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**Direct Current Potential Difference Crack
Measurement System for Zr-2.5Nb Specimens**

by

Kim Ingrid Jones B.Eng.

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

**DEPARTMENT of MECHANICAL and AEROSPACE ENGINEERING
CARLETON UNIVERSITY
OTTAWA-CARLETON INSTITUTE FOR
MECHANICAL and AEROSPACE ENGINEERING**

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**Direct Current Potential Difference Crack
Measurement System for Zr-2.5Nb Specimens**

submitted by

Kim Ingrid Jones, B.Eng.

in partial fulfilment of the requirements for
the degree of Master of Engineering.

Thesis Supervisor

for Chair, Department of Mechanical
and Aerospace Engineering

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Abstract

A study of Direct Current Potential Difference (DCPD) measurements on zirconium alloy specimens was completed. The objective of the study was to develop a system that would characterize axial cracks in the material used for the pressure tubes in the CANadian Deuterium Uranium (CANDU) reactors. This thesis reports the findings of the research carried out as part of that study, including a discussion of CANDU reactors, nuclear safety, delayed hydride cracking (DHC), and DCPD methods. The study investigated the use of DCPD to measure cracks in zirconium - 2.5% niobium plate and tube specimens, at room and high temperatures. Conclusions and recommendations for further work are included within this thesis.

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List of Symbols

n	PI
ρ	resistivity
ϵ_x	strain in the x direction
σ_x	stress in the x direction
A	cross-sectional area
a	depth of crack at voltage measurement
a_0	depth of crack at reference voltage
C	constant
I	current
L	length of specimen
Nb	niobium
R	resistance
V	voltage
V_{measured}	measured voltage
$V_{\text{normalized}}$	normalized voltage
V_0	reference voltage (Johnson's equation)
$V_{\text{reference}}$	reference voltage
W	width (depth) of specimen
x	distance between signal probes
X	through thickness direction
y	direction perpendicular to axis of crack, and perpendicular to the thickness of material
Zr	zirconium

CHAPTER 1 INTRODUCTION

1.1 General

Canada's involvement in the nuclear industry can be traced back to December 1942, when Walter Zinn, a Canadian physicist, was in charge of the emergency control rod during the first successful operation of a nuclear reactor, under the University of Chicago football stadium,{1}. Since that time, Canada's contributions to the world nuclear industry have included many remarkable achievements such as the development of pressurized heavy water reactors, and innovations in medical technology.

Today, Atomic Energy of Canada Limited (AECL) is very active in the nuclear industry. It is negotiating the sale of the two new CANadian Deuterium Uranium (CANDU) 6 reactors to China, and according to the 1995 CNS yearbook, there are more CANDU units under construction around the world than any other type

of reactor, {2}. There are more than 20 CANDU units operating worldwide, and over 30,000 direct jobs in Canada alone have been created through the nuclear industry. That being the case, more than \$4.5 billion has been injected annually into Canada's economy, as of 1994. Many other fields have benefitted from developments in nuclear technology including medicine, food and agriculture, and other technology based industries, {2}.

1.2 Nuclear Safety

Safety and reliability have always been primary concerns during the design and implementation of the CANDU reactors developed and built by AECL. In fact, as of December 1994, five of the top ten reactors over 500 MW, based on lifetime performance, were CANDUs. The Point Lepreau 680 MW unit (in service since 1982) placed second, with a lifetime capacity factor of 91.4%, {2}. From the start several design features were used in a successful effort to make the CANDUs safe and popular. These will be discussed in Chapter 2.

Of the few problems which have occurred to date, incidents at Pickering units #3 and #4 in 1972 have implicated a cracking mechanism known as delayed hydride cracking (DHC). This mechanism can occur under certain conditions, and has caused cracking in the zirconium alloy pressure tubes of the reactor. A more detailed description of the CANDU reactors, and the pressure tubes will be provided in Chapter 2.

1.3 Delayed Hydride Cracking Investigation

Delayed hydride cracking (DHC) has been a subject of on-going investigations at AECL, as it impacts the design and integrity of the pressure tubes. AECL has conducted an investigation of DHC using a type of test known as a pressure tube burst test. A more thorough explanation of a burst test will be provided in Chapter 2.

In order to aid in their investigation, AECL commissioned Carleton University to develop a system which would determine the depth and shape profile of a crack. This would be accomplished by using a remotely controlled non-destructive testing method applied to the pressure tube burst tests. It was decided in a previous study to use direct current potential difference (DCPD) methods to measure the cracks, {3}.

1.4 Objectives of Present Study

The objective of this study was to design and develop the system to measure axial internal cracks which were grown by DHC. The design of the system was heavily influenced by the environment in which it would be operating. Many factors had to be considered including accuracy, reliability, and repeatability of

the data, conditions of use, and ease of handling of the equipment by remote manipulators in the test chamber.

The system was used to investigate the effects of high temperatures on the DCPD measurements. Testing was completed on a zirconium-2.5% niobium (Zr-2.5Nb) cold rolled plate and tube. These test pieces are made of the same material as is used in the pressure tubes in CANDU reactors.

This thesis contains a discussion of the structural integrity issues surrounding the pressure tubes and DHC. It provides an explanation of the theory behind DCPD measurements, and describes the system used in the high temperature testing. Finally, it details the results and conclusions of this study, and suggests directions for future work.

Chapter 2 History and Background

2.1 General

Less than three years after the first nuclear chain reaction was started and sustained, Canada's first reactor: the Zero Energy Experimental Pile (ZEEP) achieved a self-sustaining chain reaction. The reactor was located at the Chalk River Laboratories (CRL) near Deep River, Ontario.

Canada's special efforts in nuclear safety came after the incident at the National Research Experimental Reactor (NRX) in December of 1952, where a power surge led to damage of the facility, and costly efforts to clean up afterward. This incident served to heighten the Canadian nuclear industry's commitment to safety in their designs.

In June of 1962, the Nuclear Power Demonstration (NPD) Plant at Rolphton first began feeding power into the Ontario Hydro power grid. Since then 21 CANadian Deuterium Uranium (CANDU) reactors have been built in Ontario. The CANDU reactors are made with 80% Canadian content, and 100% Canadian produced fuel. In 1995, more than 60% of Ontario's electricity was supplied by these reactors {4}.

2.2 CANDU

CANDU reactors are of the pressurized heavy water reactor type (PHWR). This means that heavy water is used both as the moderator, and as the heat transport fluid in the pressure tubes. A CANDU reactor system consists of the following main components:

- I) reactor core,
- ii) steam generator plant,
- iii) safety systems and containment buildings.

2.2.1 Reactor Core

The reactor core is contained in a large vessel known as a calandria which houses the heavy water moderator at a temperature of approximately 70°C (158°F), the uranium dioxide fuel, and the other components which are necessary to sustain and control the nuclear reaction. The calandria has 390 to 480 fuel channels running horizontally through the vessel, as shown in

Figure 2.1, {5} Each fuel channel consists of a calandria tube concentric with a pressure tube with a small gas annulus separating the two. The gas annulus helps to minimize heat transfer and acts as a safety feature to help detect leaks. This assembly is shown in Figure 2.2. The humidity level inside the annulus is monitored and if it rises, a leak is suspected, and proper corrective measures can be implemented.

In each pressure tube 12 to 13 fuel bundles are housed with the heavy water coolant pumped through them. The fuel bundles consist of zirconium alloy pencils filled with uranium dioxide pellets, as shown in Figure 2.3. The heavy water in the pressure tube ranges in temperature from 260°C (500°F) inlet end to 310°C (590°F) at the outlet end, {4}.

The pressure tubes are cold rolled into end fittings which link the pressure tubes to the rest of the heat transport system, {4}. The fittings are specially designed so that refuelling of the channels is possible while the reactor is operating, {6}. This on-power refuelling is one of the main features that sets the CANDU reactor apart from other reactors and is a major factor in the economic success of the AECL design. The end fittings are however, a source of residual stresses in the pressure tube, and can be the source of flaws which may grow into cracks.

Moan et al., {8} did tests to determine the amount of time that an operator has to

detect a leak before the crack reaches critical length. They determined that an average of 18 hours would elapse from the time that the crack first penetrates the outside surface of the tube, to the time when it reaches critical length. This period of time will depend on a number of factors including the temperature gradient across the crack face, any oxide buildup which could stop leaking and the amount of hydrogen that has been picked up by the tube during operation, {6}.

2.2.2 Physics Overview

When an atom is split into parts it will release energy to its surroundings. In the case of a nuclear reactor, neutrons are used to bombard atoms of uranium 235 (U_{235}), a radioactive and rare isotope of natural uranium. When the atom of U_{235} splits or fissions, it releases energy as well as other products including two neutrons. These neutrons are then free to bombard other U_{235} atoms, thus making further fissions and a nuclear chain reaction more probable.

When the neutrons fission out of the U_{235} atom, they are travelling at high speeds, and are known as "fast neutrons". In order to split an atom, slower (thermal) neutrons are needed. Something is needed to slow down the fast neutrons to the thermal level to allow fission to occur. The component used to accomplish this is known as a moderator.

One problem in the choice of a moderator is that many will not only slow down the fast neutrons, but will also absorb some of them, making them unavailable to bombard other atoms. The objective in choosing a moderator then is to use a material which will slow the neutrons down, without absorbing too many of them.

