tube Burst Test Temperature and Pressure vs. Time [3]

This graph is representative of the conditions used to induce DHC growth in pressure tube sections during burst testing. A temperature of 200°C to 250°C is usually necessary to induce the precipitation of hydrides. This temperature varies with the hydrogen content of the specimen.

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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PRECISIONSM RESOLUTION TARGETS

Figure 4.2 Pressure Tube Burst Test Apparatus used at Chalk River Laboratories

The pressure tube section is placed in this assembly for burst testing. The section is heated and pressurized internally to maintain conditions favorable for DHC growth. All units on drawing are in inches.

Figure 4.3 Zr-2.5Nb Test Plate #1

This plate was used for Parts I and III of the test program. Crack locations are indicated by their respective numbers. Detailed crack geometry appears in Table 4.1.

Figure 4.4 Zr-2.5Nb Test Plate #2

This plate was used for Part II of the test program. Crack locations are indicated by their respective numbers. Detailed crack geometry appears in Table 4.2.

Figure 4.5 **Zr-2.5Nb Pressure Tube Test Section**

A section of pressure tube was available for testing. Crack locations on the section are indicated by their respective numbers. Detailed crack geometry appears in Table 4.3.

Figure 4.6 **Fixed Array used for Initial Localized DCPD and ACPD Testing**

The probe contacts are zirconium wire spot welded to the plate. Contacts were linked to the data acquisition system through wire wrapped connections which were soldered to four-conductor shielded cable.

Figure 4.7 Schematic of Moveable Probe Used for Localized DCPD Testing

The moveable probe used for localized DCPD tests has four equally spaced "pogo" contacts. The outer two probe contacts were used for current input and the inner two contacts were used for voltage measurement. This produces a very localized potential distribution in the specimen. Figure is not to scale.

Figure 4.8 Block Diagram of the Localized DCPD and ACPD Equipment Layout

This representation includes the positioning frame used for automated positioning. The MDT M100 system was used for localized DCPD testing and the U-7 Crack Microgauge was used for ACPD testing. Also, the electric field was input at the plate ends only for ACPD testing. (Input of the electric current for the localized DCPD method was done using probe contacts).

Figure 4.9 **Moveable Probe Used for Localized DCPD and ACPD Testing**

For localized DCPD testing the outer two contacts were used for current injection and inner two contacts were used for potential readings. For ACPD testing, a similar two-contact probe was used to obtain potential readings. The probe contacts are spaced 2 mm apart.

Figure 4.10 Photograph of Zr-2.5Nb Test Plate #1 and Positioning Frame

The positioning frame was used in conjunction with a personal computer to facilitate automatic positioning and data acquisition for ACPD and localized DCPD tests. The probe was attached to the moving collar (on the positioning frame) using a thumbscrew.

(a)

(b)

Figure 4.11 Schematic of Moveable Probes Used for ACPD Testing

- (a) The three-contact probe used for ACPD testing is shown. Both the reference voltage and the voltage across the crack may be measured by placing the probe in a single location.
- (b) The two-contact probe used for ACPD testing is shown. To obtain voltage measurements in both the flawed and unflawed regions (i.e., V_C and V_r), the probe was placed in two locations.

Figure 4.12 Schematic of Proposed Apparatus Design

Note that the stepper motor is housed outside of the bell jar for protection from steam, hot water, and heat. Also, the motor is coupled to the leadscrew with a detachable, flexible coupling. The apparatus is fixed to the pressure tube section with metal strips secured with easily grasped latch hooks (not shown for clarity). A schematic of the proposed collar design appears separately in Figure 4.13.

Figure 4.13 Schematic of Proposed Collar Design

Note that the probe itself is removable so that it may be added once the apparatus is assembled (it is secured to the collar with a thumbscrew). This will protect the fragile probe contacts since the probe may be mounted on the collar after assembling the majority of the apparatus. The collar travels on two guide columns and a lead screw used for accurate positioning.

Figure 4.14 Flowchart of Proposed Data Acquisition Software

A flowchart of the proposed software structure is presented from the point of view of the user. Each block contains the variables that the user may customize for individual pressure tube burst tests. In order to accomplish this, the software must be linked to the stepper motor controller, the MDT system, reed switch, and a personal computer.

5 Results and Discussion

5.0 Introduction

The majority of results are presented in the form of graphs which appear in Figures 5.1 through 5.31. The range of the vertical axes on the plots has been varied to accommodate variations in the test data and to provide clear presentation of results. Also, each major division of the experimental program is discussed individually to illustrate the logical progression of the test program.

5.1 Comparison of ACPD and Localized DCPD Techniques

Several observations can be made based on preliminary testing. Initial results indicated that the localized DCPD technique is better suited for this application. This technique was capable of detecting the presence of a crack and produced data that was repeatable.

Figure 5.1 is a plot of normalized voltage and actual crack depth versus position on the plate for a typical localized DCPD test. Note that the results plotted are normalized voltage and not predicted crack depth. In order to plot predicted crack depth values, a calibration curve specific to the test conditions is needed. However, the normalized data does show that the localized DCPD technique gives a good indication of the crack shape and its surface breaking points. High temperature does affect localized DCPD measurements, but not the accuracy of the method, as can be seen from Figure 5.2 which presents the results of a test at 242°C. This result is of particular importance since pressure tube burst testing requires temperatures up to 300°C.

Localized DCPD testing was conducted on the pressure tube section to ensure that the performance of the localized DCPD technique was not significantly affected by a change in geometry. The unnormalized results of the pressure tube test are plotted in Figure 5.3. This figure illustrates that localized DCPD prediction of the crack shape, and its surface breaking points, is comparable to tests carried out on the plate sections. Further considering Figure 5.3 in conjunction with Figure 5.15 (a frontside test on Crack #9), it can be seen that voltage readings for cracks of equal depth on a plate and a tube section are similar. These results confirm two important points. First, the performance of the localized DCPD technique is virtually unaffected by the change in specimen geometry (i.e., the localized DCPD method provides similar results for cracks on a pressure tube section and a Zr-2.5Nb plate of equivalent thickness). Thus, if the technique was to be developed further, the pressure tube geometry does not appear to hinder the performance of the localized DCPD technique. Second, the use of plate sections, which are more readily available, for the preliminary study of localized DCPD characteristics on Zr-2.5Nb is valid.

The ACPD testing had limited success. It was found that ACPD is capable of detecting a through-thickness crack using a specific probe configuration (Test #3) but is unable to provide accurate depth data as can be seen in Figure 5.4. ACPD susceptibility to interference from stray electrical and magnetic fields had proved to be a problem during testing. While all leads were shielded, taped down and carried as twisted pairs whenever possible, the stability of the U-7 Crack Microgauge was poor when used on Zr-2.5Nb. The small signals to be measured with Zr-2.5Nb, combined with the limited noise filtering capability of the U-7 Crack Microgauge, led to a high degree of uncertainty in the readings.

