Large-Scale Ice Fracture Experiments
Phase I

Field Program Report
January 15-29, 1992

#178 ✓

Participating Organizations

Amoco Canada Petroleum Company
Canadian Marine Drilling Ltd.
Minerals Management Service
Mobil Research & Development Corporation
National Energy Board (Canada)
Office of Naval Research
Texaco, Inc.

Prepared by

Canadian Marine Drilling Ltd.
Clarkson University
Jessco, Inc.
Sandwell, Inc.

May 11, 1992

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May 11, 1992

Charles E. Smith
Minerals Management Service
United States Department of the Interior
Technology Assessment & Research Branch
381 Elden Street
Herndon, VA 22070-4817

Dear Charles:

LARGE-SCALE ICE FRACTURE EXPERIMENTS; File 2600-1809
PHASE 1 FIELD PROGRAM REPORT

Please find enclosed for your review a draft of the field report for Phase 1. Your comments on the document are encouraged and any suggestions for revisions and/or additions are welcome. Included with the report is a 100 minute VHS video-tape of the experiments. Highlights of the tape are detailed in Appendix D of the report.

We trust that the report will be to your satisfaction. If you have any questions or comments, please call at (403) 298-3510 or FAX (403) 298-3532.

Sincerely yours,

Kurt Kennedy

K.P. Kennedy
Civil Engineer

KPK/sej

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Summary

Phase I of the joint-industry project "Large-Scale Ice Fracture Experiments" was successfully completed during the period January 15-29, 1992 near Calgary, Alberta. Phase I was designed to assess the feasibility of large-scale sea ice fracture experiments (proposed as Phase II) by performing a series of tests in freshwater ice. While data acquisition on freshwater ice fracture was regarded as secondary to field trials of equipment and procedures, the results of Phase I represent perhaps the finest data set to date on freshwater ice fracture. Analysis of data over and above that in this report is highly recommended.

Refreezing and edge melting of rectangular beams eventually led to a change in specimen geometry. The reverse taper (RT) geometry, essentially a free-floating right-angled isosceles triangle, proved highly effective and insensitive to beam edge conditions. Using the RT geometry, a scale range from smallest to largest test specimen of 1:85 was achieved. The largest known fracture specimen of any engineering material was also realized. Fracture toughness and elastic modulus were computed for four rectangular and nine reverse taper full-thickness, freshwater ice specimens.

An innovative closed-loop servo-controlled hydraulic loading system, developed by Sandwell specifically for these tests, was able to propagate cracks stably in both rectangular and RT specimens. This represents a significant achievement, as crack tip opening displacement (CTOD) controlled fracture had not previously been achieved under either laboratory or field conditions. Numerous controlled fracture tests on a single specimen were therefore possible and allowed for investigation of the change in fracture resistance with crack growth.

Unseasonable temperatures in Calgary forced a site change midway through the field program from Bearspaw Reservoir near Calgary to Spray Lakes Reservoir near Canmore, Alberta. This move was warranted based on project progress at that time and the potential benefits of additional testing. Necessary environmental and regulatory consent was obtained prior to approval of the move by Canmar management. Combined with other unforeseen expenditures, the move to Spray Lakes resulted in a cost overrun of approximately $29,000 (Canadian), or 16% of the original project budget.

Introduction

In 1990, Canadian Marine Drilling Ltd. (Canmar), Amoco Canada Petroleum Company Ltd. and Mobil Research & Development Corporation joined efforts with Clarkson University, Sandwell, Inc. and Jessco Operations, Inc. to design an experimental program to investigate the fracture properties of ice. The joint-industry project ''Large-Scale Ice Fracture Experiments'' was conceived as a two-phase program, Phase I consisting of freshwater ice fracture tests in preparation for a more thorough set of experiments in sea ice in Phase II. Approval for Phase I was granted in September, 1991 and involved the following industry and government participants:

Project Participants

1) Amoco Canada Petroleum Company Ltd.
2) Canadian Marine Drilling Ltd.
3) Minerals Management Service (U.S. Dept. of the Interior)*
4) Mobil Research and Development Corporation
5) National Energy Board (Canada)*
6) Office of Naval Research (U.S. Dept. of the Navy)
7) Texaco, Inc.

*joint participants

This report documents Phase I of the project, conducted near Calgary over the period January 15 to January 29, 1992. The Pacific weather disturbance known as El Niño created unseasonably warm temperatures in Southern Alberta this winter. Phase I, scheduled to commence January 8, 1992 at Bearspaw Reservoir west of Calgary, was postponed to January 15 due to mild weather. On Day 5 of testing (January 19), daytime highs of 15°C made the ice at Bearspaw unsuitable for further testing. With the assistance of Alberta Provincial Parks, access was granted to Spray Lakes Reservoir near Canmore, Alberta in the Rocky Mountains. The move was made on January 21.

Field Personnel

Project management and operation of the data acquisition system were duties assumed by Canmar. Loading systems were designed, constructed and operated by Sandwell, Inc. of Calgary. All field logistics, accommodations and heavy equipment operations were the responsibility of Jessco Operations, Inc., also of Calgary. Two other projects were added to the core experiments of Phase I. Personnel from the Institute for Marine Dynamics (National Research Council Canada) were contracted by the National Energy Board to perform crack speed measurements, while Williamson & Associates monitored *in situ* ice stresses at Bearspaw Reservoir for the Office of Naval Research. Affiliations of organizations involved in Phase I are summarized in **Appendix A**.

Background

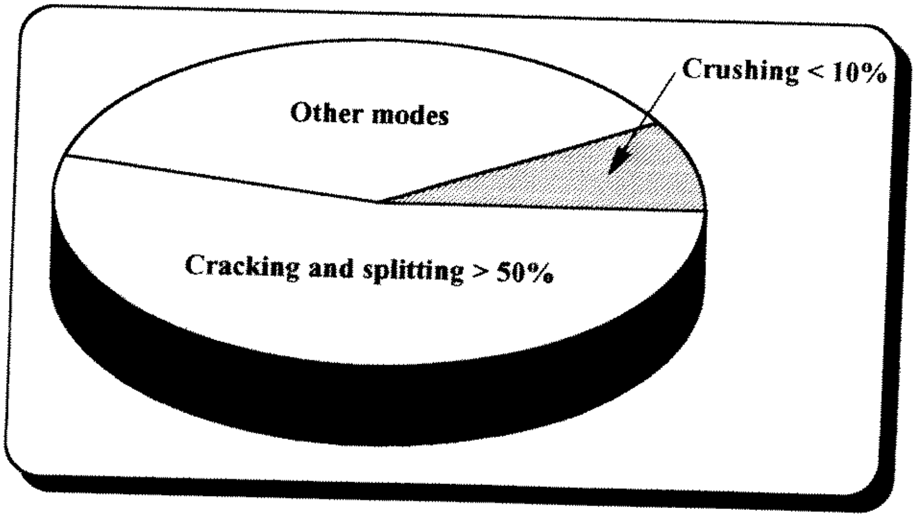
Methods to estimate global ice loads are based primarily on load limiting scenarios that assume crushing is the dominant ice failure mode. Illustrated in **Figure 1**, field observations indicate that splitting is a frequent failure mechanism, whereas crushing occurs less than 10% of the time. Zones of damaged, micro-fractured and pulverized ice form locally during ice-structure interactions, yet it is not well understood why a particular microcrack could suddenly become unstable and propagate through the entire floe. The 100-year global ice load on a structure, for example, could be reduced if the statistics of floe splitting are included. To date, quantitative measurements of the parameters involved in full-scale ice fracture have been limited.

Practical fracture mechanics theory is required to incorporate the effects of ice floe splitting into engineering procedures. This analytical theory was developed for Canmar and Mobil by Dr. John Dempsey of Clarkson University (Potsdam, New York) and served as the basis for the joint-industry project ''Large-Scale Ice Fracture Experiments''.

Phase I was conceived as a feasibility study, intended to assess whether or not the proposed experiments were possible and to optimize field procedures. Data on the fracture properties of freshwater ice was also a key goal.

Figure 1

Field observations of ice failure modes



Phase I Objectives

Phase I activities and objectives detailed in the January, 1991 unsolicited proposal ''Large-Scale Ice Fracture Experiments'' were successfully met. Briefly, these objectives were:

1) Field experimentation of:
   - beam cutting procedure
   - crack scribing procedure
   - flatjack loading system and servo-control
   - instrumentation effectiveness
   - crack speed measurement (an addition to the core project)
2) Fracture toughness of full-thickness freshwater ice
3) Apparent fracture toughness, K_Q
4) Global modulus of freshwater ice
5) Scale effects

The primary goal of Phase I was to assess the feasibility of large-scale, full-thickness ice fracture measurements. These tests were essentially highly specialized laboratory investigations carried out under field conditions. Specimen preparation was a critical element, as well as the performance of highly sensitive crack monitoring gauges and an innovative loading system. Actual field trials of the apparatus and procedures led to adjustments in the proposed testing program, as detailed below.

Site Change

Unseasonably warm temperatures forced a move from the Bearspaw Reservoir test site to Spray Lakes (Three Sisters) Reservoir, Canmore, Alberta on January 21, 1992. The average daily temperature in Calgary over the three months of December, 1991 and January and February, 1992 was -2°C, some seven degrees above the 30-year average. According to Environment Canada, January temperatures in Southern Alberta were 10.6 degrees higher than the normal mean of around -11°C.

Ice conditions at Bearspaw and Spray Lakes were quite different for a variety of reasons. Changes in water level at Bearspaw for hydropower needs were common and resulted in highly fractured *in situ* ice. Temperature fluctuations over the first five days of testing were also significant. The existing ice conditions at Bearspaw were analyzed by Williamson and Associates as an add-on to the project for the Office of Naval Research. Their results indicated a highly fractured and highly stressed ice sheet. Unlike Bearspaw, ice conditions at Spray Lakes were consistent over the testing period. *In situ* fractures were limited and large areas of ice with no visible cracks were common. Studies such as those carried out by Williamson and Associates at Bearspaw were not performed at Spray Lakes.

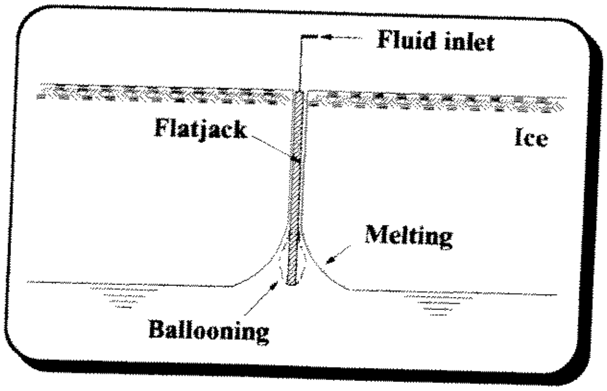
Testing procedures were perfected at the Bearspaw site and the majority of fracture tests performed at Spray Lakes. Differences in ice conditions must be considered when comparing test results from Bearspaw and Spray Lakes.

Change in Specimen Geometry

Rectangular beam tests were successful, but features of the ice slots at Spray Lakes necessitated a change in geometry. To maximize the number of tests, trenching operations were carried out on a near continuous basis at Spray Lakes. Some parallel slots (which formed the long sides of beams) were usually left for several hours or overnight before they could be readied for testing. Illustrated in **Figure 2**, melting caused by natural thermal gradients caused the slots to change in cross-section. The flatjacks required two flat, parallel surfaces to apply load to the ice specimen and curvature at the bottom of the slot resulted in ballooning of the flatjack.

Figure 2

Slot curvature caused by melting



Based on successful aboratory work at Clarkson University, the decision was made on January 24 to adopt the RT (reverse taper) geometry for subsequent fracture tests. The RT geometry is essentially a free-floating, right isoceles triangle. Since the flatjack was placed directly in the scribed crack, the RT geometry was insensitive to beam edge conditions. This geometry was also self-equilibriating in that the beam was completely free-floating and no supports were required. RT geometry fracture tests were much less complicated than rectangular beam experiments and could be carried out more quickly.