One substance which works well is water, or H_2O . Reactors which use water as a moderator are known as pressurized water reactors (PWR) or boiling water reactors (BWR). CANDU reactors however use heavy water, or D_2O . The difference between hydrogen (H) and deuterium (D) is one extra neutron in the nucleus of the deuterium atom, making it about 10% heavier than a hydrogen atom, hence the term heavy water.

Heavy water does not absorb as many neutrons as normal water, therefore by using the D_2O as a moderator, more neutrons are available for the fission process, and less U_{235} is needed. As a result, CANDU reactors are able to use natural uranium as fuel, instead of the enriched uranium which other water-moderated reactors require. The enriching process ensures that a higher percentage of U_{235} is present in the fuel which will help the reaction to continue when there are fewer thermal neutrons available. However, enriched fuel is much more expensive to manufacture and can be used in nuclear weapons. Thus the use of natural uranium fuel in the CANDU reactors is an economical and safety conscious alternative.

As described earlier the atom of uranium is fissioned when it is struck by a thermal neutron, releasing a great amount of energy to the surroundings, in this case the fuel bundle. This energy is in the form of heat, and is absorbed by the heavy water heat transport fluid, which is pumped at high pressure through the fuel bundles. The heat transport fluid carries the heat to the steam generator, a type of heat exchanger, which takes the heat from the heat transport fluid, and uses it to turn water in a secondary loop to steam. The steam is then used to power a turbo-alternator which generates electricity.

2.3 Defence in Depth

While designing all of the components of the CANDU reactors, the Canadian nuclear industry adopted a design philosophy known as defence in depth.

Defence in depth is a three-level approach to reactor design, as described by Knief, {5}. By designing a reactor to accommodate the three levels, safety is greatly enhanced. The three levels are:

- i) prevention,
- ii) protection,
- iii) mitigation.

2.3.1 Prevention

This approach to design involves avoiding dangerous situations before they begin. This defence against unsafe conditions can be summarized as follows:

- i) using only those components and designs with a high reliability,**
- ii) reducing/eliminating the amounts of negative feedback in the reactor system,**
- iii) using large safety margins,**
- iv) testing and inspecting often and stringently,**
- v) using reliable, properly adjusted instrumentation and automatic control,**
- vi) doing safety assessments, and correcting deficiencies promptly,**
- vii) training employees properly in their jobs.**

Even though a reactor may be designed with a high degree of prevention, it is impossible to completely guarantee perfection. Unfortunately, failure of some components however few and far between is inevitable. This is why there are two more levels to consider in the design of a reactor.

2.3.2 Protection

Protection is the second level of defence against an unsafe situation. The aim of protection is to stop and deal with low probability incidents quickly. This will involve:

- i) including protective measures for tripping (shutting down) the reactor,**
- ii) having pressure release valves,**

- iii) having interlocking containment so that there is more than one barrier to contain harmful substances,
- iv) having transient operating guidelines and procedures in place so that operators know how to handle problems in advance,
- v) having measurement and control of radiation and radioactivity.

2.3.3 Mitigation

The aim of mitigation is to limit the consequences of an incident. This will include:

- i) having emergency feedwater ready in case of a loss of coolant,
- ii) providing for emergency cooling of the core in case there is a loss of cooling,
- iii) providing structures for the containment of radiation, and irradiated/toxic elements and components,
- iv) ensuring that emergency planning and procedures are developed ahead of time.

2.4 Design Basis Accidents

With the defence in depth approach, safety systems are designed to cope with the worst case accidents. These are known as design basis accidents, and are considered to be the failure of one or more important systems, {5}. Design basis

accidents are used for evaluating the safety of the design of the reactor. The types of design basis accidents include:

- i) overcooling,
- ii) undercooling,
- iii) over filling,
- iv) loss of flow;
- v) loss of coolant,
- vi) certain reactivity events,
- vii) anticipated transient with failure to trip reactor,
- viii) spent fuel and waste system malfunction,
- ix) extraordinary external events such as earthquakes, {5}.

2.4.1 Loss of Coolant Accident

A loss of coolant accident (LOCA) is one of the major design basis accidents. It is defined by Marshall in Nuclear Power Technology as "the conditions which might arise when the coolant level in the primary vessel, or in the secondary circuit fails", {6}. The LOCA could result from a rupture of the primary coolant piping (this is known as a classic LOCA), a steam generator tube rupture, inadvertent valve opening, or a break in a steam line.

Research has been done to investigate the consequences of what is known as a guillotine failure, which is a classic type LOCA. Shewfelt et al., {7} developed a

model of the guillotine failure of a pressure tube using dynamic finite element methods. They determined that their model was able to predict the deformation associated with a guillotine failure with reasonable accuracy.

A loss of coolant will not result in a nuclear weapons type explosion. Instead, the danger lies in the excessive heat which will result from the fission process. This heat, if not carried away by the heat transport fluid, will build up since the fission products in the fuel continue to generate significant heat even after the nuclear reaction is halted. If the heat is not carried away, the fuel and surrounding materials can melt, leading to a release of the fission products and radioactivity. If the molten mass is not adequately cooled, it may melt through the reactor vessel, and possibly through the containment structure.

A LOCA can occur on a large scale or small scale. An example of a large scale LOCA would be the severing of the inlet pipe to the core in such a way that coolant flows out of the pipe from both of the cut ends. A small scale LOCA occurs when one of the smaller tubes leaks or bursts, and tends to be a slower event than a large scale LOCA.

2.5 Leak Before Burst

The leak before burst methodology prescribes that a pressure vessel be designed so that a crack will grow through the vessel wall causing a leak before

reaching the critical length which may cause the vessel to burst. Simply put, the thickness of the vessel must be made smaller than the critical crack length.

As part of the defence in depth approach, this design methodology was used to help mitigate any flaws in the pressure tubes which could propagate quickly without significant plastic deformation. Cracks which depend on DHC typically grow in such a way that the probability of detection during routine inspections is small. Therefore, the design must be able to withstand the growth of such a flaw to a point where it can be detected by a humidity rise in the gas annulus.

The leak before burst (LBB) design philosophy combines the considerations of material cracking characteristics and leak detection into its philosophy. By designing the pressure tubes to leak before they burst, the problem can be identified and corrected, before a LOCA occurs, {8}.

Since coolant leaks are a serious problem for reactors, investigations into any situation which may result in a loss of coolant are conducted very thoroughly. One mechanism which may (under certain conditions) cause the cracking of zirconium alloy pressure tubes is known as delayed hydride cracking, or DHC.

2.6 Delayed Hydride Cracking

Delayed hydride cracking is a cracking mechanism which has been observed in the Zr-2.5% Nb pressure tubes of the CANDU reactor under certain conditions. The mechanism involves the dissolution of hydrogen into and through the zirconium alloy during operation at the high temperatures seen under the regular operating conditions of a reactor.

As a pressure tube cools during a periodic shutdown, the hydrogen in the zirconium alloy will diffuse along stress gradients towards the highest point of tensile stress. In the case of a crack, the hydrogen would diffuse to the crack tip. Once the hydrogen solubility limit of the material in that region is reached, (30 ppm at 280°C, 536°F), hydride platelets form. The hydride platelets are planar structures of precipitated hydride which usually form with their normals parallel to the externally applied stress, ie. in the hoop stress direction, {9}.

These platelets have a much lower fracture toughness than the zirconium alloy. When the platelets have grown to a critical size, they fracture under the normal operating stress of the pressure tube, {9}. Hydrogen will then diffuse toward the newly formed crack tip causing a delay in the fracture process. This sequence of hydrogen diffusion, hydride platelet formation, fracture and delay for further hydrogen diffusion is called delayed hydride cracking, or DHC, and is described schematically in Figure 2.4.

DHC is known to have been the cause for failures observed in Pickering Reactor units #3 and #4 in 1972. According to Coleman, {10}, three requirements are necessary for DHC to occur:

- i) a source of hydrogen and the presence of hydrides,
- ii) a stress gradient to concentrate the hydrogen and enhance precipitation of hydride,
- iii) a large tensile stress to fracture the hydride.

A crack which initiates due to DHC can start on the inside or the outside of the pressure tube. Those that initiate on the inside of a tube at a surface flaw could propagate by DHC due to the cooling of the pressure tube associated with shut down, or start up {10}. Sagging of the pressure tube could cause it to contact the cooler calandria tube. This localized cooling on the outside of the tube can lead to the formation of a hydrogen blister and the possible propagation of a crack by DHC.

It is convenient to characterize DHC initiation for three different potential initiating sites, a sharp crack or notch, a shallow and very smooth notch such as a fret mark, or a smooth surface which could contain flaws less than 0.1 mm (0.004 in) deep such as scratches and crevice corrosion pits. In order for the hydrided region to fracture, the applied stress must overcome the compressive stresses in the region caused by the presence of the hydride, {11}. Smith

concluded from his theoretical analysis that the critical local tensile stress is affected by the geometry of the hydrided region and applied stress level.

Coleman has investigated the reorientation of hydrides and found that it is sensitive to the direction of the stress in the CANDU pressure tubes, {12}. He found that the hydrides were easily reoriented when there was a circumferential stress, but not when there was a longitudinal stress.

An interesting aspect of the DHC mechanism observed by Eadie et al., {13}, is a phenomenon known as crack tunnelling which can occur during the growth of a crack by DHC. When the crack reaches a certain point in the material, such as near an unflawed surface, it may begin to propagate parallel to the surface rather than breaking through as shown in Figure 2.5.