Test #4 was an attempt to improve results by reducing signal noise. All wiring was shortened as much as possible and the Keithely switching unit was bypassed. This test configuration (Test #4) did not provide satisfactory results as can be seen in Figure 5.5. The plot illustrates that the technique was unable to detect the presence of a crack. It should be noted that Figure 5.5 is the plot of a single trial since data was highly unrepeatable.

The limited success of ACPD is partly due to the equipment available for use. The U-7 Crack Microgauge, available at Carleton University, is limited to a field output frequency of approximately 6 kHz [38]. In Zr-2.5Nb, this leads to a calculated skin thickness of 5.13 mm; this is greater than the 4.2 mm thickness of the plate. Detailed calculations for skin thickness appear in Appendix C. A problem is introduced since the value of δ/a (≈ 1) invalidates the use of both theoretical models (Equations 3.2 and 3.3) discussed earlier.

The use of multi-frequency equipment would allow the skin thickness to be varied as indicated by Equation 3.1. Either higher or lower frequency currents would alter the skin thickness. For example, increasing the current frequency would lead to a smaller skin thickness. Thus, to measure a 0.5 mm and meet the criteria for Equation 3.2 (Thin Skin model), a frequency of over 50 MHz would be necessary. Such a high frequency current does not present a viable solution since it would lead to increased noise, without significant increase in potential drop readings.

The use of a lower frequency current however, presents the possibility of experimental calibration. Lewis [36] states that if the condition: $\delta \gg t$ is met, the (ACPD) potential distribution is similar to a DCPD case—facilitating calibration through standard DCPD methods. A current of 100 Hz would result in a skin thickness that is approximately 40 mm, meeting the condition stated by Lewis. The magnitude of current necessary for application of ACPD at this frequency may be higher since full body conduction of the current would be occurring. Information regarding this particular method is sparse and would have to be determined experimentally.

The multi-frequency testing is possible with the U-10 Crack Microgauge, a more recent version of the U-7 and incorporates recent advances in electronics. Limited ACPD testing was conducted using a U-10 Crack Microgauge at University College in London. While the data could not be recorded and testing was limited to 6 kHz, the U-10 displayed significantly greater stability than the U-7 when used on Zr-2.5Nb. The newer equipment was unavailable for further study at Carleton University.

5.2 ACFM Testing

The results of an ACFM backside and frontside scan on Crack #15 appear in Figures 5.6 and 5.7. The plots illustrate the variation of magnetic field values (not predicted crack depth) along the length of a crack.

There are several characteristics of the ACFM technique which are of importance. The technique is very sensitive to abrupt changes in crack profile. Figure 5.6 is a plot of a frontside scan of Crack #15 which has a ramped profile. The figure illustrates that the technique is unable to discern the surface breaking point of the crack when the geometry changes gradually (i.e., at the ramped end). However, the method is very sensitive to the left end point of the crack where the geometry varies rapidly. Thus, the surface breaking points of most real cracks, which intersect the free surface at or near 90° , would be easily detected by ACFM methods.

The ACFM technique is also effective in detecting cracks from the backside as can be seen in Figure 5.7. As in the frontside scan, the technique is very sensitive to sharp changes in geometry while the beginning or end of a very shallow crack is indistinguishable. The sensitivity of the method remains unchanged regardless of the side on which the specimen is scanned. This is illustrated by the virtually identical magnetic field plots for both the front and backside scans in Figures 5.6 and 5.7 respectively. ACFM scans at high temperature were similar to room temperature tests and produced stable readings. Data from high temperature testing, conducted at UCL, is unavailable.

The primary advantage of the ACFM technique is that no physical contact is required with the specimen. The data presented in Figures 5.6 and 5.7 was taken without physical contact, and without removal of any oxide from the specimen surface. This presents a clear advantage over techniques that require surface cleaning since specimen preparation time is reduced—especially in a hostile environment.

There do, however, appear to be limitations to the ACFM method. As mentioned in Chapter 4, the probe used for room temperature ACFM tests had previously been developed at TSC for relatively small specimen sizes. During testing it was found that the probe still had a large scanning area for the test plate (i.e., Plate #2). In some cases interference from the specimen edges, which present an abrupt change in geometry, would mask the signal of the crack being scanned. The scanning area of the probe is a function of the size of the wire loop used to sample the magnetic field. The wire loops used to sample the field may be reduced in size, but only to a point. The wire loops used in the room temperature tests were approximately three millimeters in diameter. Thus, physically, it would be difficult to reduce the probe scanning area much further with the present technology.

The physical limitation of probe size has several implications. Attempts at crack measurement on a small specimen will detect the edges of the component. Thus, interference from the component edges would complicate any attempts at measurement. Similar concerns would arise if multiple cracks existed in a small region. Since the pressure tube sections used at Chalk River are similar in size to the test plate, the large probe scanning area is a major constraint in developing this method of crack detection.

Another limitation to using ACFM for this application is that the method is capable of crack detection in Zr-2.5Nb, but crack sizing is not possible at the present time. Since the main thrust of research at TSC and the NDE Center has been detection and sizing of cracks in structural steels, several features have been incorporated into the U-10 software that are not suited to DHC crack sizing in zirconium alloys. Due to the large physical size of the structural components, and the material properties of steel, it is possible to use an extension of the simple "Thin-Skin" model for crack depth prediction. Furthermore, fatigue cracks in such components tend to take the ideal shape of a semi-elliptical surface breaking crack. This characteristic further simplifies data reduction and the incorporation of a calibration model for sizing cracks in the U-10 software.

The attempt to use the U-10 Crack Microgauge to size cracks in a zirconium plate gave erroneous values due to the inappropriate assumption of "Thin Skin" conditions inherent in the software. Theoretical calibration of the ACFM technique for use of Zr-2.5Nb is not possible at this time due to a lack of valid mathematical models for this material [36, 40]. There may be potential for experimental calibration of the technique; however, literature in this area is sparse.

The ACFM technique requires extensive development before it may be used to size DHC cracks in Zr-2.5Nb. Although beyond the scope of this project, the technique does present potential for successful crack detection in zirconium alloys with the significant advantage of not requiring physical contact with the specimen surface.

5.3 Localized DCPD Study

5.3.1 Crack Detection

Figures 5.8 through 5.17 show the results of voltage measurements from the surface breaking side of the crack using the localized DCPD technique. Several different crack geometries including semi-elliptical and ramped geometries were studied. Table 4.1 provides a detailed breakdown of crack characteristics.