Uniaxial *In Situ* Modulus Tests

A set of three cantilever beam tests were added to Phase I to directly measure the full-thickness modulus of Spray Lakes ice. These tests were performed at different scales and were carried out on the final day of testing (January 28, 1992). The cantilevers were instrumented with a highly sensitive Kaman gauge, systematically loaded and unloaded and the resulting load-deflection curve used to estimate the elastic modulus of freshwater ice.

Flexural Index Test

A full-thickness flexural strength test on a large rectangular beam was planned for Phase I, time-permitting. The delays caused by the move to Spray Lakes and the greater importance of the fracture tests left little time for flexural strength indexing. The loading difficulties encountered due to slot curvature eventually settled the decision not to conduct this test. In any event, cantilever modulus tests carried out on the last day of testing were hampered by blowing snow. A large flexural test would have been extremely difficult to pursue under those conditions. Similar tests have been detailed in the literature and should provide reasonable estimates of the flexural strength of Spray Lakes ice.

Analogue Data Backup

The Institute for Marine Dynamics' crack speed measurement apparatus included a multi-channel analogue data recorder. Use of this system was graciously offered to the project. Data from all fracture tests were simultaneously recorded on both the digital computer system and the analogue recorder, reducing the chance of data loss.

RESIDUAL STRENGTH OF DAMAGED AND DETERIORATED OFFSHORE STRUCTURES

MINUTES OF THE PROJECT STEERING COMMITTEE MEETING

Lehigh University

May 31, 1991

Attendance: by Companies and Representatives

Chevron: T.M. Hsu
EXXON: N. Zettlemoyer
Mobil : V.V.D. Nair, J. A. Volker
Shell : C.D. Edwards (for P.W. Marshall)
Texaco: J. H. Kemper

Lehigh University: A. Ostapenko, W.D. Michalerya, J.W. Fisher,
A. Chowdhury, B.A. Wood, R.W. Kowalik, W.Kim,
S.D. Dimitrakis, P.A. Grossi

Absent were the representatives of MMS (C.E. Smith), AISI (K. Almand), and UKDOE (N.W. Nichols)

BACKGROUND, OBJECTIVES AND SCOPE OF THE PROJECT

A. Ostapenko discussed the background of the project, mainly for the benefit of those who had not been involved in the formulation of the project in the earlier stages when the proposal was reviewed as it grew out of a previous project on damaged tubular members. The principal motivation for the current project was the need for tests on damaged tubular members of the proportions and of the method of fabrication used in offshore industry. Although there have been many tests conducted on dented tubular members, they were essentially all on small-scale manufactured specimens, whereas in offshore structures the fabrication process involves cold-rolling from flat plate and welding, a process which leads to greater imperfections and higher residual stresses. The small-scale specimens typically had diameters of 1.5 to 8 inches. They were cut from manufactured tubes and were also annealed to remove all residual stresses.

The present project was expanded to include not only large fabricated tubes with dents but also tubes salvaged from decommissioned platforms, some with a significant amount of corrosion.

The objectives of the project included the testing of dented fabricated and salvaged specimens, the testing of corroded and of some control straight specimens, reduction of the test data, computer analysis of the axial behavior of damaged tubes, the development of a method for analyzing dented and corroded tubular members of the proportions typical for offshore platforms.

EXPERIMENTAL WORK COMPLETED TO DATE

B.A. Wood described the techniques used in various phases of the tests that have been completed and are planned. Basically, these consisted of the following groups of activity:

a) Determination of material properties (yield stress, ultimate stress, etc.) was made in three ways: Hardness tests by using a portable hardness tester gave a preliminary indication of the yield stress of the steel used. Tests on tensile coupons gave the true static and dynamic yield stresses in the specimens. Stub column tests (short columns with the length equal to 3-4 diameters) provided the overall compressive response of the tubular section including an indication of the magnitude and probable distribution of residual stresses. A total of seven (7) stub columns have been tested.

b) Controlled dents in the specimens were made by using two arrangements. The smaller specimens were dented in a testing machine, and the denter was applied vertically. For the larger specimens of the current series, the denter was positioned horizontally by using a hydraulic jack. Both arrangements worked out very satisfactorily. A total of 11 specimens were dented: 7 large fabricated and 4 salvaged.

c) Long column tests consisted of two series. Three long column tests were completed in September of 1990. Nine more are in the present series -- two were finished before the meeting and seven more are scheduled to be done next (completed after the meeting by June 21). All of the tests were carried out in the 5-million pound universal testing machine. The test data collected included readings of the following: Strain gages, displacement gages (LVDT's, dial gages), 4 rotation gages. In each case, the specimen was loaded in small step increments to the ultimate (maximum) load and an additional axial deformation equal to 2 to 3 times the axial shortening at the ultimate load. This way, the post-ultimate behavior of the damaged tube was properly defined.

ACOUSTIC EMISSION STUDIES

R. W. Kowalik presented the background of the techniques used in detection of the initiation and progression of damage (yielding) by using acoustic sensing. He discussed the method and the instrumentation used in the current project. All long-column specimens, most of stub-columns and some tensile specimens were instrumented. Analysis of the data collected indicates that the principal source of acoustic emission was the flaking off of the mill and corrosion scale. A limited comparison of the effect of the growth of the corrosion scale was also conducted by placing some plate specimens in a corrosive environment and measuring the effect of the growing oxidation layer on the intensity of the emission when the sample was subjected to a force which would cause yielding.

CURRENT PROJECT STATUS

The financial status at the time of the meeting was relatively on target, but the charges for the present series of tests are running somewhat higher than anticipated.

OTHER RELATED RESEARCH

A. Ostapenko briefly described relevant research conducted by graduate students under his supervision outside the project.

a) Impact denting of 9 in. diameter short tubes by dropping a 200 to 400 lb weight from up to 20-ft height. The energy dissipation characteristics of impact and static (slow, as used in the Project) denting can be logically related.

b) Analytical study of dented columns with elastic end restraints. The major task is to formulate the moment vs. curvature relationship for a dented segment as a function of axial force, dent-depth, D/t, and yield stress.

c) Expansion of the database on axial behavior of simply supported dented columns by using a filite element program and a refinement of a simplified (engineering) method for computing the load-shortening curve developed in the previous project (OTC'90).

ATLSS RESEARCH

W.D. Michalerya outlined the areas of research conducted under the umbrella of ATLSS Engineering Center (Advanced Technology for Large Structural Systems) which may be of interest to oil industry. He explained that the way to influence the direction of this research and be a direct beneficiary of it is to become a General Partner in the ATLSS Center.

FUTURE WORK

The immediate future will be spent on completing the current test series; seven more specimens are to be tested. (Completed by June 21.) Some reduction of the test data and complete post-test profile measurements of the tested specimens are to be finished before going to the next test series. Salvaged tubes, three corroded and three straight, will be tested then. Spherical end fixtures will be used so that the column could deflect in any direction. This would also require a more elaborate arrangement of instrumentation for measuring lateral deflections which may be in any direction. (In the current test series, the direction of deflection was predetermined by the dent, eccentricity and/or out-of-straightness, and cylindrical end fixtures were most suitable.) We expect to complete most of the preparations for these tests, or even some of the tests, by the end of the summer.

Later work will consist of the reduction and analysis of test data, the preparation of the test report, analytical work on the development of a method for analyzing the behavior and strength of corroded tubes (for one, the determination of the corrosion damage parameter), the refinement of the previously developed method for dented columns, the completion of the report on acoustic studies, and the drafting of the final report.

PHASE II OF THE 5-YEAR RESEARCH PROPOSAL

The current Phase I of the originally proposed work started on June 18, 1990 and will formally continue till June 17, 1992. Its main thrust is on the strength and behavior of dented and corroded tubular members -- experimental and analytical work.

Phase II was originally planned to consist of the following study areas (Page 6 of Proposal for Research, dated September 26, 1989; amended November 28, 1989; supplemented May 7, 1990):

1) Fatigue (a major effort)
2) Residual Strength of Frames with Damaged/Deteriorated Members
3) Engineering Method(s) for Predicting Behavior of Damaged Frames
4) Monitoring of Damage by Acoustic Emission Sensing (a "piggy-back" study continued from Phase I)

J.W. Fisher explained that with the newly started program on ship structures ("Navy-Fleet-of-the-Future", supported by the U.S. Navy) our personnel and experimental resources of ATLSS/Fritz Lab needed for fatigue research may be heavily taxed, so that it may be difficult or impossible to carry out the work originally envisioned in the proposal under Item 1. However, the fatigue research on the Navy project will deal mainly with fatigue strength of connection details of double-hull ship structures, and the results of this work may be of interest and benefit to offshore industry.

In the ensuing discussion of the needs of Participants, it became apparent that a number of items are worthy of consideration for continuation of the present project.

Significant interest was expressed in continuing the current effort on the study of corroded members, especially, a need for more tests on typical salvaged members. However, it was not clear who might be able to contribute additional salvaged tubes.

A. Ostapenko suggested that advantage could be taken (at a considerable saving in costs) of the dented specimens tested in the current program to study repair techniques for at least partial recovery of the strength lost due to damage. For example, the damaged portion of the tube can be filled with concrete, and the tube retested to determine how much of its strength can be recovered, at least temporarily, before conditions would permit complete repairs. However, at the moment, there appeared to be no strong enthusiasm for this work by Participants.

A study of frames with damaged members was of interest, and the scope and the type of specimens have to be worked out. It would be necessary to coordinate such an effort with the results obtained in the frame tests conducted in the UK if and when the data from them become available.

Development of an engineering method(s) for predicting the strength and behavior of damaged members and frames will require an extension of the formulations proposed so far. In such a method, a compact module for defining the end force vs. deformation response of an individual damaged member can be used as input to a frame analysis program. It should be possible to take advantage of the already available commercial programs which allow incorporation of non-linear response of individual members to be computed in an independent subprogram or subroutine.

It was concluded that a proposal should be prepared and then discussed. Probably, a special meeting may be needed just for this purpose. The proposal may be for a shorter than 3-year period.

OBSERVATION OF A LONG-COLUMN TEST

The planned observation of a long-column test in progress did not quite work out since a sudden rainstorm not only made us wet on the way to Fritz Laboratory from the building where we met, but it also disrupted power so that it was impossible to safely operate the testing equipment. However, the test specimen in the machine, the four long specimens already tested, the long specimens prepared for testing in the current series, and the tested stub columns provided a reasonably good idea of the details, difficulties and utility of the test program.

ADJOURNMENT

The meeting was formally adjourned at approximately 3:15 p.m., right at the end of the visit to Fritz Laboratory, to enable those who had already seen the ATLSS facility to leave early.

TOUR OF THE ATLSS TESTING FACILITY

The 102x42 ft testing bed with adjoining reaction walls up to 50 ft in height is the largest testing facility in the U.S. for conducting multi-directional tests on full- or nearly full-sized structures. It was easy to visualize a platform subassemblage tested under loads applied vertically and in two horizontal directions. The arrangement for the denting of the last series of tubes was still on the test floor for observation.

>>> ZSEROA <<<

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February 5, 1992

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Addressee List

Large-Scale Ice Fracture Experiments

The project team is pleased to report the highly successful completion of Phase 1 of the Joint Industry Project LARGE-SCALE ICE FRACTURE EXPERIMENTS. Phase 1 commenced on Wednesday, January 15, and final demobilization of equipment took place on January 29, 1992.

Results of the experiments represent one of the finest data sets available on freshwater ice fracture. The largest fracture specimen of any material was tested and the broadest scale range (1:81) was achieved. With the servo-control system designed by Sandwell, Inc., stable cracks were propagated in fracture geometries that are unstable without closed-loop control. This is a significant achievement and Sandwell are to be congratulated, in particular Bill Graham, John Robertson, Paul Spencer and Dan Masterson. Dr. John Dempsey and Sam DeFranco of Clarkson University also deserve considerable credit for their insight into fracture processes and design of the fracture tests.