Eadie et al. suggest that as the crack begins to propagate, the crack tip is in a state of plane strain, Figure 2.6. Under these conditions, the crack will propagate perpendicular to the surface of the flaw. As the crack reaches the opposite side of the wall, the state changes to one of plane stress, Figure 2.7. The plane stress plastic zone is larger than the plane strain plastic zone, and as a result, the stresses in the area of the crack decrease. With a lower stress gradient, less hydrogen will migrate, forming fewer platelets, and slowing down the DHC. The crack begins to propagate parallel to the surface of the tube,

causing a tunnelling effect. Crack tunnelling causes a problem in that the critical crack length changes, which becomes significant when considering the leak before burst criteria discussed in Section 2.5. Studies are continuing to investigate the initiation of DHC, and the effect of the hydrostatic stress field at the crack tip, {12 and 14}.

2.7 Pressure Tube Burst Testing

The burst test is used to investigate DHC by growing flaws placed in a pressure tube specimen, under simulated reactor operating conditions. The test is carried out in a room known as a hotcell, where the walls are 1.0 to 1.2 m (42 to 48 in) thick, and the viewing window into it is constructed of layers of glass and oil, {4}. Objects inside the room are accessed by remotely controlled manipulator arms operated by technicians outside of the room.

The tests are carried out on a section of irradiated pressure tube with a flaw machined on the inside of the tube using an electro-discharge machining technique. The pressure tube section is sealed at one end with a large end cap, and the entire assembly is covered with a bell jar, Figure 2.8.

The pressure tube section is filled with heavy water at a pressure of 10 MPa, and a temperature of approximately 290°C (554°F) for a period of 3 hours. Then, it is cooled to approximately 197°C (387°F), Figure 2.9. During the initial

rise in temperature, the hydrogen from the heavy water heat transport fluid will diffuse into the pressure tube. When the tube cools, the hydrogen solubility limit will be lowered, and hydrogen platelets will form around the area of the machined flaw, facilitating DHC initiation.

The crack is allowed to grow until the tube begins to leak. The bell jar surrounding the assembly will deflect the steam which will escape from the pressure tube through the leak. The test is interrupted at this point, the tube is depressurized, and the fluid removed. A liner is placed inside the tube to prevent steam from escaping for the remainder of the test. The specimen is then repressurized, and the test resumes until the tube bursts.

Since the tests are carried out in hotcells, it was necessary to design a system which could measure the growth of these cracks while operating in an environment of high temperature and steam. The mechanical equipment had to be designed to fit around the pressure tube within the limits of the bell jar, and had to be easily handled with the remote manipulator arms.

In addition to considering all the design limitations of the environment in which the system would be operating, it was necessary to incorporate the DCPD technique discussed in Chapter 3, to develop a crack measurement system which would characterize the DHC grown flaws.

Figure 2.1 Reactor Arrangement for the CANDU System.

The reactor vessel, known as a calandria, contains the horizontal fuel channels. Each fuel channel contains a calandria tube which surrounds a pressure tube. The pressure tubes are connected to feeder pipes which feed the pressure tubes with the heavy water heat transport fluid to cool the fuel bundles contained in the pressure tubes, {5}.

Figure 2.2 Simplified Description of a Fuel Channel

Each fuel channel contains a calandria tube which surrounds a pressure tube. The two are separated by close-coiled helical garter springs. The spacing between the two concentric tubes is known as a gas annulus and is monitored for humidity. Each pressure tube contains 12 or 13 fuel bundles. The heavy water heat transport fluid is pumped in one end of the pressure tube, through the fuel bundles, and out the other end, {8}.

Figure 2.3 Fuel Assembly for CANDU Reactor

Each fuel bundle contains fuel pins which hold the UO_2 fuel pellets. The pins are separated from each other by inter-element spacers. This allows the heat transport fluid to be pumped through the fuel bundles, {5}.

Figure 2.4 Mechanism of Delayed Hydride Cracking {15}

Hydride will diffuse along a stress gradient towards the point of maximum stress, in this case the crack tip. When the hydrogen solubility limit of the material in the vicinity of the crack tip is reached, the hydrogen precipitates out. With enough hydrogen in the area, planar hydride platelets form, with their normals perpendicular to the highest stress. The hydride having poor mechanical properties fractures, and the hydrogen diffuses towards the newly formed crack tip. This causes the delay in the mechanism, while new platelets form, hence the term delayed hydride cracking.

Figure 2.5 Crack Tunnelling

The crack starts by growing in a semi-elliptical manner. As it approaches the opposite surface of the pressure tube, the crack begins to grow parallel to the surface, rather than at right angles to it. This phenomenon is known as crack tunnelling, and can seriously impede the ability of the pressure tube to leak before bursting.

Figure 2.6 Crack Tip in Plane Strain

As the crack begins to propagate through the thickness of the tube, the crack tip is in a state of plane strain. With that being the case, the crack continues to advance perpendicular to the surface of the tube.

Figure 2.7 Crack Tip in Plane Stress

As the crack tip approaches the opposite surface of the tube, the state of the crack tip changes from one of plane strain to plane stress. Eadie et al. {13}, suggest that the plane stress plastic zone is larger than that of the plane strain plastic zone, and as a result the stresses in the vicinity of the crack tip are reduced. When this happens, there is a decrease in the amount of hydrogen which will migrate, and therefore fewer platelets form, slowing the DHC mechanism.

Figure 2.8 Pressure Tube Burst Test Apparatus used at Chalk River Laboratories (3)

The pressure tube section is covered with an end cap, and pressurized with heated heavy water. The entire apparatus is covered with a bell jar, to contain the steam which will escape when the pressure tube leaks. All units on the drawing are in inches.

Pressure vs Time for Burst Test

Temperature vs Time for Burst Test

Figure 2.9 Pressure Tube Burst Test Pressure and Temperature vs Time {3}

These graphs show the pressure and temperature used for a burst test. The pressure is brought up to 10 MPa for the test and the temperature is peaked at approximately 290°C (554°F) for 3 hours. This will provide sufficient time for the hydrogen to diffuse into the material. Then the temperature is cooled, in order to lower the hydrogen solubility limit of the material, and force the hydrogen to precipitate out in the form of hydride platelets.

Chapter 3 Potential Difference Systems Theory and Practice

3.1 General

The technique used for the characterization of the flaws within the present study is a potential difference technique. Simply put, potential difference (PD) techniques involve the injection of a current into a specimen, and the measurement of a voltage, or potential difference, between two points on the specimen. Usually, a point of interest such as a flaw is placed between the two points so that the potential difference is measured across it.

Either alternating or direct currents can be used as there are PD techniques for each. If a direct current is injected into the material, then the technique is known as a direct current potential difference (DCPD) technique. If an alternating current is used then the technique is known as the alternating current potential

difference technique (ACPD). The ACPD technique was not investigated in the present research, and therefore is not discussed within this thesis.

The DCPD technique has been used by many researchers in their attempts to characterize flaws. McKeighan and Smith report that the first successful use of the potential drop method for crack length determination was by Barnett and Troiano, who used the technique for the measurement of hydrogen embrittlement in notched tension specimens of steel, {16 and 17}. The DCPD technique has been used in a variety of applications including the investigation of slow crack growth, crack length measurements, fracture toughness measurements, and the measurement of fatigue cracks in fillet welded joints, {18 - 21}.

3.2 Direct Current Potential Difference Theory

The DCPD technique is applied by injecting a direct current into a specimen, and measuring a potential difference across a portion of the specimen. The current is conducted through the bulk of the material as opposed to along the surface as in the case of an alternating current. If the current is kept constant, then the voltage measured becomes a function of the resistance of the specimen so that any changes in the specimen which would change the resistance, will also change the voltage.

The factors which affect DCPD measurements are the cross-sectional area of the direct current path, the length of the path, and the resistivity of the material. Since the material used in the present study is hexagonal closed packed (HCP) and anisotropic, its resistivity depends on the orientation of contacts with respect to the material. For a given test, the length of the current path was constant since the distance between the potential difference probes remained the same. The material, the distance between the probes, and the orientation of the contacts were all kept constant, so that the resistivity of the material would only change if the temperature or the cross-sectional area of the current path changed.

Often when the DCPD technique is used, large currents are injected across the entire body of material, leading to specimen heating. In an effort to avoid the increase in temperature associated with the use of large currents, a localized DCFD technique was used in the present work. This technique injects the current closer to the flaw, therefore requiring much lower currents. Specimen heating due to current input therefore was not a factor considered during the interpretation of the measurements made. In addition, the present system uses a short pulse of current which further minimises specimen heating.

Hicks and Pickard, describe one of the main advantages of the potential drop technique as being the use of it in a sealed environment, where visual

accessibility is limited or non-existent, {19}. They add that the system can be used for constant data collection, and can detect crack growth that cannot be resolved optically. Behr et al., report the detection limit for crack advance in their investigation of fatigue crack growth as being better than 10 microns, {22}.

3.3 Background Investigations

Often the DCPD technique is used in the investigation of single cracks which grow at right angles to the applied load. McKeighan et al. investigated how deflected and bifurcated cracks affected PD measurements, and found that these types of cracks resulted in an increase in the magnitude of the PD data, {16}.