For frontside tests, it can be seen that for semi-elliptical crack profiles there is a detectable rise in voltage readings once the crack reaches a depth of 0.5 mm. This is clearly illustrated by Figures 5.8, 5.9 and 5.10. Note that the results plotted are raw voltage, and not predicted crack depth. To plot predicted crack depth values, a calibration curve, specific to the test conditions, would be necessary. However, the technique does give good indication of the crack and its surface breaking points. This is best illustrated by Figures 5.10, 5.14 and 5.15 where a detectable voltage rise occurs within 2 mm of either end of a semi-elliptical crack.

For the ramped crack profiles, a larger crack depth is required for detection. Readings taken for Cracks #7 and #8, shown in Figures 5.12 and 5.13 respectively, indicate that a

depth of approximately 1 mm is necessary for crack detection. Thus, indication of the surface breaking points of a crack is not clear when the geometry varies gradually. Also, the ability of the localized DCPD technique to indicate crack shape is limited as can be seen by the ramped portion of the crack in both Figures 5.12 and 5.13. However, in reality since sharp crack geometries are common, a crack must be at least 0.5 mm deep before it is detected with the present equipment. Further discussion of the effect of crack geometry on potential readings is carried out in Section 5.3.4.

The detection threshold is consistent since Figures 5.8 to 5.17 illustrate that there is a high degree of data repeatability. In the majority of cases, the standard error is under 10 % of the potential drop value.

One noticeable exception is Figure 5.11 which shows results of Crack #5 and Crack #6 frontside testing. Here, the large error bars and scatter in the uncracked region make data interpretation difficult. Since this type of scatter was not observed when measuring other cracks from the frontside, the large error could be due to insufficient sanding of the plate surface in this region—leaving a layer of oxide to interfere with readings. Previous trials, conducted by Harrington [72] and the author, have showed that a thin layer of oxide leads to erratic, unrepeatable readings. It has been the author's experience that a shiny specimen surface is required for reliable readings.

Similarly, the permanent marker pen, used in backside testing to indicate crack positions, interfered with voltage readings. Figure 5.23 illustrates this extremely well (points at which the probe contacts were positioned directly on felt markings are marked by arrows). The figure shows that the presence of the felt markings leads to more scatter in the readings and, in some cases, noticeably lower voltage readings when compared to unmarked regions. This confirms that, to ensure good probe contact, a shiny specimen surface is necessary.

These observations indicate that in-service the localized DCPD technique would require surface preparation prior to a burst test. During this study it was observed that the

spring-loaded contacts, which are constantly forced against the surface of the specimen, remove a thin layer of oxide with each pass. Thus, continuous scanning of the flaw region should retard the growth of a thick oxide layer. It is likely that surface cleaning of the specimen will still be necessary at several intervals during the experiment. This point does require confirmation through long term (24 to 48 hours) high temperature testing, and potentially, modification of the experimental procedure for burst testing.

Figures 5.18 to 5.26 show the results of voltage measurements taken for Cracks #1 to #12 from the backside using the localized DCPD technique. Localized DCPD measurement taken on the backside are less sensitive to crack depth, and more susceptible to error.

The detection threshold for semi-elliptical cracks from the backside is somewhat lower than from the front. While the plots indicate a 1 mm crack may be detectable, accurate measurement would require a deeper crack. This is apparent from Figure 5.19 which is a plot of backside readings taken on Cracks #3 and #4. Both cracks are 1 mm deep, and although the plot indicates a trend of higher average voltage readings corresponding to increased crack depth, the large degree of scatter introduces uncertainty. Data for the backside test of a deeper crack (#10), shown in Figure 5.25, displays less scatter and better indication of crack shape and surface breaking points. Figures 5.26 and 5.27 confirm that prediction of crack shape and surface breaking points from the backside improves with deeper cracks. Figures 5.26 and 5.27 also demonstrate that with deeper semi-elliptical cracks, surface breaking point detection from the backside is comparable to detection from the frontside. It can be seen that a detectable voltage rise occurs within 2 mm of the crack edge as with frontside testing.

As with frontside testing, backside localized DCPD testing is more sensitive to sharp crack geometries. Figure 5.23 illustrates that a 1 mm crack depth leads to a detectable voltage rise at the right hand side of Crack #8 (having the sharper geometry); however, on the ramped end of Crack #8, a crack depth greater than 1.5 mm is necessary for a detectable voltage rise. It is important that the technique is more sensitive to the more

realistic sharp crack geometry. The figure also shows that there is better indication of the surface breaking points when crack geometry is sharp. As mentioned earlier, a detectable voltage rise occurs within 2 mm of the crack edges .

The loss of sensitivity during backside testing is due to the nature of the potential field being used. Since the current used is small, and injected using the outer two probe contacts, the potential distribution is very localized. This makes the technique less sensitive to defects that are not in the immediate vicinity of the probe. With the localized DCPD technique, backside tests (on shallow cracks) rely on the measurement of perturbations at the very edge of the potential field, where sensitivity is weakest.

Conversely, in backside testing of through-thickness cracks, the peak voltage is slightly higher than the equivalent frontside test. The peak voltage occurs over the through-thickness portion of the crack—suggesting that the localized DCPD technique is more sensitive to flaws in the immediate vicinity of the potential distribution. For example, the peak voltage for the backside test of Crack #7 (shown in Figure 5.22) is approximately 62 mV; this is significantly higher than the frontside test (Figure 5.12) which had a peak voltage just under 55 mV. Similarly, the frontside test on Crack #8 (Figure 5.13) results in a peak voltage of approximately 57 mV while the backside test (Figure 5.23) resulted in a peak voltage of approximately 64 mV.

However, the comparison of Figures 5.8 and 5.11 (frontside and backside tests of Crack #2 respectively) appears to contradict this. The peak voltage for the frontside is higher than the backside test peak voltage by approximately 4 mV. This anomaly could be a result of insufficient oxide removal for the frontside test since the error bars in Figure 5.8 are relatively large only around Crack #2. However, it would be useful to determine the nature of the potential distribution for the localized DCPD technique during backside testing to better quantify this effect. This should be possible through finite or boundary element modeling of the potential distribution.

Since localized DCPD measurements will be taken on the backside during burst testing, alternatives for increasing localized DCPD backside sensitivity need to be explored. There are two methods of increasing sensitivity to achieve greater precision in backside crack measurement. The probe contact spacing may be reduced to produce a more concentrated potential distribution. This option is limited since it would be physically difficult to construct probes with a smaller contact spacing (probe contact spacing for testing was 2 mm). Also, positioning the probe, such that two contacts are on each side of the crack, would be difficult with a smaller contact spacing.