Weather conditions in Calgary were less than favourable. The Pacific phenomenon known as El Nino has led to unseasonably warm temperatures in Calgary this winter. We have now experienced over 50 consecutive days of well above normal temperatures. On Day 5 of the project, January 19, daytime temperatures of 15°C made the ice at Bearspaw Reservoir just west of Calgary unsuitable for further testing. With the assistance of Alberta Provincial Parks, access was granted to Spray Lakes Reservoir near Canmore, Alberta in the Rocky Mountains. The move was made on January 21 and the project was successfully completed with minimal impact on the budget.

Relocating to Spray Lakes at such short notice owed greatly to the enthusiasm and resourcefulness of Jessco Operations Inc., led by Peter Jess. Digital data acquisition systems were designed and operated by Roger Saint and Kelly Mamer of Canmar. These systems performed very well under varying conditions and for a wide scope of tests. The thorough work of Max Coon and Skip Eckert (Williamson & Associates) was instrumental in site selection and ice characterization at Bearspaw, while Bruce Parsons and Trent Slade from the Institute for Marine Dynamics (IMD) provided analogue back-up of experiments. Graduate students Bin Zou and Michelle Johnson from Memorial University of Newfoundland undertook ice characterization at both Bearspaw Reservoir and Spray Lakes.

Due to Denis Blanchet's transfer from Canmar to Amoco's Tulsa Research Centre just prior to Phase 1, on-site project management for the experiments was assumed by Kurt Kennedy of Canadian Marine Drilling Ltd.

If you have any questions or comments regarding Phase 1, please contact Kurt Kennedy at (403) 298-3510 or Fax (403) 298-3532. The tentative date for distribution of the draft data report to all participants is April 1, 1992. We thank you for your participation in Phase 1 and trust you will find the results to your satisfaction.

Sincerely,

K. P. Kennedy
Engineer

KPK/sej

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May 22, 1992

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MMS(DOI) :	C.E. Smith
Mobil :	J. A. Volker
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Texaco:	J. H. Kemper

FROM: A. Ostapenko, Principal Investigator Ostapenko

SUBJECT: Residual Strength of Damaged and Deteriorated Offshore Structures
Draft of Final Project Report and Project Meeting

Draft of Final Project Report

A copy of the review draft of the Final Project Report is mailed to you separately . (The reason for sending this cover letter at the same time is to forewarn you about the report as it may be going through the mails more slowly.) The report describes the experimental work on the damaged and deteriorated (corroded) long-column specimens and on the relevant stub-columns and tensile coupons. Eleven specimens were made from salvaged corroded or non-corroded tubes, and seven were specially fabricated for this project. Results of the tests -- deformations, initial and post-test geometry and other data are reported for potential use by other investigators. Some limited analysis of the obtained test results was made. For example, the actual end eccentricities were computed from the readings of the strain, rotation and dial gages, and LVDT's. The test specimens were also analyzed by using several computer programs. Overall, the analytical solutions agree relatively well with the ultimate test load, but there is less agreement in the post-ultimate range.

There are two items which have not been included in this draft. One is the analysis of the effect of corrosion on the column behavior (Chapter 14). This study will be sent for your review as a supplementary item and then included in the final version. The other is the description of the tests on two small-scale manufactured specimens (Specimens P1P-S and P2P-S in Table A of the Supplement to the Research Proposal, dated May 7, 1990). These tests have not yet been conducted. (We have been having difficulty in procuring suitable manufactured tubes with the yield stresses needed in our program.) This work will be completed at a later date, and the results incorporated into the final version of the report.

The report on the acoustic emission studies conducted as a piggy-back activity within the scope of this project is being edited and will be distributed for your review, hopefully, prior to the project meeting.

Project Meeting

As you are aware from my telephone calls, our attempt to arrange a project meeting early in June fell through because of the conflicts with various conferences, and the only free period are the three days of June 23 to 25. The two-day meeting has been agreed to be as follows:

Wednesday, June 24. This day will be limited to the **current** Participants to review the project and to discuss any recommendations for the work yet to be completed and comments on the Final Project Report(s).

Thursday, June 25. The second day will be open to the **current and potential** Participants with the main purpose of establishing the needs of the oil industry in the area of structural strength of offshore platforms and defining the topics and scope of the next phase of this project.

Shortly, we will be sending you the agendas for these meetings.

Comments by J.T. Loh

Herewith enclosed are some observations made by J.T. Loh of EXXON intended for distribution to the Participants. As he states, these observations were made as a follow-up to the brief meeting held near Houston on May 8 in conjunction with an inspection of some salvaged corroded members and frames, potentially suitable for the work in an extension phase of the project. It would be appropriate to make some comments on the topics raised in the letter.

As stated above, the tests on the small-scale dented specimens are definitely going to be completed and the results included in the final version of the project report.

We fully agree that tests on the tensile coupons cut out from fabricated specimens would enhance the work completed by providing additional data on the changes of material properties as they are determined from the tensile coupons taken from the flat plate before rolling into a tube, tensile coupons after rolling, stub-column tests, and from hardness testing.

Work Remaining

In summary, the following items are still outstanding, but will be finished before the end of the project:

1) The write-up of the corrosion analysis.

2) The report on the acoustic emission studies.

3) The tests on two small-scale manufactured specimens and the accompanying stub-columns and tensile coupons.

4) Tests on tensile coupons cut from the fabricated specimens.

5) Production of the Final Project Reports.

Budget and Termination Date

We have sufficient funds to complete the outstanding work listed above, but more time is needed. Since the formal project termination date is June 17, 1992, we will need an extension. Thus, we will be officially requesting for an amendment to the Agreement for a no-cost extension of the termination date till August 31, 1992. This period would also give us the lead time to formulate the next phase of the project.

OFFSHORE DIVISION
STRUCTURAL ENGINEERING

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CONFIRMATION NO. (713) 940-3704

DATE: May 14, 1992

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SUBJECT: JIP on Residual Strength of Damaged and Deteriorated Offshore Structures

FILE: 3765

PAGES: 1 (INCLUDING THIS HEADER PAGE)

Dear Alex:

It is encouraging that the attendees had a productive discussion on future testing directions for a potential Phase II of the subject project during the meeting at Exxon Friendswood site on May 8, 1992. In general, the project has been conducted as planned and meaningful test results have been generated. However, there are two issues that require further consideration. The purpose of this fax is to document these two issues.

First, for the new fabricated specimens, some tensile coupons should be cut out from the rolled specimen for testing. This will complete the material testing for the new fabricated specimens and we'll have plate tensile coupon tests, pipe tensile coupon tests, and pipe stub column tests.

Second, three planned tests have not been conducted. Two of them are small scale new specimens. The primary objective of these small scale tests was to verify that there are no discernible scale effects with all of the published small scale, dented member test data. It is our understanding that there were significant problems in locating suitable pipe for these specimens, but that this particular work is ongoing.

The other specimen is a salvaged specimen that has moderate to high corrosion. The specimen is made up of two lengths of pipe with the circumferential weld at about the third point. Hardness test results suggest that the yield strengths are 50 and 65 ksi for the longer and shorter segments, respectively. Testing this salvaged specimen as a long column may not be too meaningful. However, it could be used for preliminary corrosion work in Phase II.

We look forward to working with you in defining the workscope for Phase II.

REGARDS,

Jim

Jim Loh

Specimen Preparation

Phase I experiments were essentially in-plane fracture toughness tests on full-thickness freshwater ice. Considerable effort was required to fashion a testing specimen from the parent ice sheet and great care was taken to avoid damaging the beam prior to a test. Specimen preparation involved selecting a test site based on ice thickness measurements and proximity to previous tests, surveying beam dimensions and then cutting the specimen from the ice sheet. Only long sides of beams were cut with the DitchWitch trencher, to avoid loading the unfinished beam. Short sides were cut free with chainsaws and small specimens prepared with chainsaws only. Although some experimentation was required to optimize the cutting procedure, beams were generally insensitive to vibrations caused by the DitchWitch and other activities.

Beam Cutting Procedure

The success of the experiments depended on the ability to cut free-floating beams from the ice sheet. A Wajax DitchWitch 3210 trenching unit was selected based on its ability to cut a wide (4 inch) slot in the ice. After some experimentation, the unit performed well though downtime was encountered to tighten bolts and replace ice teeth jarred loose by the trenching process.

Trenching Optimization

Several factors affected the optimum cutting characteristics of the DitchWitch. Variations in DitchWitch speed, chain speed, chain angle and the placement and number of ice cutting teeth altered the observed trenching process. Some experimenting demonstrated that slow forward movement of the unit coupled with the highest possible chain speed resulted in the straightest, cleanest cuts. High chain speed also resulted in flooding of the ice sheet, which caused the DitchWitch to lose traction. Adjustments to the chain speed limited the amount of water pumped onto the ice. For slots of required linearity and uniformity, optimum trenching speed was 15 metres per hour.

For rectangular beam tests, two long parallel slots were cut by the DitchWitch, manually cleared of the cuttings and packed with styrofoam to prevent refreezing. A pair of ramps or bridges had been constructed to allow the DitchWitch to cut the short sides of the beams without bearing on the beam itself, but the bridges tended to slip during trenching. Short sides were cut with chainsaws instead, which proved very efficient. The operator could then concentrate on trenching the long dimensions of other specimens. No working clearance was required on short sides of beams, so a wide slot was unnecessary.

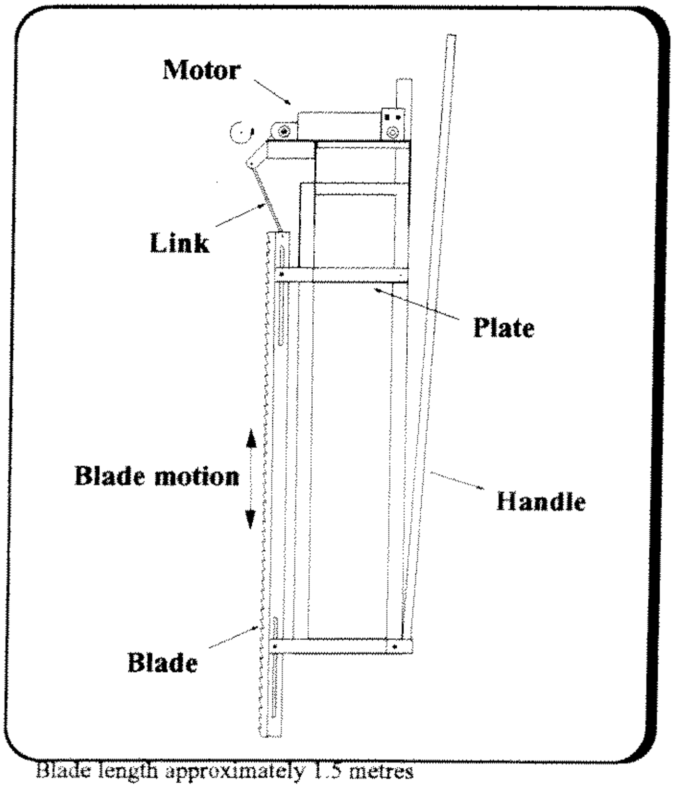
Crack Scribing

The critical parameter in any fracture toughness test is notch acuity, or the degree of sharpness of the introduced crack. In metals, a sharp crack is fatigued into the specimen, while in laboratory fracture tests on ice, a scalpel or similar instrument is used to etch (or scribe) the crack. Reproducing this technique on a full-thickness ice specimen under field conditions was a challenge.

Target crack lengths were specified for each beam size. In all cases, most of the overall crack length could be quite coarse, i.e., a chainsaw cut. Only the last few inches of the crack needed to be accurately scribed. Based on these requirements, Sandwell designed and constructed a reciprocating crack scribing saw, depicted in **Figure 3** and shown in operation on the enclosed videotape. This device successfully produced a straight, perpendicular sharp crack through the full thickness of the test specimen. Refreezing was prevented by inserting a thin ruler into the crack, though the actual acuity of the notch was impossible to determine.