More in line with the present investigation, Saka et al., investigated the use of DCPD to measure circumferential flaws on the inside of a pipe, by taking measurements on the outside of the pipe, {23}. They were able to detect the point of maximum depth of the crack, but did not try calibrating the results to give an actual depth of the flaws based on the measurements made. Since they were not using a localized method, their currents were much higher, as was the length between probe contact points.

Harrington et al. used a localized DCPD technique, and report that non-uniformity of the DC field in the material makes it difficult to calibrate a PD

reading to a specific crack depth, {24}. They used a boundary element method (BEM) model of their specimen to effectively calibrate the localized DCPD system. They found that the 3D effects of the crack are not adequately taken into account with the 2D calibration equations suggested by other authors. Their method not only gave information on crack depth, but also information concerning crack shape.

Many other researchers have tried to calibrate the method with varying success. Johnson analytically derived a closed form calibration for middle-cracked finite width plates using the following equation, {25}:

$$\frac{V}{V_o} = \frac{\cosh^{-1} \frac{(\cosh(\frac{\pi g}{2W}))}{(\cos(\frac{\pi a}{2W}))}}{\cosh^{-1} \frac{(\cosh(\frac{\pi g}{2W}))}{(\cos(\frac{\pi a_o}{2W}))}} \quad 2.1$$

where W is the total width of the specimen, V is the potential at a specimen crack length a/W , V_o is a measured potential at an initial crack length a_o/W and g is half the potential probe gauge length. If a_o is 0, then the denominator becomes $\pi g/2W$. Reducing, and manipulating equation 2.1 gives:

$$\frac{V_o}{V} = \ln \left(\cos \frac{\pi a}{2W} + \sqrt{\left(\cos^2 \frac{\pi a}{2W} - 1 \right)} \right) \quad 2.2$$

Calibration uncertainties according to McKeighan and Smith include specimen geometry, contact positioning, and electrical connections, {16}. Based on their results, they urge the use of visual crack length measurements during any testing to verify or modify any calibration technique used, {16}. They developed six different calibration techniques, five of which are based on Johnson's equation, with some modifications. Che-yu and Wei, developed a method which measures an unknown flaw based on a known flaw, {18}.

3.4 High Temperature Effects

As outlined in section 3.1, temperature will have an effect upon the magnitude of the DCPD measurements taken. From Ohm's law:

$$V = I * R \quad 2.3$$

where V represents voltage, I represents current, and R represents resistance.

The resistance of a material can be described by the following equation:

$$R = \rho * \frac{L}{A} \quad 2.4$$

where ρ is the electrical resistivity of the material, and L and A are the length and cross-sectional area of the specimen, respectively. In the present study, an increase in temperature results in an increase in the resistivity of the material used.

If two measurements are taken at two different temperatures on the same sample, (therefore L, A, and I are constant), then the following ratios can be used:

$$\frac{V_{T1}}{V_{T2}} = \frac{C}{C} * \frac{\rho_{T1}}{\rho_{T2}} \quad 2.5$$

$$\frac{V_{T1}}{V_{T2}} = \frac{\rho_{T1}}{\rho_{T2}} \quad 2.6$$

In order to eliminate the effects of temperature and common mode errors, a process called normalization is employed in the analysis of the DCPD measurements. Normalization is carried out by using the following equation:

$$V_{normalized} = \frac{V_{measured}}{V_{reference}} - 1 \quad 2.7$$

where $V_{measured}$ is the potential difference at the point of interest across the flaw, and $V_{reference}$ is the potential difference taken where there is no flaw.

Jones and Frise found that the normalization of the data efficiently eliminates the effect of temperature, while not affecting the increase in potential difference due to the presence of a flaw, {26}.

In order for the normalization to be effective, it is imperative that V_{measured} , and $V_{\text{reference}}$ be taken at the same temperature. Otherwise, the temperature effects will not be eliminated, and the normalization will yield results which are incorrect. As temperature effects on the DCPD system were investigated in the present study, normalization was also used.

In the present study a localized DCPD technique was used to characterize flaws in Zr-2.5Nb specimens. The equipment used in this study is described in Chapter 4.

CHAPTER 4 EXPERIMENTAL EQUIPMENT

4.1 General

The equipment used in the present crack measurement investigation can be divided into three main systems: the probe system, the electrical equipment and the control software. The probe system includes the probe and guide assembly and the test bed. The electrical equipment comprises the data acquisition equipment and the motor controller. The control software consists of the code written for the crack measurement testing in BASIC, the data analysis in MATLAB, as well as the software package INDEXER LPT.

A system schematic which shows how all the components of the system are integrated is shown in Figure 4.1.

4.2 Test Equipment

The probe and guide assembly for the tube specimen and the test bed were designed by the author based on a conceptual sketch by a previous student {3}. The probe and guide assembly were designed to fit inside the bell jar (described in Section 2.7) during a pressure tube burst test. The test bed was designed to be used only at Carleton University. It was used to hold the pressure tube, and provide a mount for the guide assembly and the motor while data were being taken.

The design of the equipment was heavily influenced by the environment in which it would be used. Proposed sketches and drawings were sent to AECL Chalk River Laboratories where the burst testing, described in Section 2.7, is carried out. Close contact was kept with AECL to ensure that the system was designed so that it could be easily handled by the remotely controlled manipulator arms inside the hotcell. Considerations which were incorporated into the design include:

- i) the use of socket head cap screws, which are easily handled by the manipulators,
- ii) the use of aluminum where possible to decrease the weight, also for the benefit of the unpowered manipulators,
- iii) careful design of the guide assembly and coupling so that it could be assembled by the manipulators without difficulty.

The motor controller was built by ETC-Electronics at Carleton University, and the data acquisition unit was built by MDT Engineering in Cambridge, Ontario. Photographs of the system can be found in Figure 4.2 and 4.3.

4.2.1 The Test Bed

The test bed was used to support both the pressure tube, and the guide assembly during testing. It simulates the arrangement of the pressure tube burst test apparatus. The test bed consists of a top and base plate, two angle braces, and a compression bar. Figure 4.4 shows the test bed which supports the guide and probe assemblies used with the tube specimen.

The top plate of the test bed has provision for mounting the stepper motor to mimic the fitting which would be required on the top of the bell jar in the actual hot cell apparatus.

The base plate contains a groove for the pressure tube which is used to align it properly with the rest of the system. An aluminum riser is included in the base plate, to provide flexibility in the system by allowing the test bed to accommodate pressure tube samples of different lengths.

The aluminum angle braces are two 1 x 2 angles which have slots in them to provide adjustability. These braces are used to join the top and base plates

together and the slots are used for mounting the compression bar.

4.2.2 The Guide Assembly

The guide assembly is used to guide the moving probe during a test. The assembly consists of the following components:

- i) motor,
- ii) coupling,
- iii) lead screw,
- iv) top and bottom guide plates,
- v) guide bars.

The motor is a Slo-Syn Synchronous/Stepping Motor model number M061-LF-408. It has 200 steps per revolution, can be used in full or half step mode and is rated for a holding torque of 0.054 kg-m (75 oz-in) and a maximum temperature rise of 65°C (149°F). The stepper motor is mounted to the top plate of the test bed, and secured to the lead screw via a motor coupling. If used in a hot cell the motor would be secured to the bell jar, but would still be linked to the lead screw by means of the same coupling.

The phase windings and electrical ground of the motor are connected to the motor controller via a 9-pin connector. This was done to improve serviceability

since this type of connector makes it easier to change motors when the need arises and is easily handled by the remote manipulators.

The coupling is used to mechanically connect the lead screw to the stepper motor in such a way that it can transmit the necessary torque without having a fixed connection. This is done to allow the motor to be attached to the bell jar, and the lead screw attached to the rest of the guide assembly. During a burst test, the guide assembly would be clamped to the pressure tube. Then the bell jar (with the motor attached) would be placed over top. The coupling is designed to ensure that the shaft and lead screw align properly and that the torque from the motor to the lead screw is transmitted without slipping.

A photograph of the coupling can be found in Figure 4.5. As can be seen in the Figure, the coupling consists of several components. The top portion is connected to the stepper motor shaft, and the bottom to the lead screw. The coupling has cone shaped plug and socket pieces which ensure that it is properly aligned. The toothed pieces ensure that no slippage occurs. An exploded view of the coupling is shown in Figure 4.6.

The lead screw is an Acme 3/8-10 right hand thread and is made of AISI 303 stainless steel that has been precision ground to size. It was obtained from Designatronics Foreign Sales Corporation, New York. The lead screw passes

through the top and bottom guide plates, and through the lead screw drive nut which is secured to the probe assembly. A stopper is fastened to the bottom of the lead screw in order to ensure that it does not back itself out of the assembly.

Oil-lite bronze bushings are placed in both the top and bottom guide plates as an interface between the plates and the lead screw. These are impregnated with a lubricant which sweats out of the bushing when it is heated.

The guide plates are nearly symmetrical with only a few minor differences between the top and bottom units. The plates are used to secure the system to the pressure tube. Figure 4.7 shows a photograph of the guide assembly.

The guide plates have an opening into which the pressure tube specimen fits and securing arms that are used to clamp the pressure tube in place. Once the tube is placed in the opening, the securing arms are moved into position and fastened with a clamping device, as shown in Figures 4.8 a,b, and c. The plates and arms are made of aluminum to decrease the weight of the system and make them easier for the manipulators to handle.