An alternative method of improving sensitivity is to increase the 2.5 A current being used. While the full effect of increasing current needs to be quantified, it should lead to better sensitivity during backside testing since the potential distribution will cover a larger area. Also, sensitivity should increase, for both frontside and backside testing, since the potential gradient will be steeper. Thus, for a larger current a more significant change in potential should occur for a given increase in crack depth. The steeper potential gradient will also lead to a greater sensitivity to probe positioning. In Figure 5.12 (Crack #7 frontside test), the right hand side of the crack has a rapidly varying geometry resulting in a steep potential gradient. This confirms that a steep potential gradient leads to large changes in voltage measurements for a small change in probe position. Thus accurate probe positioning will have to be ensured through the positioning frame design.

As mentioned above, testing has shown that the localized DCPD technique gives a good indication of the frontside surface breaking points of the crack. This is true regardless of which surfaces (frontside or backside) voltage measurements are taken on. However, the plot of frontside test results on Crack #12 (Figure 5.17) gives no indication of the crack surface breaking points on the backside. Figures 5.12 and 5.13, plots of frontside tests on through-thickness cracks (Cracks #7 and #8 respectively), also illustrate that localized DCPD measurements do not give any indication of the crack's backside surface breaking points. Figures 5.22, 5.23, and 5.27 (backside test of Cracks #7, #8, and #9) indicate

similar results. A lack of information regarding the backside surface breaking points of a crack hinders the development of an accurate crack profile.

The explanation for this behavior is relatively simple. As mentioned earlier, the frontside detection threshold, which is sensitive to crack geometry, is approximately 0.5 mm with the present equipment. This means a 0.5 mm deep semi-elliptical crack, or perhaps a shallower crack with a sharper geometry, is necessary for the localized DCPD technique to detect it. However, the points at which the through-thickness cracks in this study break through the backside, represent a relatively gradual change in geometry (i.e., the rate at which crack depth changes is limited by the radius of the saw used to produce the cracks). Thus, the present localized DCPD equipment is not sensitive enough to detect the small change in local crack geometry that backside surface breaking points represent.

A lack of information regarding the backside surface breaking points of a crack does raise concerns. It is known that DHC can result in cracks which actually "tunnel" through the pressure tube material [3]. That is, a crack may propagate for some distance before breaking through either surface of the pressure tube. It is likely that the presence of any crack tunnelling would affect potential drop readings. Depending on the nature of the tunnelling, perturbations in the potential field from crack surface breaking points (either frontside or backside) may not be detectable. Should this occur, the determination of crack profiles would be difficult.

The possibility of not detecting the surface breaking points of cracks makes it essential to study real DHC flaws, which have tunnelled, to determine their effect on potential readings. This variable must be studied using real DHC flaws since it is not possible to machine flaws that would be representative of tunnelling cracks.

5.3.2 Effects of Temperature and Water

Figures 5.28 and 5.29 illustrate the results of the two tests performed to determine the effects of high temperature and the presence of water since the localized DCPD technique

would be subjected to both in-service. Figure 5.28 is a plot of both high temperature and room temperature test results. It is clear that the high temperature leads to higher voltage readings at crack depths greater than 1 mm. High temperature does not appear to affect the accuracy of the localized DCPD technique but it does indicate the necessity for temperature dependent calibration. Note that voltage readings, taken over an unflawed region, are higher for the room temperature test. Higher contact pressure may explain this behavior (see Section 5.3.3).

During a standard room temperature test on Crack #12, boiling water was poured onto the test plate to see the effect of this variable. Figure 5.29 shows the results of this test (arrows indicate the points at which boiling water was added). Data from a single trial is shown since it is difficult to repeat the experimental procedure precisely. However, several trials were carried out to confirm the trends indicated by this graph. The graph clearly indicates a sharp increase in voltage readings upon the addition of boiling water. This effect is due to decreased conductivity (and therefore increased resistivity) resulting from the increase in temperature. During the latter stages of the test, water remained on the plate. As Figure 5.29 illustrates, the presence of the cooled water did not affect DCPD readings. Results in Figure 5.29 indicate that prediction of crack shape, and surface breaking points, is still satisfactory.

Attempting to quantify the effect of heat, water and steam on localized DCPD performance demonstrated the need for better simulation of pressure tube burst test conditions. This is an important area because the presence of water flashing to steam, as would occur in a burst test once the crack grew through the thickness of the pressure tube, may have an added effect. The work done in this study provides an indication of localized DCPD performance under pressure tube burst test conditions; however, for calibration, a more consistent method for high temperature testing will be necessary. More precise work will also require testing at under actual burst test temperatures (up to 300°C). An alternative to simulating burst test conditions is to calibrate the system once it has been installed. This

would require taking voltage measurements during burst tests and correlating the data with actual crack depths from burst test specimens. While this method makes burst testing a more labour intensive process initially, it may be only practical way of obtaining accurate data for localized DCPD calibration.

5.3.3 Effects of Probe Contact Pressure Variation

As discussed earlier, spring loaded contacts are used in the probe. It is therefore conceivable that probe contact pressure differences would affect voltage readings. The results of both "high" contact pressure trials and "low" contact pressure trials appear in Figure 5.30. In the "high" contact pressure trial, the contacts were mounted such that a larger compressive force was exerted by the contact spring. That is, for "high" contact pressure the probe tip was deflected by 2-3 mm; in "low" contact pressure trials, the probe tip was deflected by less than one millimetre. Figure 5.30 shows that the higher contact pressure leads to higher voltage readings—particularly in the unflawed regions of the plate. The plot also shows that the effect of contact pressure diminishes as the voltage readings increase. The small error values in these experiments confirms that contact pressure is a factor in voltage measurements. While the effect of contact pressure variation is noted, it should not be a concern in this study since its effects will be nominal over the course of a single test. Any variation of contact pressure over numerous tests will also be nominal since all data will be normalized.

It is still of interest to consider why contact pressure variations affect voltage readings. Intuitively, higher contact pressure should result in a better electrical connection between the specimen surface and probe tip; thus, the current would encounter a lower resistance across this point. This theory would predict that lower voltage readings will result for a higher contact pressure. However, the results of Figure 5.30 appear to contradict this since higher voltages result for a higher contact pressure. This would occur if a higher contact pressure results in wearing the probe tip down such that another metal is exposed,

changing the contact resistance. This theory is the most plausible since it is supported by the results presented in Figure 5.30. This is an interesting observation and should be studied further to fully understand this effect.

As discussed in Section 5.3.2, higher test temperatures should lead to higher voltage readings when compared to tests at lower test temperatures. However, the voltage readings over an unflawed region in Figure 5.28 (242°C) and Figure 5.30 (room temperature) appear to contradict this. These trials were conducted at different times and a higher contact pressure may be responsible for the larger voltage readings measured over unflawed regions at room temperature when compared to similar readings at 242°C. As Figure 5.30 indicates, the effect of increased contact pressure should diminish as voltages (or crack depths) increase. This is indeed the case when Figures 5.28 and 5.30 are compared at higher voltages (or crack depths).