Figure 3

Reciprocating crack scribing device



Blade length approximately 1.5 metres

Test Matrix

Presented in **Table 1**, the test matrix for Phase I follows closely that of the original proposal with the exception of the reverse taper (RT) tests. Two Griffith's crack experiments were planned for Phase I to investigate stable fracture in freshwater ice. Griffith's tests G-1 and G-2 were significantly affected by high stresses in the ice sheet at Bearspaw Reservoir. The complexity of the stress regime made it difficult to analyze the Griffith's experiments.

Eight rectangular beam tests over a scale range of 1:8 had been planned and four were completed before the change to the reverse taper geometry. Nine RT geometry tests, most with multiple loadings, yielded a scale range of 1:85 and great quantities of data. These results could not have been realized with rectangular beams due to the complexities of specimen preparation and the melting problems detailed in **§ Site Change**.

Rectangular and RT beam tests performed with nitrogen gas were generally unstable, i.e., the specimen cracked into two pieces. Most of the servo-controlled tests involved multiple loadings and stable crack propagation. The ability of the servo-controlled loading system to arrest a through-thickness crack under field conditions was a highlight of Phase I.

Notes on Table 1

Only the Griffith's experiments, rectangular beam tests and reverse taper tests are included in the Phase I test matrix. Cantilever modulus tests are detailed in **§ Test Results**. ''Test Mode'' refers to the method of flatjack inflation used for the test, i.e., either nitrogen gas, operated by a manual valve, or oil, operated by the servo-controlled hydraulic loading system. ''No. of Loads'' specifies the number of times a test specimen was loaded and generally indicates that stable cracking was achieved during multiple loadings.

Parameters ''a'' and ''b'' are specimen dimensions defined as follows: Griffith's Crack Tests; not applicable. Rectangular Beams; a = beam width, b = beam length. Reverse Taper Beams; a = length of equal sides of isosceles triangle, b = triangle altitude. These dimensions are further detailed in **§ Test Results**. ''Data File(s)'' denotes the filenames of raw data (in Viewdac format) collected by Canmar. Due to the high sampling rates used in the experiments, these data files are very large. Advanced data processing software is required for practical analysis.

Table 1
Phase I Test Matrix

Griffith's Tests

Rectangular Beam Tests

Reverse Taper Tests

Test Date	Test I.D.	Test Mode	No. of Loads	a (m)	b (m)	Data File(s)
January 15	G-1	Nitrogen	1	-	-	D920115A.VDT
January 17	G-2	Nitrogen	1	-	-	D920117A.VDT
	B-1	Nitrogen	2	0.18	0.51	D0117B1.VDT D0117B2.VDT
January 18	B-2	Servo	2	0.16	0.51	D920118A.VDT D920118B.VDT
January 23	B-3	Servo	1	0.13	0.53	D920123A.VDT
	B-4	Nitrogen	1	0.15	0.52	D920123B.VDT
January 24	RT-1	Nitrogen	2	2.0	1.41	D0124A1.VDT D0124A2.VDT
	RT-2	Nitrogen	1	0.6	0.41	D920124B.VDT
	RT-3	Nitrogen	1	6.0	4.24	D920124C.VDT
January 25	RT-4	Nitrogen	1	0.5	0.34	D920125A.VDT
	RT-5	Nitrogen	2	1.5	1.04	D0125B1.VDT D0125B2.VDT
	RT-6	Nitrogen	2	13.5	10.36	D0125C1.VDT D0125C2.VDT
January 26	RT-7	Servo	3	4.5	3.18	D0126A1.VDT D0126A2.VDT D0126A3.VDT
	RT-8	Servo	5	4.5	3.20	D0126B1.VDT D0126B2.VDT D0126B3.VDT D0126B4.VDT D0126B5.VDT
January 27	RT-9	Nitrogen	5	40.5	28.64	D0127A1.VDT D0127A2.VDT D0127A3.VDT D0127A4.VDT D0127A5.VDT

Loading Systems

Two loading systems were designed and built by Sandwell to meet the various requirements of the test program. For the faster tests (typically unstable fracture) with displacement feedback control, a servo-control system was designed. For tests of longer duration such as Griffith's experiments and slow unstable fracture with less control, a nitrogen regulated system was employed.

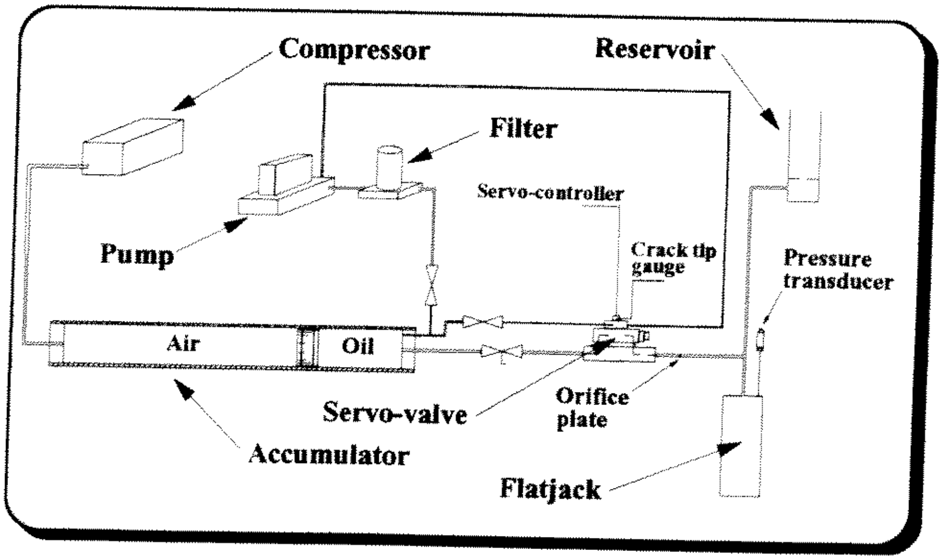
Servo-Controlled System

Closed loop or feedback control is a method by which system output is fed back for comparison with the input to minimize the difference between the input command and output response. Closed loop control offers the advantages of increased linearity and high performance. Since the command signal typically takes the form of a time varying voltage, the ability to automate or test using complex signal profiles is inherent to the system. The system must be carefully designed to avoid instability, however.

The servo-controlled loading system is illustrated in **Figure 4**. An air-over-oil accumulator was used to provide power to the servo-valve and was pressurized using a high pressure air compressor. Oil was then pumped into the other side of the accumulator. Oil chosen for the tests was a biodegradable vegetable based oil. Filters capable of filtering to 3 microns absolute were used to ensure that dirt fragments did not interfere with the operation of the servo-valve. A Moog Model DO79B-211 servo-valve was employed, capable of flows up to 900 litres per minute at pressures up to 35 MPa. This valve was

Figure 4

Servo-controlled loading system



provided free of charge to the project by Memorial University of Newfoundland's Ocean Engineering Research Centre.

Servo Loop

The various transducers, flatjacks, amplifiers and coupling mechanisms constitute what is commonly called a servo-loop. The servo-loop permits servo-control of one process variable. For operational reasons, the controlled variable during Phase I was displacement, specifically crack tip opening displacement. A stationary mount for the displacement feedback transducer relative to the ice specimen was necessary if the required displacement profile was to be achieved.

Of critical importance in the operation of the servo-logs is to employ the appropriate type of feedback system to ensure the overall loop gain is correctly set. While the crack tip gauge measures displacement, the flow splitting technique used (see below) dictates that the servo-loop is actually a flow of oil rather than a displacement. This can be appreciated by noting that in the usual method of oil feeding into an actuator, actuator displacement is given by the integral of the oil flow. The servo-controller was therefore modified to include an integrator following the comparison of the feedback and command signals. Two types of electronic integrators were employed: a simple R.C. low pass filter with a time control of 10 seconds and a true integrator using an operational amplifier. The R.C. approach was selected because of problems with drift and initial start-up of the tests.

Loop Gain

Loop gain is an important parameter. If set too high, the system will oscillate, while if set too low, the servo-system will not be responsive. Overall loop gain is determined by a number of factors mechanical, electrical and hydraulic. The electrical and hydraulic factors were estimated and/or measured but the mechanical aspect included the effective stiffness of the test beam. The latter involved both the geometry of the beam and its elastic/viscoelastic properties. Initial field tests were used to estimate these parameters.

Another difficulty to be overcome was start-up transients in the servo-system. Although it is a closed-loop system, until the servo-valve is open and oil is flowing, the feedback loop is broken. This was overcome by manually setting the error signal to the servo-controller such that the valve was just closed, and then providing a small DC offset to just barely open the valve. Once oil was flowing, the command ramp signal was applied.

Feedback Stability

The stability of the feedback signal was crucial in terms of control. The system cannot distinguish between a real change in (crack) displacement and an electronic/mechanical drift in the displacement sensor. This mechanical stability is emphasized by noting that crack propagation can occur at displacements of about 2 mm to 5 mm. Warm temperatures (above freezing) in the field made mechanical stability difficult to achieve and drift made the technique marginal. A distinct advantage of closed-loop control was the ability to reduce the applied load to zero at crack initiation. This type of feedback had not previously been used in either field or laboratory ice fracture experiments.

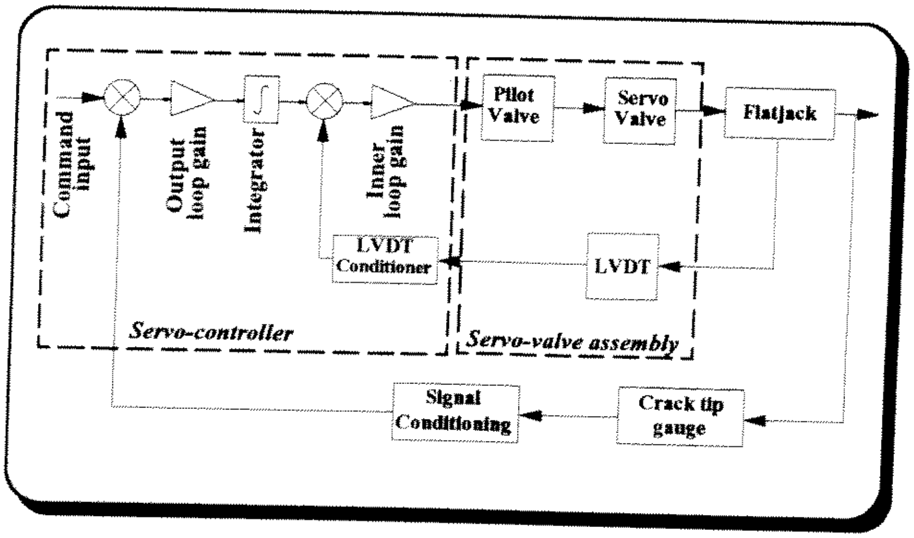
Design of the servo-loop system involved selection and/or design of the various system components to achieve desired performance. A block diagram of the complete system is presented in **Figure 5**. The system actually consists of two loops, one completely within the other.

Flow Splitting

The servo-valve employed was capable of flows and pressures higher than the test requirements and modifications were necessary. A technique of flow-splitting was used to lower the pressure at the flatjack. To function properly, a drop of 7 MPa across the valve was needed. Pilot valve requirements dictated that oil be supplied to the servo-system at a pressure of 15 MPa. At the outlet of the Moog valve, an orifice plate was mounted in the oil line which caused a drop in pressure and restricted the oil flow. Pressure supplied to the flatjack was at a maximum of around 1.4 MPa and flow rate was kept to an allowable range. The line then split into two, one line going to the flatjack and the second to a storage tank. The line to storage was sized to give the appropriate back-

Figure 5

Servo-control system block diagram



pressure at the flatjack. Many factors had to be considered to achieve proper displacement rates including the required pressure drop through the valve, orifice size, specified rate of flow into the flatjack, pressure required to propagate the cracks, flatjack size resistance down the return hose, and total oil flow. The crack tip opening signal ultimately controlled the opening and closing of the servo-valve which, in turn, controlled the crack opening.