The guide bars are attached to the top and bottom guide plates and are used to steady the structure as well as guide the probe assembly up and down the lead screw. The guide bars are made of case hardened steel in order to increase

their wear resistance. Oil-lite bushings are used to act as an interface between the probe assembly and the guide bars.

4.2.3 The Probe Assembly

The probe assembly is the assembly which moves up and down the lead screw and carries the equipment which actually makes the DCPD measurements. The assembly consists of the following components:

- i) probe housing,
- ii) probe plate,
- iii) plexiglass probe.

The probe housing is made of aluminum and is attached to the lead screw drive nut. It is guided up and down the lead screw by the steel guide bars discussed above and consists of two pieces, one which contains a cavity for the probe plate, and the other which acts as a cover plate.

The probe plate is a skewed rectangular plexiglass plate and is used to hold the probe and provide a path for the electrical wiring to the probe. Because it is made of plexiglass, it insulates the signals which the probe measures.

The plexiglass probe is a small rectangular plate which has four pogo contacts at a spacing of 2 mm (0.078 in) mounted to it. The contacts are secured to the

probe with a two-part epoxy adhesive. The conductors are soldered to the contacts, and to a nine 9-pin connector. This connector allows the probe to be easily changed without having to change the wiring to the data acquisition unit.

The probe with the contacts attached is fixed to the probe plate using socket head counter-sunk screws. This assembly operation would take place outside the hotcell. The leads to the pogo contacts would then be attached to the 9-pin connector so that they can be electrically joined to the equipment outside the hot cell. This assembly, shown in Figure 4.9, is then inserted into the probe housing by the remotely controlled manipulator arms, as suggested in Figures 4.10 a and b.

The pogo contacts are P/N P26636 - 1R1S from Newark Electronics Co. Ltd., and were 0.655 ± 0.05 mm in diameter. A photograph of one of the pogo contacts is shown in Figure 4.11. The contacts were placed into the probes, and secured with a two part epoxy. Leads from a shielded cable were soldered onto the pogo contacts. Pogo contacts were chosen to ensure that contact was always made with the tube or plate regardless of any small irregularities in the specimen, as shown in Figure 4.12.

4.2.4 Flat Plate Specimen Equipment

The probe and guide assembly for the flat plate specimen was designed by a

previous student {3}. It was designed for the preliminary investigations carried out at Carleton University, and not for use in the hotcells. The flat plate specimen and test apparatus was used for a large portion of the testing within the present investigation, including the high temperature portion of the testing. The basic components are functionally the same, but are not geometrically similar. Figure 4.13 shows the guide and probe assemblies for the flat plate specimen.

4.3 Electrical Equipment

The electrical equipment includes the data acquisition equipment and the motor controller.

4.3.1 Data Acquisition Unit

The data acquisition unit is an MDT Model M100 data acquisition system designed and built by MDT Engineering Ltd in Cambridge, Ontario. The system is designed for direct current potential difference crack measurement, and is described in detail in {27}. It can accommodate 512 data acquisition channels, and has a four order of magnitude gain range capability, (ie. 10^0 - 10^3).

The system requires an IBM compatible computer with an MDT Data Acquisition Interface card. The card has 9 bit TTL (transistor-transistor logic, a type of digital integrated circuit which uses bipolar junction transistors, {28}), digital

output signals which control the channel selection, gain range, and excitation power to the unit. There is also an analogue to digital (A/D) converter on the card which converts the analogue output of the data acquisition system to digital form for disk storage.

There are two modules which accompany the unit. The first module is the main control module which controls the channel selection, excitation power and gain selection. The multiplexer/pre-amplifier module selects one of 16 channels in whichever of the 8 slots the modules are installed. It also pre-amplifies the signal.

The leads from the contacts on the probe are attached to the potential difference conditioner module that measures the voltage which is indicative of the depth of the crack. Four leads extend from this module, they are labeled as P+, S+, S-, P-. The P's indicate power, or excitation current while the S's denote signal, or voltage reading across the crack.

The data acquisition unit had to be calibrated for the lab environment. This was done through a procedure outlined by the MDT manual, {27}.

The unit obtains voltages by stepping the excitation current in such a way as to produce a square pulsed wave signal, Figure 4.14. A voltage reading is taken

when no current is passing between the power probes (Point A in Figure 4.14), as well as when there is maximum current passing between the probes (Point B in Figure 4.14). The difference of these two voltage readings ($V_{\min}$ and $V_{\max}$) is recorded as the potential difference between the two signal probes. This type of differential approach is used to reduce the common mode noise in the measurements.

Each reading recorded by the data acquisition system is an average of several readings. The number of readings taken and averaged is called the sample size. Most often a sample size of 10 was used, meaning that for every data point recorded by the data acquisition system, 10 readings were taken and averaged.

The system starts with a gain of 1, and attempts to obtain a reading within a certain range. If the reading is greater than that range, then the gain is increased to 10, and the reading repeated. This process is continued until the reading lies within the range, or a maximum gain of 1000 is obtained. The software is written in such a way as to account for the gain, in order to ensure that the reading is recorded correctly.

4.3.2 Stepper Motor Controller

The stepper motor controller was designed and built by ETC-Electronics at

Carleton University. The controller acts as an interface between the PC and the motor, as well as the limit switches, and the test interrupt signal. The controller incorporates a programmable logic circuit (PLC) in its operation.

The controller has inputs for mode, clock, and direction. These inputs are all outputs of the software designed to control the system. The limit switches and test interrupt switch are all fed into the motor controller and from there are relayed back to the PC and the system software.

4.4 Control Software

4.4.1 General

The control software in GWBasic, was written jointly by an undergraduate student, R. W. Armitage, and the author at Carleton University. It incorporates portions of software written by Dr. U.H. Mohaupt of MDT Engineering Ltd. Two machine language programs provided by Dr. Mohaupt are loaded into memory at the outset of the execution of the system software.

This software uses a package called Indexer LPT, which is a stepper motor controller software package. This software provides versatility and flexibility with regard to the speed of operation of the motor, and makes external signal detection very simple. It controls the stepper motor from the parallel printer port (LPT 1) of the PC. A total of six axes of motion can be controlled with this

software. However, the crack measurement system only uses one axis.

The Indexer LPT software loads as a device driver. Commands are written to the "motor" device and the system software communicates interactively with this device. The Indexer LPT software controls the speed, acceleration, mode, direction, position, limit switches, and test interrupt switch.

The objective of the system software is to provide a user interface to control the motor and the data acquisition system. It has been designed to offer two modes of operation. The first mode is automatic and allows the user to input necessary test parameters by using a test parameter file which is read in by the software. The test is then carried out according to the parameters specified in the file.

The second mode of operation is manual and the user is able to interactively input parameters, or complete sections of the test while omitting others. Both modes of operations are fully functional in the present system.

The software records via the printer and/or a disk file, the position and voltage reading (both raw and normalized voltage). This information is then passed through various MATLAB routines which are responsible for generating some useful data, as well as the characteristic graphs of the data.

The MATLAB routines are able to take data from several different files, and average them. This information can be compared with graphs of the actual crack profile. Thus, a relationship between the voltage readings and the actual crack profile can be obtained.

4.4.2 Operation

Since a localized DCPD system was used, it was possible to conduct testing on the frontside and the backside of the specimen. A frontside test is one where the pogo contacts are placed on the same face of the specimen as the opening of the flaw, as shown in Figure 4.15, while a backside test is one where the pogo contacts are placed on the opposite face of the specimen, as in Figure 4.16.

Two specimens were used in the testing: a flat plate of pressure tube material shown in Figure 4.17, and a section of an actual pressure tube as shown in Figure 4.18. Table I shows the characteristics for the flaws in the two specimens.

The tube sample was not used extensively due to difficulty in physically measuring the flaws for comparison with the DCPD data taken. It was hoped that the Ultrasonics Laboratory at NRC would be able to characterize them, however due to a heavy work-load they were unable to complete these measurements before the end of this work.

Figure 4.1 Schematic of Test Apparatus

The test apparatus contained the Stepper Motor Controller, built by ETC Electronics at Carleton University, the MDT M100 Data Acquisition Unit, built by MDT Engineering in Cambridge ON, the test specimen, the probe and guide assembly, an external power supply for the data acquisition unit, and a PC. The data acquisition unit and the stepper motor controller were both controlled by software run on the PC.

Figure 4.2 Photograph of Test Equipment

The apparatus shown in Figure 4.2 consists of:

- i) Personal Computer,
- ii) MDT M100 data acquisition unit,
- iii) power supply,
- iv) stepper motor controller,
- v) specimen,
- vi) probe and guide assembly for flat plate testing.

Figure 4.3 Photograph of Test Apparatus

When tests were conducted on the tube instead of the plate, the only components which would change from the previous figure would be items v) and vi). The equipment used for the tube is shown above.

Figure 4.4 Photograph of Test Bed

The test bed was used to support the pressure tube, guide and probe assembly.
The test bed consisted of:

- i) top plate,
- ii) two angle braces,
- iii) compression bar,
- iv) base plate.

Figure 4.5 Photograph of Coupling

The coupling connects the lead screw to the stepper motor and is designed to be self-aligning and engaging. The coupling needed to be designed so that the motor could be attached to the outside of the bell jar, and connect to the lead screw when the bell jar was lowered over the pressure tube burst test apparatus.

Figure 4.6 Exploded view of Coupling

This exploded view shows the components of the coupling depicted in Figure 4.6. The assembly in this photograph clearly shows the cone shaped piece used to align the coupling together during the lowering of the bell jar over the pressure tube burst test set up. The toothed pieces ensure that no slippage occurs.