Contact pressure does appear to affect potential drop values. However, over an uninterrupted test, contact pressure should remain unchanged—effectively negating the effect of this variable for an individual test. A method for minimizing the effect of variables such as contact pressure on potential drop values over numerous tests is to normalize the data with a reference voltage; this was discussed in Section 3.2.1.

5.3.4 Effects of Crack Geometry

It was discussed earlier how crack geometry affects the detection threshold of the localized DCPD technique. While real cracks tend to be quite narrow, it is interesting to note the effect of crack width. Figure 5.31 shows the results of tests done on Cracks #3 and #4 which have the same profile but different widths. It can be seen that Crack #3 (having a width of 1.14 mm) resulted in higher voltage readings when compared to Crack #4 (having a width of 0.33 mm). This is a logical result since the current would have a longer path to travel in the case of a wider crack leading to a larger voltage reading. In practice however, crack width is not a significant factor since real cracks tend to be narrow.

Another aspect of crack geometry to consider is the crack profile. For example, consider Figure 5.12 which is a plot of Raw Voltage and Actual Crack Depth versus Position for Crack #7. Note that Crack #7 has a profile that is ramped on one side and semi-circular on the other side. For a crack depth of 3 mm, on the ramped side a voltage reading of approximately 23 mV was observed, yet on the semi-circular side a voltage reading of approximately 40 mV was observed. In this case, the two different profiles have resulted in readings that differ by a factor of almost two.

While the ramped profile discussed here is not representative of DHC flaw geometry, it demonstrates the significant effect that changes in crack geometry can have on voltage readings. This point leads to several factors that must be considered. For example, readings taken for Crack #7 (shown in Figure 5.12) demonstrate that a sharp crack profile leads to higher voltage gradients in its immediate vicinity. This emphasizes the importance of accurate probe positioning since a small change in position would lead to a relatively large change in voltage.

Another consideration for calibration arises if the crack being measured has significant changes in profile over its length (i.e., for example if one end of the crack profile is very steeply sloped while the profile of the other crack end has a shallow slope). An extreme example of this, mentioned earlier, would be Crack #7 (having both a ramped and semi-circular geometry) which could require two different calibration curves—one for each end. Also, if the general crack geometry is unknown, then it would be difficult to differentiate between a deep thin crack and a shallower, but wider, crack. Thus, despite the fact that real cracks tend to be quite thin, accurate crack depth prediction does require a calibration curve that accounts for changing crack geometry.

5.4 Localized DCPD Calibration

Calibrating the localized DCPD technique will involve several stages. Most importantly, general information about the potential distribution for different crack configurations in

Zr-2.5Nb is necessary. This has been accomplished in the present work.

The second stage of calibration involves taking measurements of several DHC flaws to determine patterns that are characteristic of DHC flaws. A particular area of concern is the effect of crack tunnelling. Measurements of tunnelling cracks are important to determine whether crack surface breaking points are still detectable. Also, DHC results in narrow cracks that will, in some instances, lead to crack bridging [70]. The physical contact between two crack faces would affect potential readings. These types of recognizable patterns could then be incorporated into the computer software relatively early on in the calibration process.

After initial study of real DHC flaws, normalized data should be correlated with actual crack depths; these could be determined optically. Normalizing the data with a reference voltage should remove specimen dependent effects such as variation in composition as well as small changes in test conditions such as temperature and contact pressure. The curve developed from the correlation of potential drop data and crack depths should involve sufficient sample sizes of each to ensure validity of the calibration.

The last step in the calibration process is essentially refinement. This can be accomplished through on-going confirmation of predicted crack depths when possible. Also, experience in interpreting potential drop data for DHC flaws will lead to other improvements in calibration.

Figure 5.1 Initial Localized DCPD Test on Crack #1 and #2 [75]

This is a room temperature frontside test. Note that the data plotted on this graph is normalized potential drop, not predicted crack depth. Also, the graph shows that the localized DCPD technique accurately predicts the surface breaking points of the crack.

Figure 5.2 Initial High Temperature Localized DCPD Testing on Crack #1 and #2 [75]

This is a frontside test. Note the good indication of crack surface breaking points and crack shape prediction at high temperature (242°C). Beyond an increase in potential drop values, the technique appears to be unaffected by temperature variations. This indicates that calibration will be temperature sensitive.

Figure 5.3 Results of Localized DCPD Test Conducted on Pressure Tube Section

This is a frontside test. In this case, voltage readings have not been normalized with respect to a reference voltage; thus, the potential readings are not zero (even when crack depth is zero). Performance of the technique is unaffected by a change in gross geometry of the specimen since there is still good crack shape prediction and indication of crack surface breaking points.

Figure 5.4 Initial ACPD Testing on Crack #2-Test Configuration #3 [75]

This is a frontside test. Note that the ACPD technique is capable of detecting the presence of a crack. However, the data, used with the Thin Skin model, results in poor agreement between predicted and actual crack depths.

Figure 5.5 Initial ACPD Testing on Crack #2-Test Configuration #4 [75]

This is a frontside test. Note that the ACPD crack depth predictions are not in agreement with actual crack depths. There is no indication of the presence of a crack.

Figure 5.6 Frontside ACFM Scan on Crack #15 [76]

This is a plot of magnetic field components and actual crack depth. This method requires no physical contact with the specimen surface. Note the good indication of the right-hand side surface breaking point of the crack.

Figure 5.7 Backside ACFM Scan on Crack #15 [76]

No physical contact with the specimen surface is necessary for this technique. Comparing this figure to Figure 5.6, the ACFM technique appears to be effective regardless of which surface is scanned (i.e., either front or back).

Figure 5.8 Localized DCPD Tests on Crack #1 and #2 (Frontside)

Note the good indication of crack ends as well as crack shape. Error values are relatively large around Crack #2 are still within 10% of the measured voltage. The larger errors may be due to insufficient removal of oxide which interferes with potential drop readings.

Figure 5.9 Localized DCPD Tests on Crack #3 (Frontside)

Crack #3 is a semi-elliptical crack with a maximum depth of 1 mm and a width of 1.14 mm. Note the good indication of crack shape. Error values appear to increase with crack depth but are still within 10% of the measured voltage.

Figure 5.10 Localized DCPD Tests on Crack #4 (Frontside)

Crack #4 is a semi-elliptical crack with a maximum depth of 1 mm and a width of 0.33 mm. Note the good indication of crack shape and end points.

Figure 5.11 Localized DCPD Tests on Crack #5 and #6 (Frontside)

Cracks #5 and #6 both have a ramped profile. Crack #5 has a width of 1.14 mm and Crack #6 has a width of 0.33 mm. These results displayed large error values—possibly due to insufficient oxide removal from the specimen surface. Also, note that readings are higher for the wide crack (Crack #5).