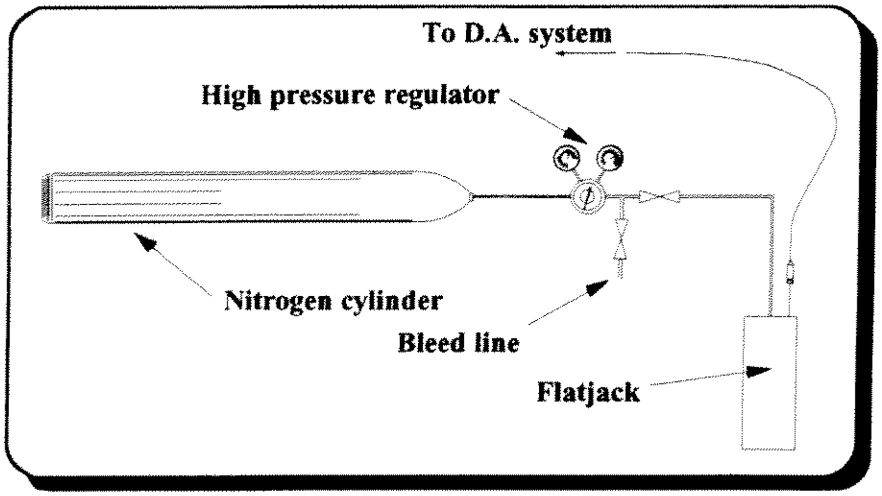
Nitrogen Regulated System

This system was not servo-controlled and was therefore much simpler in design and operation. A high pressure nitrogen cylinder was connected to a high pressure, high flow regulator through a long, small-bore tube to the flatjack. When test speed, flatjack size and approximate maximum pressure were known, pressure through the regulator was set and the feed tube bore and length were determined. The system is illustrated schematically in **Figure 6**.

Test speed and loading rate could be varied by changing the initial pressure, tube length and tube diameter. Once the crack was initiated in the ice specimen, there was no further control on the rate of load application and crack opening displacement. This arrangement provided for a linear load ramp relatively independent of beam displacement. Tests indicated that the pressure rise in the flatjack was linear to about 1% - 2% up to half of the final (supply) pressure.

Figure 6

Nitrogen regulated loading system



Data Acquisition

The durations of individual fracture tests ranged from seconds to minutes. Design of a data acquisition system was based on two requirements: high speed sampling on the order of 1000 Hz to 10 kHz per sensor channel and the ability to view data immediately after a test is completed. A digital system was necessary to meet these criteria and was purchased by Canmar for Phase I.

Apparatus

Main components of the digital data acquisition system included:

1) 386SX notebook computer with 387 math co-processor, grey scale VGA LCD monitor, 8 MB of RAM, an 83 MB hard drive and equipped with a 3½'' high density disk drive, one serial port for a trackball mouse and one parallel port. An external colour monitor was connected onsite to facilitate viewing of the data following a test.

2) Expansion box with power supply and Keithley/Metrabyte DAS-20 high performance analog/digital (A/D) interface card. This card allowed a maximum of 100 kHz A/D, 16 single-ended or 8 differential input channels and two 200 kHz analog output channels. The expansion box was connected to the notebook via a 50 pin connector.

3) Four SSH-4 simultaneous sample and hold cards, each capable of data acquisition over four channels (maximum) with less than 30 nanoseconds (10^{-9}) uncertainty between channels. Up to 16 channels of data could be sampled simultaneously and held until data from all channels was recorded by the computer.

4) STA-20 terminal board connecting the analog output from the DAS-20 card to the sensors to be triggered by the compute.

5) Keithley/Asyst Viewdac© software, with capabilities including comprehensive data acquisition, control analysis, graphics and applications development functions. Viewdac afforded real-time multi-tasking and offered a windowing interface for ease of use.

6) 1400 Series 1000 VA Uninterruptable Power Supply (UPS) for power conditioning. This was a vital element, as power to the data acquisition system was supplied by gas-powered portable generators.

All data acquisition equipment was thoroughly checked prior to shipping to the test site. A bug in the Viewdac software was encountered early in the experiments and measures were taken to bypass the problem. The manufacturer had been unaware of the bug.

D.A. Procedures

Viewdac was pre-programmed by Canmar to ensure a standard data acquisition procedure for every fracture test. This standardization guaranteed that data would be acquired exactly to specifications set out for each test, and with minimal risk of data loss.

The initial procedure involved setting the number of channels, time duration and sampling frequency for each test, subject to two main limitations. The first involved the relationship between the number of channels and the sample rate, the second due to memory restrictions. Essentially, no more than 360,000 samples per test, i.e., product of the (number of channels), (test duration) and (sample rate), were feasible.

The number of channels and total number of samples were input through a special A/D window. Gain and slope of each channel were also set in this window. The gain was adjusted to allow data acquisition over the full voltage range of the A/D card. The slope setting converted the raw data into proper engineering units for analysis. These values were set at the beginning of the experiments and were generally left unchanged.

Prior to a test, the main display window within Viewdac was activated. This screen consisted of:

1) 16 channel digital readout. Each channel was scanned once every second to give a continuous readout between tests. This allowed the operator to calibrate and zero the gauges and to ensure minimal drift once zeroed. Readout was controlled by start and stop buttons at the top of the display and was deactivated (with the stop button) when a test was readied.

2) Analog output test button. This button issued a specified voltage signal to Channel 0 of the analog output of the DAS-20 card. If this terminal was connected to an input channel, that input channel showed the voltage on the digital readout. This test was performed before all experiments needing an analog output signal to ensure it was functioning properly.

3) Pre-trigger time setting (milliseconds). This specified the length of time over which data would be collected before load was applied to the ice fracture specimen.

4) Scan rate setting. The data sampling rate was set with this option and could be changed quickly if desired.

5) Test identification message, by test number and date.

6) Trigger button. Once digital readout was de-activated and all settings correct, this button was clicked to start data acquisition. The computer was then isolated from further commands until all data was acquired, converted to engineering units and safely stored to hard disk.

7) Graphing capabilities. Once data was stored to hard disk, specific channels could be immediately plotted on-screen.

As noted, data was automatically saved to hard disk before the keyboard and mouse were reactivated, ensuring that data would be safely stored. Data was also copied to 3½'' diskettes and filed immediately following a test. All sequences (Viewdac sub-programs) and a D.A. daily log were also copied to diskettes at the end of the day. Included as **Appendix B**, this daily log contains details of each test, settings for all channels and data filenames.

Safety

Protection of personnel and the environment were foremost considerations in the design of the experiments. A series of operating procedures were set out prior to activities at Bearspaw Reservoir and Spray Lakes. Canmar's Safety Advisor was present during the early stages of the experiments to ensure these procedures were maintained. Ice thickness was thoroughly checked and monitored around work areas on a daily basis. Two cellular phones provided by Canmar provided continuous communication with the Calgary offices and visitors en route to the site.

Signs explaining the experiments were posted at public access points to the sites. Work areas were signed as hazardous and test sites roped off immediately following an experiment. All equipment, generators and tools were removed from the ice at the end of the day and stored onshore. Materials left on-ice overnight such as signs, ropes and posts were flagged with reflectors. Access to the ice at both Bearspaw and Spray Lakes was controlled. Large equipment such as pick-up trucks and the Ditch-Witch trencher were stationed onshore and brought out to the site only when required.

External Monitoring

The test site was visited on several occasions by members of Alberta Fisheries & Wildlife, Peter Lougheed Provincial Park and Transalta Utilities. Safety and environmental protection procedures instituted by the project team met with the full approval of these representatives. No mishaps of any kind were encountered during the course of the experiments, though equipment was on-hand to assist if a problem did arise. The hydraulic loading system was filled with a small volume of biodegradable canola oil, minimizing environmental risk.

DitchWitch trenching operations were continuously monitored and maintenance performed at regular intervals, e.g., bolt tightening, ice teeth replacement, chain lubrication. Chainsaw activities were carried out by experienced operators from Sandwell and Jessco Operations only.

Daily Log

A tabulated summary of the daily highlights of the experimental program is presented in **Appendix C**.

Test Results

Background

Fracture research on size effect for construction materials such as concrete and steel are limited, for practical reasons, to laboratory sized specimens. Determination of cracking parameters necessary for fracture control in full sized structures can only be predicted by extrapolation from laboratory tests. Ice is ideal for performing large-scale fracture experiments due primarily to its low fracture toughness relative to concrete or metals, which permits the use of portable loading systems capable of providing sufficient failure loads.

An immediate consequence is the ability to experimentally verify full-scale fracture loads from laboratory size effect tests. Additionally, the minimum specimen size necessary to determine fracture toughness, K_{Ic}, is a direct outcome of the large-scale tests. The significant question of whether or not this specimen size is feasible in the laboratory can be addressed. Crucial parameters in the field experiments are the temperature gradient of the ice and cracks caused by thermal action. The influence of these effects on fracture toughness has not been investigated to date.

Three separate experiments were performed during Phase I:

1) Griffith fracture experiments, which simulate a crack in an infinite sheet. Results from a successful experiment of this type yield the size dependent fracture toughness, K_{Ic}.

2) Notched three-point bend fracture experiments (rectangular beam tests). Floating beams of various geometrically similar sizes are tested, from which size effect laws can be used to predict the size independent fracture toughness. Ideally, the Griffith experiments should verify predictions from the size effect laws.

3) Reverse taper (RT) compact tension tests. This geometry is capable of effecting slow crack extension in many materials. The fracture resistance behaviour of a stably propagating crack can be determined by the RT experiment.

From the above fracture experiments, the effective elastic modulus of the specimen can be determined from the slope of the load vs. displacement curve.

Griffith Experiments

Two Griffith experiments were performed at Bearspaw Reservoir. The complex stress regime in the ice sheet made it difficult to extract useful information from these tests. The results are currently being examined by Clarkson University.

Rectangular Beam Tests

The three-point bend fracture geometry was used with the aim of investigating size effect on *in situ* ice possessing a thermal gradient and a natural thermal crack density (**Figure 7**). Difficulties were encountered with the specimens freezing in place and wide sides melting, causing flatjack bearing surfaces to be unsuitable for loading. This behaviour was especially evident in specimen B-4. Despite these problems, an initiated crack was arrested in specimen B-2 by closed-loop control of the servo-hydraulic system with a crack tip displacement gauge. Closed loop control of crack displacements had never been performed in a laboratory ice fracture experiment, which makes the occurence of controlled cracking in a field experiment especially significant.

The apparent fracture toughness results are presented in **Table 2**. The large increase in toughness for experiments B-3 and B-4 is due to the type of ice encountered at Spray Lakes as compared to Bearspaw Reservoir (see § **Ice Characterization**). Due to the aforementioned difficulties in performing the rectangular beam tests, a different geometry requiring no load reaction from the parent ice sheet was adopted.