Figure 4.7 Photograph of the Guide Assembly

Shown in the photograph are the following components of the guide assembly:

- i) top guide plate,
- ii) guide bars,
- iv) lead screw,
- v) bottom guide plate.

The guide plates secure the system to the pressure tube, and the guide bars and lead screw are used to actuate the probe assembly.

4.8a

4.8b

4.8c

Figure 4.8 Securing Arm Assembly

To secure the pressure tube to the test assembly, it is first put into the cavity in the test bed base plate. The securing arm is then brought around it as shown in Figure 4.8a. The thumb screw is then moved into the slot in the securing arm as shown in Figure 4.8b, and tightened so that the arm is pressed against the tube section securing it in place as in Figure 4.8c.

Figure 4.9 Probe Plate Assembly

The pogo contacts are attached to the probe plate with a two part epoxy. The probe is then fastened to the probe plate with socket head flat screws. The leads soldered to the contacts are brought through the cavity in the plate, and are attached to the data acquisition system via a 9-pin connector.

4.10a

4.10b

Figure 4.10 Probe Plate and Housing Assembly

The probe plate is inserted into the probe housing in the orientation shown in Figure 4.10a. The complete assembly is shown in Figure 4.10b.

Figure 4.11 Pogo Contact

The pogo contact was purchased from Newark Electronics Co. Ltd. (P/N P26636-1R1S) and is 0.655 ± 0.05 mm in diameter. The contact is spring loaded to ensure that it always makes contact with the specimen material regardless of any irregularities in the surface of the specimen.

Figure 4.12 Pogo Contact with Tube

The photograph shows the contact between the pogo contacts and the pressure tube. The probe will be moved vertically along the axis of the flaw, and in this case the tube as it scans using the DCPD technique.

Figure 4.13 Flat Plate Guide and Probe Assembly

The apparatus used to test the flat plate is shown in the photograph. The stepper motor on the left drives the lead screw which moves the probe horizontally along the axis of the flaw. The equipment is laid on top of the specimen with the axis of the lead screw along the axis of the crack.

Signal Voltage vs Time

Figure 4.14 Excitation Signal of Pulsed DCPD Equipment

The signal produced by the data acquisition unit is a pulsed wave form. This particular signal allows for the sampling at both the maximum and minimum current (corresponding to the maximum and minimum potential differences respectively). By subtracting the reading taken at the minimum from that taken at the maximum, the effect of background noise can be reduced. The system samples at approximately 2 Hz.

Figure 4.15 Frontside Testing Configuration

Probe contacts are on same surface as the opening of the sawcut. The sawcut is placed between the two pogo contacts. The leads from the contacts on the probe are attached to the potential drop conditioner module. They are labeled as P^+ , S^+ , S^- , P^- . The P's indicate power, or excitation current while the S's denote signal, or voltage reading across the crack.

Figure 4.16 Backside Testing Configuration

Probe contacts are on the opposite side as the opening of the sawcut. The sawcut is placed between the two signal pogo contacts. This configuration is analogous to an internal crack in a pressure tube.

Figure 4.17 Photograph of Plate Specimen

The plate specimen contained 12 sawcuts made to simulate cracks. Sawcuts #9 through #12 were used for the bulk of the testing. The characteristics of each of the sawcuts is given in Table I. The discolouration of the plate is due to the heating done during the high temperature testing.

Figure 4.18 Photograph of Tube Specimen

The specimen in this photograph is an non-irradiated section of pressure tube provided by AECL for this study. The tube has a flaw, shown in the photograph as #13. Some testing was completed on this flaw.

Specimen	Crack #	Length (mm)	Width (mm)	Depth (mm)	Profile
Plate	1	29.5	< 0.25	2.1	Semi-Elliptical
Plate	2	35.5	<0.25 to 0.5	4.2	Semi-Elliptical
Plate	3	33	1.14	1	Semi-Elliptical
Plate	4	33	0.33	1	Semi-Elliptical
Plate	5	60	1.14	2.1	Ramped
Plate	6	56.5	0.33	2.1	Ramped
Plate	7	101	0.33	4.2	Ramped
Plate	8	110.5	1.14	4.2	Ramped
Plate	9	27	0.33	1	Semi-Elliptical
Plate	10	29.5	0.33	2	Semi-Elliptical
Plate	11	33	0.33	3	Semi-Elliptical
Plate	12	37	0.33	4.2	Semi-Elliptical
Tube	13	19	0.33	2.5	Semi-Elliptical

Table I Summary of Crack Characteristics for Plate and Tube Specimen {3}

Chapter 5 Experimental Results

5.1 Understanding the Equipment

5.1.1 Discovery of Drift

The first test carried out was a familiarization test which was done to determine what the magnitude of the readings would be and what trend the data would follow. Both the internal and external power supplies were used, one after the other, for this test. The tests were done on a single point on the plate specimen, ie. without moving the probe. The surface of the plate was cleaned with a fine grit sandpaper in order to remove the layer of oxide which had built up over time. The sample size for this test was 10 readings.

In Figure 5.1, it can be seen that the voltage readings obtained with the external power supply were much higher than those obtained with the internal supply. In the case of the external power supply, the readings steadily increase beginning

at 50 μV and finishing near 56 μV at the end of the 2–3 minute test. The rise in readings is apparent in the measurements made with the internal power supply, though to a much lesser extent.

The results of this test when normalized should have yielded zero, since the probe was always measuring the same spot. This however, was not observed in the testing of the power supplies, Figure 5.2. This phenomenon is referred to as drift.

The increase appears to be exponential in nature, and it is not clear if, at the end of the test, the values have reached a plateau, or if they are still increasing.

This drift is important since it can skew the results of the measurements. If a reference voltage is taken at the beginning of a test, but the magnitude of the measured potential difference rises artificially, then the normalized voltage will increase, even though there may not be an increase in the depth of a flaw, or a temperature rise.

5.1.2 Source of Drift

The next series of tests were used to try and determine the source of the drift. It was hypothesized that either the power supply, or the probes themselves were the cause of the drift. If the probes were experiencing an increase in resistance as the test went on, it would register as an increase in voltage. The increase in

resistance could be due to the heating of the pogo contacts during the test. If the power supply required a certain amount of time to stabilize, but was not allowed that time, it is possible that the output current of the data acquisition unit might not be uniform, and the measurements would reflect that fact.

To test this theory, three tests were carried out. The first test was conducted with neither the power supply, nor the probes being warmed up prior to the readings being taken. This test was done by scanning along the axis of a flaw with a reference taken on an unflawed region of the plate, and the results are shown in Figures 5.3 and 5.4. The readings taken at the unflawed portion of the plate before the probe reached the flaw, are slightly lower than the measurements taken at the unflawed portion of the plate on the far side of the flaw. While not as dramatic as the increase in magnitude of the measurements for the external power supply in Figures 5.1 and 5.2, the rise is still important as it could lead to a mistaken conclusion that the flaw had grown.

In the second test the power supply was allowed to warm up by turning it on for 60 minutes before use, but power was not supplied to the probes. The results are shown in Figures 5.5 and 5.6. It is seen that the readings taken on the reference side of the flaw are much closer in magnitude to those taken on the far side of the flaw. This suggests that warming up the power supply decreases the drift of the system.

Finally, a third test where both the power supply and the probes were warmed up was completed. The warm up of the probes was carried out by allowing them to sample data for a time before recording measurements. (ie. a non-pulsating DC current was allowed to flow between the probes). The test was conducted on a single spot, and the results are shown in Figures 5.7 and 5.8. Instead of a rise in readings, which would have occurred had there been drift, a decay was observed.

Another test was carried out with the probe warm up period extended, and the results are shown in Figures 5.9 and 5.10. As the warm up time increased, the initial measurements increased, as did the decay rate.

As a result of these tests, it was determined that the source of the drift was the power supply, and that the problem could be eliminated by allowing the power supply to warm up before beginning a test. By warming up the power supply for one hour prior to any test, the effect of drift was found to be negligible.

The voltage decay observed when the probes were allowed to warm is believed to have been caused by localized heating of the pogo contacts, increasing their resistance and therefore, increasing the voltage reading. This would explain why the voltage begins high and decays as the heat is dissipated during the test.

Therefore it is not only unnecessary to warm up the probes prior to a test, it is in fact undesirable.

5.1.3 Excitation Signal

In order to better understand the behaviour of the system a Nicolet P30 model number P30C digital storage oscilloscope was used to capture the power signal from the current injection (P) probes. The captured pulsed square wave is shown in Figure 5.11. Two regions are observed, the constant power-on region, and the pulsed regions. The frequency of the pulses is 2 Hz, but the width of the pulses is not constant. The pulses represent the periods when samples are being taken.

The system takes a sample and checks to see if it is within a certain magnitude range. If the sample is not within that range, the system goes through an algorithm to change the gain. This algorithm is repeated until the sample is within the magnitude range, during which time, new samples are being taken. Depending on the magnitude of the data, the system may take slightly longer to adjust the gain to place the reading in the proper range. This is why the width of the pulses may differ. The constant, non-pulsing region represents the time allotted for the movement of the probes to a new location. The longer the spacing between measurement locations, the longer this constant period will be.