Figure 5.12 Localized DCPD Tests on Crack #7 (Frontside)

Crack #7 is a through-thickness crack with a ramped geometry. It has a width of 0.33 mm. Note the significantly different voltages for a given crack depth depending on local geometry. At a 3 mm crack depth, a voltage of 40 mV is measured for the steeply sloped crack end as compared to 23 mV for the gradually ramped crack end.

Figure 5.13 Localized DCPD Tests on Crack #8 (Frontside)

Crack #8 is a through thickness crack with a ramped geometry. It has a width of 1.14 mm. Note the significantly different voltage readings resulting from differing crack geometries. There is still good indication of the crack ends.

Figure 5.14 Localized DCPD Tests on Crack #9 (Frontside)

Crack #9 is a semi-elliptical crack with a depth of 1 mm. Note the good indication of crack shape. Error values are within 10% of measured voltages.

Figure 5.15 Localized DCPD Tests on Crack #10 (Frontside)

Crack #10 is a semi-elliptical crack with a depth of 2 mm. Note that in many cases the error value is too small to appear on the graph. This indicates good repeatability.

Figure 5.16 Localized DCPD Tests on Crack #11 (Frontside)

Crack #11 is a semi-elliptical crack with a depth of 3 mm. Note the good indication of crack shape and surface breaking points. Only one point has an error value exceeding 10%.

Figure 5.17 Localized DCPD Tests on Crack #12 (Frontside)

Crack #12 is a through-thickness crack with a semi-elliptical profile. Note the good indication of crack extents on the frontside. However, the technique does not give any indication of the crack's backside surface breaking points. Also, error values are too small to be visible on the plot—indicating good repeatability of data.

Figure 5.18 Localized DCPD Tests on Crack #1 and #2 (Backside)

Note that localized DCPD sensitivity is reduced during backside testing. However, small error values indicate data repeatability is still satisfactory.

Figure 5.19 Localized DCPD Tests on Crack #3 and #4 (Backside)

Cracks #3 and #4 both have semi-elliptical profiles with a maximum depth of 1 mm. Crack #3 is the wider crack. Note that the decreased sensitivity, coupled with error values, leads to a high degree of uncertainty in predicting the shape of these shallower cracks.

Figure 5.20 Localized DCPD Tests on Crack #5 (Backside)

Crack #5 has a ramped profile. Note that while sensitivity is reduced during back-side tests, voltage readings are still affected by local geometry as in the front-side tests.

Figure 5.21 Localized DCPD Tests on Crack #6 (Backside)

Crack #6 is a crack with a ramped profile. Note that the decreased sensitivity, coupled with error values, leads to a higher degree of uncertainty in predicting crack shape when testing from the backside.

Figure 5.22 Localized DCPD Tests on Crack #7 (Backside)

Crack #7 is a through-thickness crack with a ramped profile. Note that the sensitivity is reduced for crack depths smaller than approximately 3.5 mm but increases for larger crack depths when compared to an equivalent front-side test.

Figure 5.23 Localized DCPD Tests on Crack #8 (Backside)

Crack #8 is a through thickness crack with a ramped profile. Note the arrows indicating the position of felt markings on the plate. The presence of the felt markings results in lower voltage readings, and increased scatter, in the data.

Figure 5.24 Localized DCPD Tests on Crack #9 (Backside)

Crack #9 is a semi-elliptical crack with a depth of 1 mm. Note that the decreased sensitivity, coupled with error values, leads to a high degree of uncertainty in predicting the shape of shallower cracks from backside testing.

Figure 5.25 Localized DCPD Tests on Crack #10 (Backside)

Crack #10 is a semi-elliptical crack with a depth of 2 mm. Note that the voltage measurements predict a crack shape which is slightly skewed to the right. This could be due to misalignment between the crack and the path scanned by the probe.

Figure 5.26 Localized DCPD Tests on Crack #11 (Backside)

Crack #11 is a semi-elliptical crack with a depth of 3 mm. Note the good prediction of crack shape and end points. Error values are within 10% of measured voltages—indicating good repeatability.

Figure 5.27 Localized DCPD Tests on Crack #12 (Backside)

Crack #12 is a through-thickness crack with a semi-elliptical profile. Note the good indication of crack shape and surface breaking points on the frontside. The localized DCPD technique does not give any indication of the crack's backside surface breaking points.

Figure 5.28 Localized DCPD High Temperature Tests on Crack #1 and #2

This is a frontside test. Note the higher voltage readings for the high temperature test at 242°C. Crack shape prediction and indication of surface breaking points is still satisfactory. This indicates the need for temperature sensitive calibration.

Figure 5.29 Localized DCPD Boiling Water Tests on Crack #12 (Frontside)

Note the higher readings that result when boiling water is introduced. Points at which water was added are indicated by arrows. Any water remaining on the plate during testing does not affect voltage measurements.

Figure 5.30 Localized DCPD Contact Pressure Variation Tests on Crack #12

This is a frontside test. Note the higher contact pressure leads to larger voltage readings in the unflawed areas. Contact pressure appears to have little effect as crack depth increases.

Figure 5.31 Effect of Crack Width on Localized DCPD Values (Frontside)

Cracks #3 and #4 are both semi-elliptical cracks of equal length with a depth of 1 mm. Note that Crack #3, having a width of 1.4 mm, does result in higher voltage readings than Crack #4 which has a width of 0.3 mm.

6 Conclusions and Recommendations

6.0 Conclusions

- 1. A study, comparing two potential drop techniques for use in pressure tube burst testing, was conducted using the equipment available at Carleton University. The localized DCPD method provided consistently repeatable data while ACPD testing was unsuccessful with the available equipment.**
- 2. Through two visits to University College in London (England), a third crack measurement technique, ACFM, was tested. Limited ACPD testing was also conducted using the latest equipment. Both techniques showed merit. However, information regarding the calibration of these techniques for materials, other than steel is limited, making them unviable for this particular project.**
- 3. The geometry of a pressure tube section does not hinder the accuracy of the localized DCPD technique. The localized DCPD measurements taken on a pressure tube section and a Zr-2.5Nb plate of equivalent thickness are similar; thus, the use of a Zr-2.5Nb plate for testing is acceptable.**
- 4. The localized DCPD technique is more sensitive when measuring cracks from the surface breaking side as opposed to measurements on the backside of the specimen.**
- 5. Frontside and backside measurements will require different calibration curves due to the localized nature of the potential distribution.**
- 6. The localized DCPD technique accurately detects frontside surface breaking points of cracks. However, in tests conducted for this project, the technique does not**

appear to be sensitive to the backside surface breaking points of through thickness cracks.