Figure 7

Rectangular (three-point bend) fracture test specimen

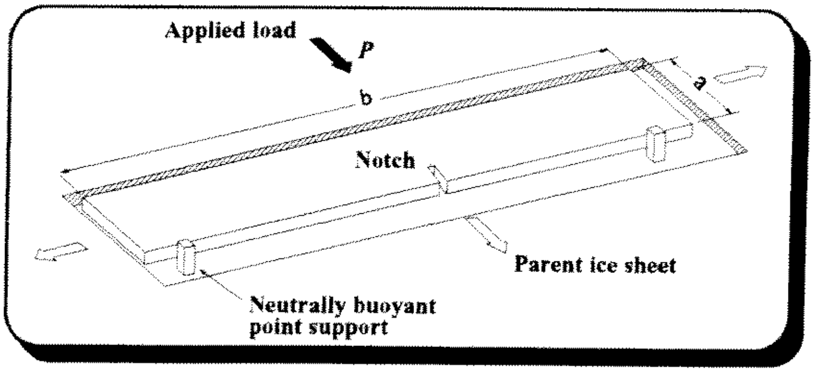


Table 2
Rectangular Beam Tests Results

Test I.D.	Test Mode	a (m)	b (m)	h (m)	K_Q (kPa $m^{1/2}$)	$\dot{K}$ (kPa $m^{1/2}s^{-1}$)	Air Temp.
B-1	Nitrogen	0.18	0.51	0.55	114	3	-2.4 C
B-1	Servo	0.16	0.51	0.55	115	38	+5.3 C
B-3	Servo	0.13	0.53	0.51	147	-	-1.6 C
B-4	Servo	0.15	0.52	0.46	273	2	-2.1 C

h = approximate average ice thickness
K_Q = apparent fracture toughness
$\dot{K}$ = stress intensity rate

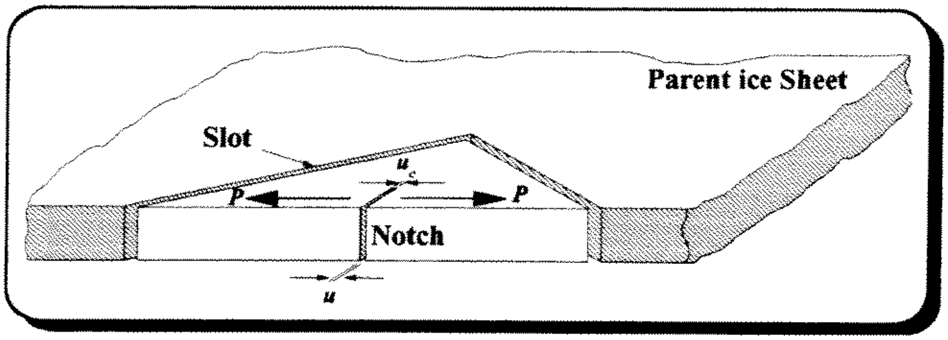
RT Experiments

In Phase I, fracture experiments on freshwater ice were performed over a size range of approximately 1:85 through the use of the reverse taper compact tension specimen, illustrated in **Figure 8**. Reducing the specimen width with crack length, d, is conducive to slow crack extension through rapidly increasing compliance with crack extension. The fracture initiation results are presented in **Table 3** and plotted versus dimension L in **Figure 9**.

Flatjack pressure vs. time for experiment RT-6 is illustrated in **Figure 10**. The trace is linear up until near peak, where slight nonlinearity is evident. In most of the experiments, a rapid dropoff occurred at the peak pressure with little or no nonlinearity. **Figure 11** shows a plot of crack tip opening displacement (CTOD) vs. time. The importance of measuring crack opening displacements during fracture experiments is revealed by the sudden discontinuity in the plot at time 17.6 seconds, which corresponds to a pressure of 320 kPa (see Figure 10). At this pressure, the crack initiated at an initiation toughness of 126 kPa·$m^{1/2}$. If crack displacement was not measured, fracture toughness calculated from the peak load is around 25% higher, not representative of the actual cracking event. The first loading of RT-6 was intended to be a load/unload trial, resulting in the determination of only the elastic modulus.

Figure 8

Reverse taper (RT) fracture test specimen



P = applied load (flatjack placed in notch)
u = crack mouth opening displacement (CMOD)
u_c = crack tip opening displacement (CTOD)

Table 3
Reverse Taper Tests Results

Test I.D.	Test Mode	d (m)	L (m)	K_Q (kPa·m$^{1/2}$)	$\dot{K}$ (kPa m$^{1/2}$s^{-1})	E' (GPa)	Air Temp.
RT-1	Nitrogen	0.43	1.41	122	4	5.70	0 C
RT-2	Nitrogen	0.14	0.41	99	9	6.81	-0.3 C
RT-3	Nitrogen	1.23	4.42	159	5	8.80	-0.6 C
RT-4	Nitrogen	0.95	0.34	137	5	n/a	+0.4 C
RT-5	Nitrogen	0.39	1.04	232	5	2.04	>0 C
RT-6	Nitrogen	3.12	10.36	126	13	3.44	>0 C
RT-7	Servo	0.99	3.18	235	47	3.39	0 C
RT-8	Servo	0.99	3.20	144	756	3.87	-3 C
RT-9	Nitrogen	8.98	28.64	297	56	8.58	>0 C

d = total notch length including scribed crack (approximately L/3)
L = altitude of triangle (also presented in Table 1)
a = not shown above: length of equal sides of triangle (presented in Table 1)
K_Q = apparent fracture toughness
$\dot{K}$ = stress intensity rate
E' = effective elastic modulus

Figure 9

Apparent fracture toughness, K_Q, vs RT beam dimension L

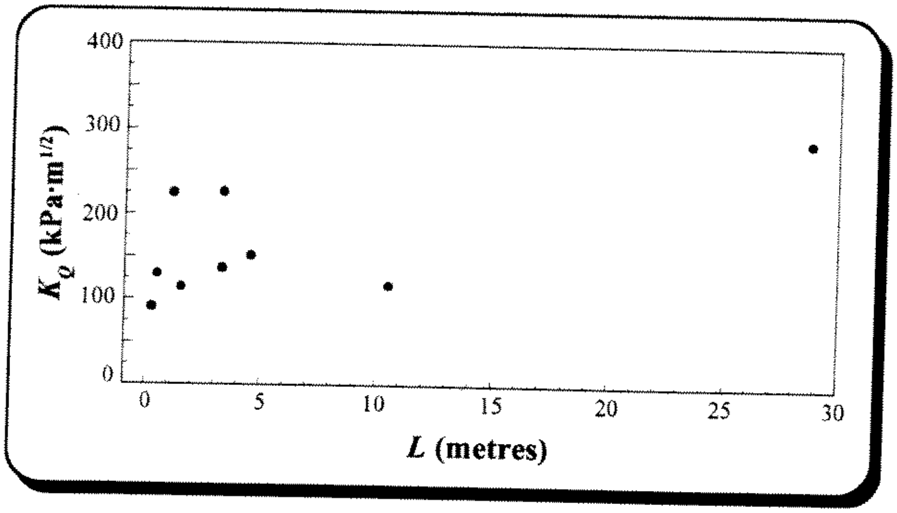


Figure 10

Flatjack pressure vs. time trace, test RT-6

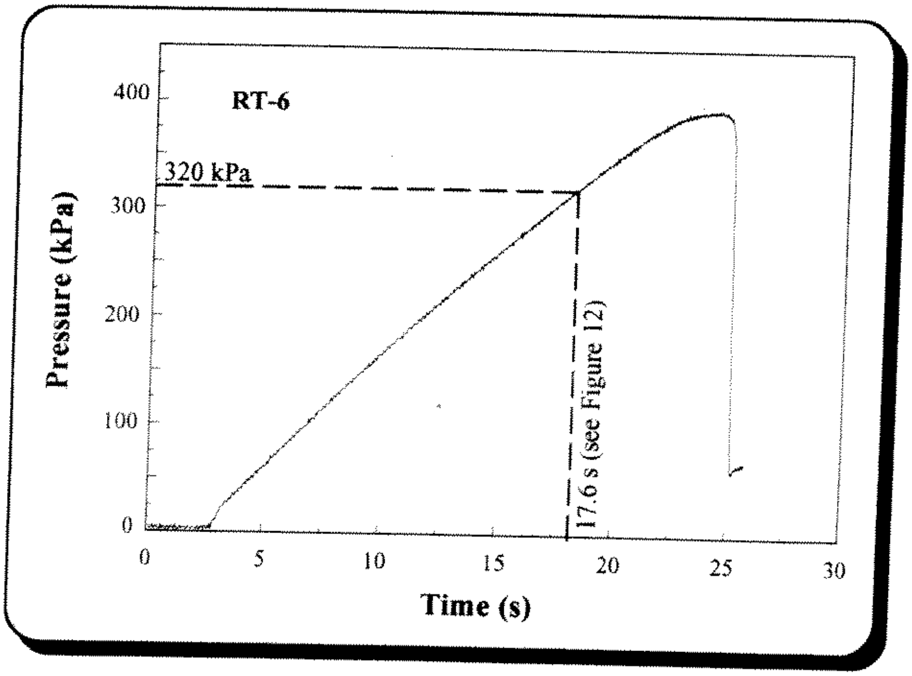


Figure 11

CTOD vs. time, test RT-6

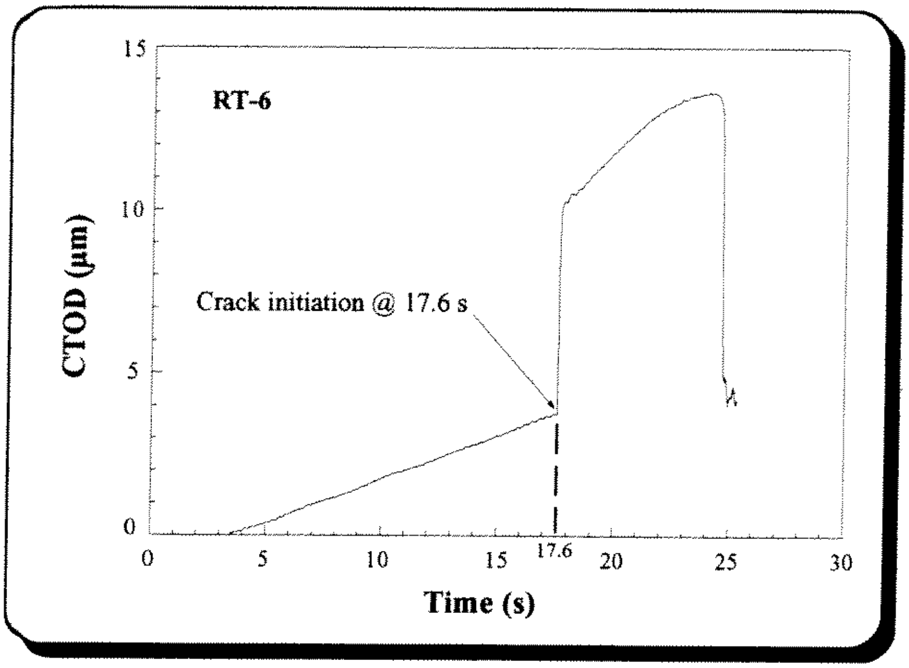
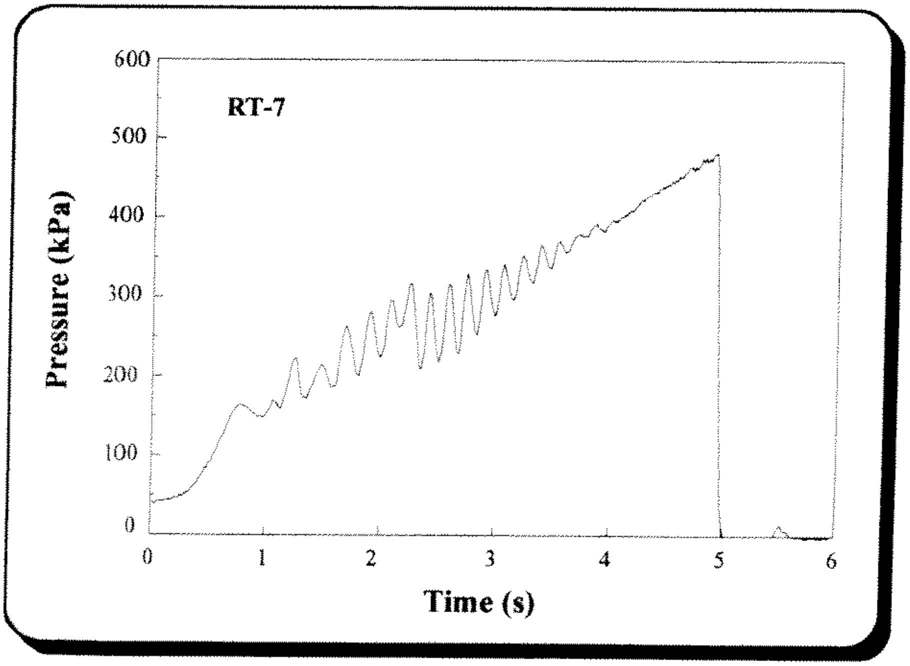


Figure 12

Flatjack pressure vs. time, test RT-7



An interesting aspect of Phase I is shown in **Figure 12**, a pressure vs. time plot for specimen RT-7. Oscillations in pressure are due to the servo-control system attempting to match the control signal with a preset ramp. Ideally, a one-to-one match of the control signal and ramp would occur, but due to weather conditions and the sensitivity of the Kaman ''2810-lu'' CTOD gauge, the signal oscillated around the ramp.