5.2 DCPD Results on Zirconium Alloy Specimens

5.2.1 Room Temperature Testing

A test on Tube #01, Crack #13 was carried out where the system did 10 passes over the frontside of the flaw, recording measurements every 2 mm (0.078 in) along the length of the crack. A photograph of Crack #13 is shown in Figure 5.12. The average reading from each of the locations is plotted in Figure 5.13. The Figure shows that the readings follow the profile of the flaw quite closely.

A plot of normalized voltage vs crack depth ratio is shown in Figure 5.14. It suggests a linear type relation of slope 6.7 between normalized voltage and crack depth ratio.

A test was carried out on crack #12, a through-crack on the plate specimen, measured from the backside, Figure 5.15. The results are quite interesting in that the plot does not follow the profile as closely as that in Figure 5.13, as seen in Figure 5.16. The system does not indicate the surface breaking points of the flaw, nor is it able to show the length over which the flaw breaks through the opposite surface as clearly as with a frontside flaw. In a plot of normalized voltage vs crack depth ratio, Figure 5.17, the relationship is more exponential in nature.

Johnson's equation, (equation 2.1), was used in conjunction with these data. As suggested by Mohaupt and Costanza {29}, Johnson's equation was applied for depth, and the results compared with the data gathered, and the actual crack depth as shown in Figure 5.18. It is interesting to note that Johnson's predicted data follows the measured data closely. Unfortunately, Johnson's equation cannot be solved at points where the flaw breaks the surface on the opposite side, and so the curve for Johnson's predicted data stops where the depth is 4.2 mm (0.17 in).

Since both Johnson's equation and the measured data were unable to follow fully the profile of the flaw, it is believed that the through crack case is a special one for measurements using the DCPD system. Since the electric field around a through crack is radically different than that of a non-through crack, the PD readings are fundamentally different as well. Since the resistance of the material is dependant upon the cross-sectional area of the specimen, it is reasonable that the geometry of a through crack, results in a problem which Johnson's equation does not describe. Further study would be required to achieve a more complete understanding of the electric field present in the through crack case and its effect upon the measurements.

A frontside test was carried out on crack #10 in the plate specimen, shown in Figure 5.19, and was compared with the results of crack #13. It was found that

the magnitude of the readings from the plate were higher than those for the tube. Figure 5.20 shows that the readings follow the profile of the flaw closely. In a plot of normalized voltage vs crack depth ratio, a nearly linear relation with a constant slope 2.7 can be seen, Figure 5.21.

For comparison, Johnson's equation was again used to predict the value of normalized voltage which would be obtained for the test carried out on crack #10. The results shown in Figure 5.22 show that the Johnson's predicted values do not follow the measured values as closely as they did in Figure 5.18. This could be due to the fact that this test was done on a flat plate, and the specimen geometry affects the readings. More research into this area is required.

In Figure 5.23, the results of a test carried out on crack #10 are shown. This test was done in order to compare results with those in Figure 5.20 and to determine repeatability. The magnitudes are close, and differ by approximately 10%, which for this type of work, was considered to be repeatable. Figure 5.24 of normalized voltage vs crack depth ratio shows a nearly linear relation with a slope of 2.0. Since Johnson's equation would yield the same results as in Figure 5.22, they are replotted with the current results for comparison in Figure 5.25. It can be seen that again, the predicted values do not follow the measured values as closely as they did for the test on the tube specimen.

5.2.2 High Temperature Testing

During a pressure tube burst test, high temperatures are experienced by the test apparatus, as described in Section 2.5. In order to determine the effects that the high temperatures may have on the DCPD measurements, high temperature testing was carried out. This constituted the second phase of the experimental program.

Single spot tests were conducted at a range of different temperatures, and the results shown in Figure 5.26. From this data, it is clear that the magnitude of the readings increases as the temperature increases. The normalized data is shown in Figure 5.27 and it shows that the normalization is effective in eliminating the temperature effects.

During this high temperature testing of the flat plate specimen, a problem was discovered as can be seen in the last few data points at 249°C (480.2°F) in Figure 5.27. The tests were conducted in such a way that the temperature was kept constant while the probe scanned the axis of the flaw. During these tests, it seemed that at elevated temperatures, the last few data points (those at the higher temperatures) did not follow the trend as the other points did.

It was discovered that the readings became unpredictable due to the oxidation of the surface of the plate. Zirconium oxidizes very quickly in a high temperature

environment and the layer of oxide produced is believed to obstruct the measuring capability of the system.

A single spot test was conducted which measured the potential differences at varying temperatures in order to study the nature of the PD-temperature relationship. The temperature was measured using a thermocouple, Figure 5.28, and the data from this test can be seen in Figure 5.29. As the temperature increased, the magnitude of the DCPD measurements also increased, which supports the discussion in Section 3.4 where it was drawn from theory that as temperature increased, the magnitude of the measurements would also increase.

A test was carried out on crack #10, and the results are shown in Figure 5.30. The readings follow the profile of the flaw, and increase with temperature. Normalization eliminated the effects of temperature on the measurements, as demonstrated in Figure 5.31 by the overlap in normalized data points.

To overcome the problem of oxidation, measurements were taken at each location through the variety of temperatures, without moving the probe. The results of these tests are shown in Figures 32 and 33. By using this method an oxide layer was not able to form at the point of contact between the probes and the plate. A method will need to be developed to eliminate the problem of

Normalized Voltage vs Time

Figure 5.2 Power Supply Normalized Voltage Comparison

Ideally, the normalized voltage for both supplies should be zero, as the test was carried out without moving the probe. However, this is not the case, as in Figure 5.1 the slow increase in the external power supply data can be seen clearly. The rise in the internal power supply data is not as dramatic, but is still evident at the beginning of the curve.

oxidation on the tube for use inside the hotcell.

Tests were also carried out on cracks #9, 11, and 12, and it was found that no matter what the temperature, an increase in the depth of the saw cut caused an increase in the normalized measurement, thus demonstrating that the system can be used to measure cracks at high temperatures. It was found that as long as the temperature at the reference voltage is the same as that of the measured voltage, the normalization is effective in eliminating the temperature effects.

Raw Voltage vs Time

Figure 5.1 Power Supply Raw Voltage Comparison

As can be seen in Figure 5.1, the external power supply gives readings in a range much higher than the internal power supply. The external power supply gives a steadily increasing curve. The internal power supply also increases although not as dramatically as the external power supply.

Normalized Voltage vs Time

Figure 5.2 Power Supply Normalized Voltage Comparison

Ideally, the normalized voltage for both supplies should be zero, as the test was carried out without moving the probe. However, this is not the case, as in Figure 5.1 the slow increase in the external power supply data can be seen clearly. The rise in the internal power supply data is not as dramatic, but is still evident at the beginning of the curve.

Raw Voltage vs Position

External Power Supply

Figure 5.3 No Warm-Up Period Results

This test was carried out with no warm-up period for either the power supply or the probes. The test was carried out along the axis of the flaw, with a reference taken on the unflawed portion of the plate. The readings taken at the unflawed portion of the plate yield magnitudes slightly lower than those taken on the opposite side of the flaw. This is a direct result of the drift. While not as dramatic as the rise in Figures 5.1 and 5.2, it is still important as it could lead to a misinterpretation of the results.

Normalized Voltage vs Position

External Power Supply

Figure 5.4 Normalized No Warm-Up Period Results

Drift is clearly seen in Figure 5.4 when comparing the normalized voltages on either side of the crack. The normalized voltage should be 0 on either side of the crack, however, this is not the case.

Raw Voltage vs Position

External Power Supply

Figure 5.5 Power Supply Warm-Up Results

For this test, the power supply was given time to warm-up, but the probes were not. The readings taken on either side of the flaw match more closely than those of the previous test. This suggests that the warming-up of the power supply decreases the effect of drift.

Normalized Voltage vs Position

External Power Supply

Figure 5.6 Normalized Power Supply Warm-Up Results

As can be seen in the figure, the normalized readings on either side of the flaw are much closer to one another in magnitude, than they were in Figure 5.4.

Raw Voltage vs Time

External Power Supply

Figure 5.7 Probe and Power Supply Warm-Up Results

For this test, both the power supply and the probes were warmed up, and measurements were taken at a single spot. As can be seen, the readings begin high, and decay steadily, unlike Figures 5.3 and 5.4 where the result of drift was an increase in the readings.

Normalized Voltage vs Time

External Power Supply

Figure 5.8 Normalized Probe and Power Supply Warm-Up Results

Ideally, when normalized, the normalized voltage should yield a straight and horizontal line of 0, as the probe was not moved during the test. Clearly, this is not the case as the normalized voltage steadily decays.

Raw Voltage vs Time

External Power Source

Figure 5.9 Increased Warm-Up Time results

This test was conducted in a similar manner as that for Figures 5.7 and 5.8. The only difference is that for this test, a longer warm-up period was used. As the warm-up time increased, the initial measurements increased, as did the decay rate.

Normalized Voltage vs Time

External Power Source

Figure 5.10 Normalized Increased Warm-Up Time Results

With the normalized results, the decay rate is clearly seen. With a longer warm-up period, the decay rate, and initial readings increased as compared with Figure 5.8.