7. Crack geometry has a significant influence on potential drop measurements. Thus, all three dimensions of a crack (width, depth, and length) must be considered during calibration (i.e., the relationship between crack depth and voltage change is not linear).
8. The specimen surface must have a shiny (oxide-free) surface to ensure good electrical contact with the probe. The surface may need to be cleaned at several intervals during burst test experiments.
9. The influence of contact pressure on potential drop measurements can be significant when readings are taken over an unflawed area (i.e., when potential drop values are lower).
10. Temperature has an effect on potential readings. A temperature increase of 220°C resulted in voltage readings up to 20% higher than room temperature values.
11. The presence of water or steam appears to affect potential drop readings only if a temperature change also occurs. Once the temperature has stabilized, no effect on potential drop values is observed.

6.1 Recommendations

1. The present work did not include measurements of a real flaw caused by delayed hydride cracking. While saw cuts were sufficient for preliminary study of potential drop techniques for this application, they are not realistic simulations of actual DHC geometry and may not provide sufficient information for calibration. Calibrating a real crack may involve complications due to crack face bridging, crack tunneling, and oxidation of the metal surfaces. Thus, further study should be conducted using real DHC flaws.
2. While the advantage of the localized DCPD technique is that it allows the use of small currents, an increase in the 2.5 Amp current may improve sensitivity for

backside measurements of cracks. Further testing will be necessary to quantify the effect of increasing the current.

3. It would be of interest to model the potential distribution using a method such as finite element analysis. While this has been done for conventional DCPD techniques, the results should be quite different for the localized technique used here. The analysis should also aid in calibration.
4. The effect of contact pressure variation was noted during this study. This variable should be investigated further to gain a better understanding of its influence on the performance of the localized DCPD technique.
5. It would be beneficial to develop the ACFM technique for this application. This method is particularly appealing since it is a non-contacting method which would reduce the handling of irradiated materials by minimizing the surface preparation of the specimen. The ACFM technique is also much more sensitive to surface breaking points of the crack and would provide more crack profile data over the course of the test.

Appendix A

Summary of Canadian Commercial Reactors and Basic Design Information

Name	Type	Capacity MW-Gross	First Power	In Service	Present Status
NPD Gen. Stn.	CANDU	25	1962	1962	Shutdown May 1987
Douglas Pt.	CANDU	218	1968		Shutdown May 1984
Gentilly 1	CANDU- BLW	266	1972		Shutdown 1973/1976 & since 1978
Pickering 1	CANDU	542	1971	1971	†Shutdown for retubing 1983-1987
Pickering 2	CANDU	542	1971	1971	†Shutdown for retubing 1983-1988
Pickering 3	CANDU	542	1972	1972	†Shutdown for retubing 1989-1991
Pickering 4	CANDU	542	1973	1973	†Shutdown for retubing 1991-1992
Bruce 1	CANDU	815	1977	1977	Operating
Bruce 2	CANDU	825	1977	1977	Operating
Bruce 3	CANDU	815	1978	1978	Operating
Bruce 4	CANDU	825	1979	1979	Operating
Pt. Lepreau	CANDU	680	1982	1983	Operating
Gentilly 2	CANDU	685	1982	1983	Operating
Pickering 5	CANDU	540	1982	1983	Operating
Pickering 6	CANDU	540	1983	1984	Operating
Pickering 7	CANDU	540	1984	1985	Operating
Pickering 8	CANDU	540	1985	1986	Operating
Bruce 5	CANDU	885	1984	1985	Operating
Bruce 6	CANDU	885	1984	1984	Operating
Bruce 7	CANDU	890	1986	1986	Operating
Bruce 8	CANDU	890	1986	1987	Operating
Darlington 1	CANDU	935	1989	1990	Operating
Darlington 2	CANDU	881	1988	1990	Operating
Darlington 3	CANDU	881	1991	1991	Operating
Darlington 4	CANDU	881	1992	1992	Operating

Table A1: Commercial Power Reactors In Canada [4]

This table presents a brief summary of commercial reactors in Canada. Nineteen CANDU reactors are currently operating in Canada.

† Presently Operating

	Douglas Point	Pickering Units 1 & 2	Pickering Units 2 & 3	Bruce 1- 4	Gentilly II	Point Lepreau	Darlington
# of Channels	306	390	390	480	380	380	480
Coolant Pressure (psi) (MPa)	1400 (9.65)	1400 (9.65)	1400 (9.65)	1480 (10.2)	1610 (11.1)	1610 (11.1)	1610 (11.1)
Coolant Temperature (K)	563	563	580	580	580	580	740-600
Material	Zircaloy-2	Zr-2.5Nb	Zr-2.5Nb	Zr-2.5Nb	Zr-2.5Nb	Zr-2.5Nb	Zr-2.5Nb
Wall Thickness (mm)	4.0	5.1	4.1	4.1	4.1	4.1	4.1
Internal Diameter (mm)	83	103	103	103	103	103	103
Design Stress (psi) (MPa)	16000 (110)	16000 (110)	21000 (145)	22200 (153)	23100 (159)	23100 (159)	21000 (145)

Table A2: Basic Design Data for CANDU Units [2, 3]

Design data for commercial reactor units in Canada appears in the table. All of the reactors are CANDU units with only slight differences in operating conditions.

	Specifications	Actual Values
Nb	2.4-2.8 wt %	2.5-2.7 wt %
O	900-1300 ppm	1100-1200 ppm
N	65 ppm max	< 55 ppm
H	20 ppm max	< 16 ppm

Table A3: Current Compositional Data (for Zr-2.5Nb). [26]

Specified values for niobium, oxygen, nitrogen and hydrogen concentration in pressure tubes appear in this table. The actual concentrations, resulting from the fabrication process, are well within specified tolerances and are also presented.

Test Temperature	Test Direction	Position in Tube	Irradiation Dose (n/m ⁻²)	0.2% Yield Stress (MPa)	UTS (MPa)	Elongation (%)	Reduction in Area
295 K	L	-	0	643	790	13	35 %
295 K	T	-	0	-	813	15	48 %
295 K	L	-	10 ²⁴	980	980	6	20 %
295 K	T	-	10 ²⁴	-	1080	-	23 %
575 K	L	Front	0	330	469	14	53 %
575 K	L	Back	0	380	531	16	55 %
575 K	T	Front	0	-	538	13	53 %
575 K	T	Back	0	-	572	12	55 %
575 K	L	-	10 ²⁴	683	752	5	22 %
575 K	T	-	10 ²⁴	-	820	-	26 %

Table A4: Typical Tensile Properties of Cold-Worked Zr-2.5Nb Pressure Tubes [24]

This table summarizes the change in tensile properties of cold-worked Zr-2.5Nb resulting from irradiation, test direction, position along the pressure tube, and temperature. The test direction indicates whether specimens were tested in the longitudinal (L) or transverse (T) direction with respect to the pressure tube axes.