Uniaxial *In Situ* Modulus Experiments

An additional evaluation of specimen size on elastic modulus was made using three *in situ* floating cantilever beams as shown in **Figure 13**. Several load/unload trials were performed on each specimen. Experiments CM-1 and CM-2 were successful and the results are presented in **Table 4**. For experiment CM-3, displacement gauges drifted due to warm temperatures and strong winds, and no useful data was obtained.

Figure 13

Cantilever specimen, uniaxial modulus test

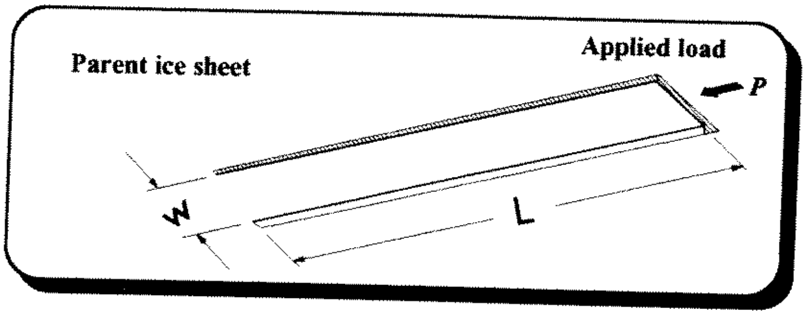


Table 4
Uniaxial Modulus Tests Results

Test I.D.	Test Mode	L (m)	w (m)	E' (GPa)
CM-1	Nitrogen	0.36	0.09	2.84 3.19
CM-2	Nitrogen	1.08	0.27	6.12 6.35 7.23 6.44

Temperature approximately 0° C for all tests.

Ice Characterization

Details of ice type and grain structure were carried out before, during and after the Phase I experiments. Ice samples from Bearspaw Reservoir were shipped to Clarkson University in December, 1991 for analysis. Fracture parameters were then tailored to suit the ice type found at the Bearspaw site. As well, graduate students from the Ocean Engineering Research Centre, Memorial University of Newfoundland were on hand to characterize ice at both the Bearspaw and Spray Lakes Reservoirs during Phase I.

Thin sections revealed that the Spray Lakes ice was dominantly S1 type, while S2 ice was dominant at Bearspaw. S1 ice typically has a much larger average grain size than S2, a vertical optical axis (or c-axis), and is much tougher than S2 freshwater ice.

On January 27, 1992, a 1.2 m x 1.2 m x 0.5 m thick block of freshwater ice was recovered from Spray Lakes in a region completely free of visible *in situ* fractures. This sample was packed in snow and trucked to Calgary, where it was then boxed in a custom built insulated crate and shipped to Clarkson University by air-freight. The sample arrived undamaged and is currently being prepared for laboratory fracture tests. These tests should expand on the 1:85 scale range realized in the field.

Reduced Data

The volume of data collected during Phase I is immense and distribution of the raw data set, which constitutes over thirty-five 3½'', 1.5 megabyte diskettes, is impractical. Raw data files listed in Table 1 are available upon request, but are stored in VDT format, which requires the Viewdac© data acquisition and analysis software to access. Data files were reduced to ASCII format by Clarkson University for analysis and computations of apparent fracture toughness and effective elastic modulus. Data traces presented in the previous section are representative of the fracture tests as a whole and illustrate the data analysis procedures.

Video Records

High speed video was originally considered as a means to estimate crack speed in a fracture test. The lighting requirements and costs associated with such a system were prohibitive, but it was still desirable to video-tape the fracture tests. Portability, ease of use, performance in adverse weather and video quality were foremost considerations in selecting a recording format. Super VHS (S-VHS) proved to be a cost-effective system for these purposes.

Since multiple copies of the video-tape were required, it was beneficial to use the highest available resolution for the master recording. The S-VHS system offers over 400 lines of resolution as compared 220 lines available in the VHS format. As a result, the image quality of VHS copies dubbed from an S-VHS master tape will be comparable to a VHS master.

A 100 minute VHS copy of Canmar's S-VHS video-tape of the fracture tests is included with this report. S-VHS copies are available upon request but cannot be viewed on standard VHS equipment (a VCR showing the S-VHS symbol is required). Highlights of the video-tape are annotated in **Appendix D** and referenced by both VCR tape counter number and elapsed time. Additional video of the experiments was recorded by other members of the project team in 8 mm format. These videos are of a more general nature.

Attempts were made to video-tape each and every test performed in Phase I. Griffith's tests were not well suited to video and only the first test (G-1) was recorded. The final and largest beam test (RT-9) was not recorded due to camera problems caused by blowing snow and cold temperatures. The great size of the specimen also made video-taping impractical. Weather conditions on the final day of testing were very poor and the cantilever elastic modulus tests were not video-taped.

High-tech video systems are under consideration for Phase II with the aim to estimate crack speed from a frame-by-frame analysis of the video-tape. Motion analyzers currently used by industrial engineers and quality control specialists produce colour S-VHS recordings at 1000 frames per second (standard VHS and S-VHS camcorders record at 30 fps). As it appears that physical measurements of crack speed with conducting strips are difficult to achieve, high speed video or photography may be a viable alternative.

Cost Tracking

The original project budget for Phase I was US $145,800 (or Can $ $171,500), corresponding to a participant fee of US $24,300. The total project budget, which included the digital data acquisition system provided by Canmar, was approximately **Can $183,000**. A detailed cost tracking procedure was initiated by Canmar to ensure that Phase I remained within this baseline budget. Daily field expenditures were monitored and adjustments made to the proposed 14-day testing schedule as required.

When it became evident that weather conditions at Bearspaw Reservoir made further testing impossible, only 30% of the test plan had been conducted. Termination of the experiments at this point was not a valid option and a move to a new testing site, though at additional cost, was preferred. Most of the additional expenditure derived from shipping costs, accommodations, meals and personnel expenses. It was also necessary to ship a large quantity of ice to Clarkson University both before and after the tests for ice characterization studies. Temperatures onsite were unsuitable for such work. Other expenses unforeseen in the original budget of January, 1991 included repairs to Kaman gauges damaged during the tests, purchase of additional safety equipment and the construction of bridges by Sandwell for DitchWitch trenching.

Overall, relocation of the testing program to Spray Lakes Reservoir and other unforeseen expenses resulted in a budget overrun of approximately Can $29,000 or 16% (**Table E-1, Appendix E**). Setting aside those costs not anticipated in the Phase I proposal and those directly associated with the unfavourable weather conditions in Calgary, a budget overrun of less than 2% was experienced (**Table E-2**).

Conclusions

Preliminary conclusions drawn from the results of the Phase I fracture experiments are summarized as follows:

Field Fracture Tests Freezing of the notched test specimens and melting of the sides made the three-point bend geometry ineffective in the field. Instead, a geometry conducive to stable crack growth and one not requiring support reaction from the parent ice sheet was utilized, i.e., reverse taper. Griffith experiments were difficult to perform and analyze due to complex *in situ* stresses at Bearspaw Reservoir and the interaction of the main crack with natural thermal cracks.

Fracture Toughness The fracture toughness of the freshwater ice specimens exhibited significant scatter over the range of sizes tested in Phase I. Even though this study represents the largest controlled ice fracture tests performed to date, it is possible that the minimum specimen size necessary to determine size independent fracture toughness was not realized. The presence of a natural thermal crack density is believed to be the cause of the field scale effect.

Elastic Modulus The effective elastic modulus of freshwater ice was successfully determined by measurements of the crack opening displacements in the fracture tests. Additionally, uniaxial in situ modulus tests were performed to independently measure this parameter.

Closed Loop Control A significant feature of the Phase I experiments was the successful implementation of crack tip opening displacement control of ice fracture. Controlled crack growth was consistently obtained by this method, allowing several fracture toughness measurements on a single specimen. Furthermore, the change in fracture resistance with crack growth can be quantified by CTOD control.

Acknowledgements

The success of Phase I is owed greatly to the contributions of many individuals and organizations. John Dempsey and Sam DeFranco (Clarkson University) acted as scientific and technical advisors for the experiments, while Denis Blanchet (previously with Canmar and now with Amoco Production Company's Tulsa Research Centre) was instrumental in the development and planning of the joint-industry project. Phase I would not have been realized without the significant effort and insight of these individuals.

Access to Spray Lakes Reservoir was arranged through Peter Lougheed Provincial Park with the consent of Alberta Fisheries and Wildlife and TransAlta Utilities. Special thanks are extended to these groups for their support of the experiments and their quick response when it became necessary to change testing sites.

Design and construction of the loading systems and other activities too numerous to mention were capably performed by Sandwell, Inc. The professionalism and creativity of Bill Graham, Dan Masterson, John Robertson and Paul Spencer contributed greatly to the success of the project.

Field logistics, accommodations, heavy equipment operation and miscellaneous work were the responsibility of Jessco Operations, Inc. Special thanks to Pete Jess and Richard Day for their enthusiasm and adaptability under often adverse field conditions.

Special thanks are extended to Max Coon and Skip Echert of Williamson and Associates for their contributions to the project and helpful discussions. The field experience of Bruce Parsons and Trent Slade of the Institute for Marine Dynamics proved a valuable asset to Phase I and their assistance with data acquisition and the fracture experiments in general is greatly appreciated. Thanks also to graduate students Michelle Johnson and Bin Zou from Memorial University of Newfoundland for their assistance in ice characterization at Bearspaw and Spray Lakes.

Canmar was represented in the field by Hugh Gillespie, Kurt Kennedy, Kelly Mamer and Roger Saint. Thanks to Bengt Johansson of Canmar for his strong support of this project and to management and colleagues for their helpful suggestions.

Appendices

Appendix A	Phase I Participants/Personnel
Appendix B	Data Acquisition Log
Appendix C	Daily Log Summary
Appendix D	Video-tape Annotation
Appendix E	Phase I Budget

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Appendix A
Phase I Participants/Personnel

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**Funded externally over and above Phase I core project.*

Appendix B
Data Acquisition Log

January 15, 1992

Test G-1 14:45 Sequence TST0115A.BEQ reconfigured to run first Griffith's test: 500 Hz sample rate over 120 seconds, for a total of 60,000 samples. More samples caused a disk swap between RAM and hard drive, bogging down the system.

Chn 0	Pressure	1-6 VDC	20 PSI/V	137.8952 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400 mV/mm	SSH-4 Gain = 10
Chn 2	Kaman 2310-3u	1.200 V FS	400 mV/mm	
Chn 3	Kaman 2810-BP	1.000 V FS	40 mV/mm	SSH-4 Gain = 10
Chn 4	Kaman 2810-JPD	1.000 V FS	40 mV/mm	SSH-4 Gain = 10

Channels 1,3 and 4 not connected because Kaman gauges melted into the ice. Pressure was only applied for around 80 seconds before pressure transducer overranged. Crack appeared after 20 seconds. Data in D920115A.VDT.

January 17, 1992

13:49 System presently being hooked up. A new pressure transducer, capable of a full scale of 5000 psi, is in use. The 2810 Kaman gauges are 40 mV/um: calibration has been changed.

Chn 0 Pressure 0-5 VDC 1000 PSI/V 31485 kPa delta 5V -200 kPa offset
SSH-4 Gain = 10 1000 FS at 10V

Chn 1 Kaman 2310-1u 0.400 V FS 400mV/mm
SSH-4 Gain = 10 1.0mm FS at 4V

Chn 2 Kaman 2310-3u 1.200 V FS 400mV/mm
SSH-4 Gain = 10 2.5mm FS at 10V

Chn 3 Kaman 2810-BP 1.000 V FS 40mV/um
SSH-4 Gain = 10 25um FS at 10V

Chn 4 Kaman 2810-JPD 1.000 V FS 40mV/um
SSH-4 Gain = 10 25um FS at 10V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM

Pressure Transducer: PSI-TRONIX INC, Simi Valley, Ca., psi 5000 Range: 5000 psig., S/N 5817 pin-outs: a-wht = positive excite, b-red = positive output c-blk-2knots = negative output d-blk-1knot = negative excite exitation = 12 to 32 VDC 20 VDC used.