Signal Voltage vs Time

Figure 5.11 Pulsed Square Signal Wave

Two regions can be observed in this Figure. The first region is constant, and represents the movement of the probes across the plate. The second region is pulsed, and represents the moments when samples are being taken. Every pulse represents a sample. The pulses are of different width because the data acquisition system takes a sample and checks to see if it is within a certain range. If not, it changes the exponential multiplier, and goes through the algorithm again. Depending on the magnitude of the reading, it may take slightly longer to place the reading in the proper range, hence the differences in widths of pulses. Once the proper range has been identified, then the unit takes the required number of samples, in this case 10.

Figure 5.12 Crack #13

This photograph shows crack #13 on the tube specimen. The crack is approximately 19 mm long and 0.33 mm wide. It is of semi-elliptical shape

Raw Voltage vs Reading Number

Figure 5.13 Typical Room Temperature Readings

This test was carried out on tube #01, crack #13. The system performed 10 passes over the frontside of the flaw, recording measurements at 2 mm (0.080 in) intervals. The DCPD measurements follow the profile of the flaw quite closely.

Normalized Voltage vs Crack Depth Ratio

Figure 5.14 Normalized Voltage vs Crack Depth Ratio

A plot of normalized voltage vs depth ratio for the tube specimen shows a linear type relationship where the best fit line has a slope of 6.7.

Figure 5.15 Crack #12 - a through crack (backside)

The photograph shows Crack #12 on the flat plate specimen. The crack is 37 mm in length, 0.33 mm in width and is through the specimen at its deepest point.

Raw Voltage vs Position

Figure 5.16 Raw Voltage vs Position for a Through Crack

A backside test was done on a through crack. As can be seen the measurements do not follow the profile of the flaw or show the surface breaking points as well as in Figure 5.13. However, the measurements clearly indicate the presence of the flaw. It is reasonable that the measurements may be in error since the electric field through the specimen must change because the crack goes all the way through the thickness of the material. The effect of the change in electrical field could be used to calibrate this system for the through crack case.

Normalized Voltage vs Depth Ratio

Figure 5.17 Normalized Voltage vs Depth Ratio for Through Crack

For the through crack case, the normalized voltage vs depth ratio yields a curve which is more exponential in nature than the curve shown in Figure 5.14.

Normalized Voltage vs Position

Figure 5.18 Predicted Johnson's Comparison for Crack #12

Johnson's equation was used with the known depths, to predict the values of normalized voltage which should be obtained. As can be seen, Johnson's equation predicts values very close to the actual data. Johnson's equation however, cannot be used for a through crack when the reference voltage taken was at a non-flawed area. That is why the curve for Johnson's equation stops at the point where the flaw breaks the surface.

Figure 5.19 Crack #10

The photograph shows Crack #10 on the flat plate specimen. This crack was 29.5 mm in length and 0.33 mm in width. The crack was semi-elliptical in profile.

Figure 5.20 Raw Voltage vs Position Results for Crack #10 (frontside)

A test was carried out on Crack #10 to be used as a comparison with those data obtained on crack #13. The magnitudes of the data for the plate were higher than that for the tube, but again the readings follow the profile of the flaw closely.

Normalized Voltage vs Depth Ratio

Figure 5.21 Normalized Voltage vs Depth Ratio for Crack #10

This figure shows the normalized voltage vs depth ratio relationship for the data obtained on crack #10. The relationship is linear, as it was in the case for crack #13. The slope is 2.7, which is different from Figure 5.14, showing that the geometry of the specimen is important.

Normalized Voltage vs Position

Figure 5.22 Johnson's Predicted Normalized Voltage for crack #10

Johnson's equation under-predicted the values obtained on the frontside test. It follows the profile of the crack, as well as the measured data. Therefore, it should be possible to use the Johnson's equation to calibrate the system for the zirconium alloy plate. Further research is required to determine what may affect the relationship between Johnson's equation and the measured data.

Raw Voltage vs Position

Figure 5.23 Raw Voltage vs Position Results for Crack #10 (frontside)

This test was carried out on Crack #10 in order to compare the results with those shown in Figure 5.20. The magnitudes are close, differing by approximately 10%. The data follows the profile of the crack closely, as it did in Figure 5.20.

Normalized Voltage vs Depth Ratio

Figure 5.24 Normalized Voltage vs Depth Ratio for Crack #10

Figure 5.24 shows a linear relationship for normalized voltage and depth ratio for data obtained for crack #10. The slope of 2.0 is similar to that of Figure 5.21(also crack #10) showing that the results obtained are repeatable.

Normalized Voltage vs Position

Figure 5.25 Johnson's Predicted Normalized Voltage for Crack #10

Here again, Johnson's equation under-predicted the measured data and yields the same shape as the measured data. It is comparable to Figure 5.22 since it differs from the measured values by approximately the same amount.

Raw Voltage vs Position

High Temperature Testing

Figure 5.26 Raw Voltage vs Position - single spot high temperature test

This test was carried out at a single spot, and the temperature was varied. Clearly, as the temperature increases, the measurements also increase.

Normalized Voltage vs Position

High Temperature Testing

Figure 5.27 Normalized Voltage vs Position for Single Spot High Temperature Test

This test was carried out on a single spot, and the temperature was varied. It is clear that the normalization eliminates the effect of temperature, since all of the curves lie one on top of another except at times greater than 90 seconds. Here, at the higher temperatures, the plots do not lie as closely together. The reason for this is that the specimen oxidizes quickly when it is heated, and the oxidation caused problems for the DCPD measurements.

Figure 5.28 Thermocouple Used in High Temperature Testing

The thermocouple used was a T type thermocouple mounted on a hollow ceramic tube. This was used to measure the temperature at any spot on the surface of the plate during the high temperature tests.

Raw Voltage vs Temperature

Figure 5.29 Raw Voltage vs Temperature for the Plate Specimen

This test was carried out at a single spot, and the temperature steadily increased. There is a linear relationship between the voltage measurements and the temperature, as outlined in Section 3.4.

Raw Voltage vs Position

High Temperature Scan

Figure 5.30 High Temperature Scan Results for Crack #10 (frontside)

This test was carried out on Crack #10. The plate was scanned while the temperature was kept approximately constant. As can be seen, the lower temperatures follow the trend seen earlier in the other data. However, the upper temperature data does not follow the trend quite as well. It was found that the oxidation hastened by the high temperatures interfered with the measurements.

Normalized Voltage vs Position

High Temperature Scan

Figure 5.31 High Temperature Scan Results for Crack #10

The lower temperature readings normalized successfully, whereas the data at the higher temperature did not. The conclusion was that the plate was oxidizing at an increased rate at the higher temperatures, and the oxidation was having an adverse effect on the data.

Raw Voltage vs Position

High Temperature

Figure 5.32 Raw Voltage vs Position for Crack #10 - probe stationary (frontside)

This test was carried out on crack #10. The temperature was varied while the probe was kept at the same location. As a result, oxidation was not a problem. It can be seen that as the temperature increases, so does the magnitude of the DCPD measurements. As well, the general profile of the crack is indicated by the measurements.

Normalized Voltage vs Position

High Temperature Testing

Figure 5.33 Normalized Voltage vs Position for Crack #10 - probe stationary

This test was carried out on crack #10. The temperature was varied while the probe was kept at the same location and as a result, oxidation was not a problem. Note that the normalized measurements lie closely on top of each other, while still outlining the profile of the flaw. This indicates that the normalization eliminates the effect of temperature on the DCPD measurements.

Chapter 6 Conclusions and Recommendations for Further Work

6.1 Conclusions

Based on the work carried out, the following conclusions are made:

1. It is necessary to warm up the power supply for 60 minutes in order to avoid measurement drift.
2. The system is able to detect the profile of the flaw, and may be used for crack characterization.
3. There is a linear type relationship between normalized voltage and the crack depth ratio. Specimen geometry and crack geometry effect the DCPD measurements. The linear relationship between normalized voltage and crack depth ratio is not the same for the tube as it is for the plate specimen. As well, due to field changes within the plate for through-wall cracks, the DCPD measurements change.

4. Johnson's equation could be used to predict the DCPD measurements for cracks which do not penetrate through the wall of the specimen.
5. The system is more sensitive to frontside testing than backside testing.
6. The system gives repeatable data (within 10% was used as this work is experimental in nature).
7. As temperature increases, the magnitude of the DCPD measurements also increases, as expected. The normalization eliminates the effects of temperature, provided that the reference voltage is taken at the same temperature as voltage at the point of interest. As a result the temperature must be kept constant during a given test.
8. Oxidation during testing of the material occurs faster at the higher temperatures compare to lower ones. The oxide layer causes erroneous DCPD measurements and must be taken into account when conducting tests at high temperatures.

6.2 Recommendations for Further Work

There is still much work to be completed to completely understand all the factors involved in the use of DCPD measurements. The results seen in Section 5.2.1 suggest that it would be valuable to characterize the electrical field which occurs when the depth of the crack nears the thickness of the specimen.

Since geometry has been proven to play such a large role in the DCPD measurements, it would be valuable to carry out testing on cracks which have tunnelled in order that the system be calibrated for such a situation

Johnson's equation was shown to be able to predict the measurements made by this system. More extensive testing would be needed in order to determine how to use the results of the Johnson's equation to aid in interpreting test data.

The oxide layer which developed during the high temperature testing significantly affected the results of the DCPD measurements. With the present system, the oxide layer is not adequately removed by the scanning of the probes during a test. Therefore, a mechanism for removing the oxide will need to be developed prior to the system being used in a hotcell.

In order to use the system on the tube specimen, more extensive testing will need to be carried out in order to interpret the data.

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