Appendix B

Calculation of Critical Crack Length for a Pressure Tube in Service

Calculation of Critical Crack Length for a CANDU reactor pressure tube under reactor conditions:

Dimensions of a pressure tube:

- l = Pressure tube length (6.3 m)
- d_i = Pressure tube inside diameter (0.103 m)
- d_o = Pressure tube outside diameter (0.1114 m)
- t = Pressure tube wall thickness (0.0042 m)

Maximum pressure quoted for a Darlington Reactor is 11.1 MPa (Appendix A). So for the hoop (maximum) stress calculation for a pressure vessel:

$$\sigma_h = \frac{Pr}{t} \quad (1)$$

- where
- P = Pressure (MPa)
 - r = Radius (m)
 - t = Thickness of pressure tube wall (m)

Substituting:

$$\begin{aligned} \sigma_h &= \frac{11.1(10)^6 \times 0.0515}{0.0042} \\ &= 136.107 \text{ MPa} \end{aligned}$$

Now from Bannantine, Comer, and Handrock [7]:

$$K = f(g)\sigma\sqrt{\pi a} \quad (2)$$

- where
- K = Stress Intensity Factor
 - σ = Stresses near a crack tip
 - a = Crack length
 - $f(g)$ = Correction factor for geometry

This expression reduces to:

$$K_I = \frac{1.12}{\sqrt{Q}} \sigma \sqrt{\pi a} \quad (3)$$

- where
- K_I = Stress intensity factor
 - σ = Stresses near a crack tip
 - a = Crack length
 - Q = Shape factor (where the $Q = 1$ for a straight fronted crack)

For leak-before-break, set crack length equal to the thickness of the pressure tube wall (4.2 mm). Substituting values into (3):

$$K_I = 1.12 \times 136.107(10)^6 \sqrt{0.0042\pi}$$

$$= 17.51 \text{ MPa}\sqrt{\text{m}}$$

Chow and Simpson [24] state that in the fast fracture of a pressure tube $K = 40\text{-}50 \text{ MPa}\sqrt{\text{m}}$. Since the calculated K is less than the $40 \text{ MPa}\sqrt{\text{m}}$, the pressure tube should meet leak-before-break.

Now, using $40 \text{ MPa}\sqrt{\text{m}}$ as a K_C value, a critical crack length, a_C may be calculated from (3):

$$a_C = \left(\frac{K_C \sqrt{Q}}{1.12\sigma\sqrt{\pi}} \right)^2$$

substituting values:

$$a_C = \left(\frac{40(10)^6 \sqrt{1}}{1.12 \times 136.107(10)^6 \sqrt{\pi}} \right)^2$$

$$= 0.02193 \text{ m}$$

$$= 21.9 \text{ mm}$$

This calculation underestimates the critical crack length since typical values from [24] were found to be 60-120 mm. This is most likely due to the conservative K_C value used in the calculations. Using a K_C value of $60 \text{ MPa}\sqrt{\text{m}}$ results in a more realistic critical crack length of 50 mm.

Appendix C

Calculation of Alternating Current Skin Thickness in Zr-2.5Nb Alloy

ACPD Skin depth calculation for Zr-2.5Nb at a frequency of 6 kHz:

Using Equation 3.1 from Chapter 3:

$$\delta = \frac{1}{\sqrt{\mu_r \mu_o \pi \sigma f}} \quad (3.1)$$

where: δ = skin depth (m)
 μ_r = relative permeability of conductor
 μ_o = permeability of free space (4×10^{-7} H/m)
 σ = conductivity of specimen (S/m)
 f = frequency of alternating current (Hz)

for this material (taken from references [3, 49]):

$\mu_r \approx 1$
 $\mu_o \approx 4\pi \times 10^{-7}$ H/m
 $\sigma \approx 1.923 \times 10^6$ S/m
 $f \approx 5$ kHz

Substituting:

$$\begin{aligned} \delta &= \frac{1}{\sqrt{4\pi(10)^{-7} \times 1.923(10)^6 \times 5(10)^3}} \\ &= 5.135(10)^{-3} \text{ m} \end{aligned}$$

This value of 5.1 mm is greater than the 4.2 mm thickness of the plate.

Appendix D

Calculation of Standard Error

The calculation of standard error for the plots in Chapter 5 was carried out as follows:

Assuming a data set of 10 values for a given point:

Trial #	mV
1	15.5
2	16.1
3	14.4
4	15.2
5	16.2
6	14.8
7	14.3
8	15.6
9	14.3
10	16.1

Data Table 1

The mean of the sample is first calculated as follows:

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad (1)$$

$\bar{x}$ = Sample mean
 n = Sample size (In this case $n = 10$.)

Substituting values from Data Table 1, the mean of the sample is found to be:

$$\bar{x} = \frac{15.5 + 16.1 + 14.4 + 15.2 + 16.2 + 14.8 + 14.3 + 15.6 + 14.3 + 16.1}{10}$$

$$= 15.25 \text{ mV}$$

The mean of 15.25 can be used to determine the standard deviation by using the following equation:

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

S = Standard deviation
 $\bar{x}$ = Sample mean (In this case $\bar{x} = 15.25 \text{ mV}$.)
 n = Sample size (In this case $n = 10$.)
 S = Standard deviation

Substituting values from Data Table 1, first sum all terms of the form: $(x_i - \bar{x})^2$ (this sum will be referred to as "a"):

$$a = \left[\begin{aligned} &(15.5 - 15.25)^2 + (16.1 - 15.25)^2 + \\ &(14.4 - 15.25)^2 + (15.2 - 15.25)^2 + \\ &(16.2 - 15.25)^2 + (14.8 - 15.25)^2 + \\ &(14.3 - 15.25)^2 + (15.6 - 15.25)^2 + \\ &(14.3 - 15.25)^2 + (16.1 - 15.25)^2 \end{aligned} \right]$$

$$a = 5.85$$

Then substituting into (2):

$$\begin{aligned} S &= \sqrt{\frac{5.85}{n-1}} \\ &= 0.765 \end{aligned}$$

The standard deviation of 0.765 can be used find value of standard error using the equation:

$$S_e = \frac{S}{n} \quad (3)$$

$$\begin{aligned} S_e &= \text{Standard error} \\ n &= \text{Sample size (In this case } n = 10.) \\ S &= \text{Standard deviation} \end{aligned}$$

Substituting values into (3), the value standard error is determined to be:

$$\begin{aligned} S_e &= \frac{0.765}{10} \\ &= 0.077 \end{aligned}$$

This is the value used to plot error bars on the graphs appearing in Chapter 5.

References

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