Test G-2 15:00 Experiment was run successfully, acquiring data for four minutes at 250 Hz. After two minutes, the flatjack pulled away from the pressure fitting, due to ice wedging. Data was stored to hard drive in the following two files D920117A.VDT and D920117.TBL (in tabular form). The VDT file was saved to diskette, along with the ASCII sequence.

2310-3u and 2810-jpd Kamans on north side of crack for test A.

Test B-1 16:44 Set-up up for first beam test. Same sensors as above except:

- Pressure sensor changed out to 1-6 VDC 20 psi per volt sensor. No gain on SSH-4 card. Therefore, slope is 137.8952 kPa/V and offset is -137.8952. Hooked into channel #0. Pressure sensor is Schaevitz model P5041-B-100SG P/N 02780465-000 S/N 2189-0016. Excitation voltage is 10 to 20 VDC set at 15 VDC.

- Only Kaman gages 2310-1u (channel #1) and 2810-BP (channel #3) are mounted on the specimen.

January 18, 1992

Test B-2 11:20 All data from the January 17 tests has been saved as D0117B1.VDT and D0117B2.VDT. A beam is being cut now. Gauges the same as January 17: pressure transducer (size still unknown) and Kaman gauges. Servo-control feedback will be used.

Chn 0	Pressure 0-10 VDC 10V 0 kPa offset	100 PSI/V 689.476 kPa/V 6894.76 kPa delta SSH-4 Gain = 1 1000 FS at 10V
Chn 1	Kaman 2310-1u	0.400 V FS 400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS 400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-BP	1.000 V FS 40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	Kaman 2810-JPD	1.000 V FS 40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS

Continued...

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	

Pressure Transducer: Validyne model DP-15-60, 0-1000 psig, 0-10 V output. Built in power supply, 5V rms excitation.

Pin-out: red - positive output; black - negative output

14:30 A new pressure transducer has been set up (see above). The beam has been cut and the servo feedback system is being set up for the necessary pressure.

15:15 A total of 6 input channels have now been set up. A sampling frequency of 6 kHz has been chosen, with 60,000 scans per channel.

17:00 The servo feedback is still being set up. It looks like the test will begin after dark. The analog out works fine.

17:50 Kaman feedback has been wired up and the first dry run looks good. The analog out looks good on the oscilloscope. We will have to wait about an hour to start because some hose was left back at the shop.

First Loading 19:08 We ran the experiment. The data was saved as D920118A.VDT. We almost ran out of D.A. time and came close to missing the break point and peak pressure. Sampling rate was 6038 Hz. The test was very significant.

Second Loading 19:40 Another test will be run on the same beam, since a stable crack was generated on the first loading. The settings will be the same as for Part A.

20:15 All tests done and working properly. Data in D920118B.VDT.

January 22, 1992

15:05 The D.A. trailer is now on site. Planned for today is the splitting of two small beams, side by side, one using the servo-control system, and one using the gas system. A total of 10 channels will now be used.

Chn 0	Pressure delta 10V	0-10 VDC 0 kPa offset	100 PSI/V 689.476 kPa/V 6894.76 kPa SSH-4 Gain = 1 1000 FS at 10V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V

Chn 3	Kaman 2810-BP	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS	SSH-4 Gain = 1
Chn 6	LVDT 1020	5.000 V FS	102mV/mm SSH-4 Gain = 1 49.02mm FS at 5V
Chn 7	LVDT 1019	5.000 V FS	105mV/mm SSH-4 Gain = 1 47.86mm FS at 5V
Chn 8	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 1 28.57mm FS at 5V
Chn 9	LVDT 1036	5.000 V FS	186mV/mm SSH-4 Gain = 1 26.94mm FS at 5V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	
Ch 6	Slope = 9804 uM/V	One AD Step = 49.02 uM
Ch 7	Slope = 9571 uM/V	One AD Step = 47.86 uM
Ch 8	Slope = 5714 uM/V	One AD Step = 28.57 uM
Ch 9	Slope = 5388 uM/V	One AD Step = 26.94 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output.
Built in power supply, 5V rms excitation.
Pin-out: red - positive output; black - negative output

16:30 No experiments performed today.

January 23, 1992

Test B-3 09:25 The D.A. trailer is again on site. Planned for today is the splitting of two small beams, side by side, one using the servo-control system, and one using the gas system. A total of 10 channels will now be used. The line filter purchased for the UPS did not seem to work today. The AC line faded in and out and the UPS inverter did not start up. The double generator start was once again used, i.e., power up from the Honda generator then switch to the more stable Coleman.

Continued...

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-BP	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS	SSH-4 Gain = 1
Chn 6	LVDT 1020	5.000 V FS	102mV/mm SSH-4 Gain = 1 49.02mm FS at 5V
Chn 7	LVDT 1019	5.000 V FS	105mV/mm SSH-4 Gain = 1 47.86mm FS at 5V
Chn 8	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 1 28.57mm FS at 5V
Chn 9	LVDT 1036	5.000 V FS	186mV/mm SSH-4 Gain = 1 26.94mm FS at 5V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	
Ch 6	Slope = 9804 uM/V	One AD Step = 49.02 uM
Ch 7	Slope = 9571 uM/V	One AD Step = 47.86 uM
Ch 8	Slope = 5714 uM/V	One AD Step = 28.57 uM
Ch 9	Slope = 5388 uM/V	One AD Step = 26.94 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output

11:45 All wiring in place. The analog system is being used as a backup to the digital system. With 10 channels in place, we are scanning at a frequency of 3.5 kHz for 10 seconds, giving 35,000 scans per channel.

Gauge Location:

- Kaman 2810-BP is on the crack tip
- Kaman 2810-JPD is in the middle
- Kaman 2310-1U is on the edge of the beam.
- LVDT 1020 is second furthest south.
- LVDT 1019 is second furthest north.
- LVDT 1040 is furthest north.
- LVDT 1036 is furthest south.

14:30 A sample rate of 3.5 kHz was too high for 10 channel sampling. The multiplexer was having problems. Therefore, we are now using a rate of 1 kHz for 10 seconds, yielding 10000 scans per channel.

Servo-control system values: Gain setting was x10, 100 on the dial.

14:45 The test was successfully completed. Data in D920123A.VDT.

16:35 We are setting up for a gas test: 120 seconds at 250 Hz. The LVDTs have been changed for a SSH-4 Gain = 10, giving slopes as follows:

Ch 6	Slope = 980.4 uM/V	4.902mm FS at 5V
Ch 7	Slope = 957.1 uM/V	4.786mm FS at 5V
Ch 8	Slope = 571.4 uM/V	2.857mm FS at 5V
Ch 9	Slope = 538.8 uM/V	2.694mm FS at 5V

17:10 The SSH-4 Gain for the LVDTs has been set back to 1, so the slopes are the same as for Part A.

17:25 Test completed, but it took 3 minutes to crack. Therefore, the DA system did not get all the data. Data file is D920123B.VDT.

January 24, 1992

Test RT-1 11:00 We are setting up for the first test of the day using a new geometry called the reverse taper (RT). To instrument the specimen, we are only using 3 gauges: the two 2310 Kaman gauges and the 2810 Kaman gauge at the crack tip. Kaman 2310-1u is in the middle. Therefore, we only need four channels: pressure transducer and the three gauges. The settings are the same as for previous tests, as shown below. Only channels number 0, 1, 2 and 3 are used. The sample rate is 250 Hz for 240 seconds, yielding 60000 scans per channel. The size of the beam is 2m x 2m x 2.8m right triangle.

Continued...

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-BP	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS	SSH-4 Gain = 1
Chn 6	LVDT 1020	5.000 V FS	102mV/mm SSH-4 Gain = 1 49.02mm FS at 5V
Chn 7	LVDT 1019	5.000 V FS	105mV/mm SSH-4 Gain = 1 47.86mm FS at 5V
Chn 8	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 1 28.57mm FS at 5V
Chn 9	LVDT 1036	5.000 V FS	186mV/mm SSH-4 Gain = 1 26.94mm FS at 5V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	
Ch 6	Slope = 9804 uM/V	One AD Step = 49.02 uM
Ch 7	Slope = 9571 uM/V	One AD Step = 47.86 uM
Ch 8	Slope = 5714 uM/V	One AD Step = 28.57 uM
Ch 9	Slope = 5388 uM/V	One AD Step = 26.94 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output

First Loading 12:50 The test was run for a while, but stopped before there were any cracks. Data for this test was saved in a file called D0124A1.VDT.

Continued...

Second Loading 13:05 The test was run again on the same specimen and it cracked within one minute. The data for this experiment is saved in a file D0124A2.VDT.

Test RT-2

14:15 The next experiment is being set-up, on a similar geometry of size 0.6m x 0.6m x 0.85m. The same sampling rate (250 Hz) and same time span (240 sec) as the first test are being used. The 2310-1u was at the crack tip and the 2810 was beyond the crack tip.

14:50 The test was completed successfully in approx 20 seconds. The data is in the file D920124B.VDT.

Test RT-3

15:10 The trailer is being moved to a new location and a third RT beam readied for testing. Sample rate and time span are the same as above. Beam size is 6m x 6m x 8.6m. The gauges are the same.

15:40 The test was completed successfully with data in the file D920124C.VDT.

January 25, 1992

Test RT-4

10:05 The geometry of the day is again the reverse taper. All tests today will be done with the gas system. The first test, being done shortly, will be on a size of 0.5m x 0.5m x 0.7m. The pressure will be built up slowly, unlike yesterday when it was built up quickly.

For the first test, only channels 0 through 3 will be used, with the settings as shown below. Only two kaman gauges will be hooked up. The 2310-1u is at the crack tip, and the 2810bp is beyond the crack tip.

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-BP	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10
Chn 4	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS	SSH-4 Gain = 1

Continued...

Chn 6	LVDT 1020	5.000 V FS	102mV/mm SSH-4 Gain = 1 49.02mm FS at 5V
Chn 7	LVDT 1019	5.000 V FS	105mV/mm SSH-4 Gain = 1 47.86mm FS at 5V
Chn 8	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 1 28.57mm FS at 5V
Chn 9	LVDT 1036	5.000 V FS	186mV/mm SSH-4 Gain = 1 26.94mm FS at 5V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	
Ch 6	Slope = 9804 uM/V	One AD Step = 49.02 uM
Ch 7	Slope = 9571 uM/V	One AD Step = 47.86 uM
Ch 8	Slope = 5714 uM/V	One AD Step = 28.57 uM
Ch 9	Slope = 5388 uM/V	One AD Step = 26.94 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output

11:10 The test was performed successfully. Kaman gauge 2810 did not work, so it gave no useful data. Only the 2310-1u gave data. All data is saved in a file D920125A.VDT.

Test RT-5 12:25 The second RT test of the day is being set up. Size is 1.5m x 1.5m x 2.1m. LVDT 1040 will be used and has been moved to channel 5, with the same gain as before. The gauges are placed as follows: 2810-JPD on the crack tip, 2310-3u next, 2310-1u next and LVDT at the edge of the specimen.

First Loading 13:20 The test was run, but the flatjack slipped out before the ice cracked. Channels 4 and 5 were not working, so their data will be strange. The data is saved in the file D0125B1.VDT.

14:00 The same specimen will be tested again.

Second Loading 14:25 The test ran successfully. Data is stored in the file D0125B2.VDT.

Continued...

Test RT-6 15:15 The third test of the day is being set up. Gauges are the same as for the last test. Size of the RT is 13.5m x 13.5m x 19m.

First Loading 16:20 The test was run but the flatjack slipped out early again. The test will be repeated soon. Data for this test is in D0125C1.VDT.

Second Loading 16:45 The test was completed successfully. Data is in D0125C2.VDT.

January 26, 1992

Test RT-7 12:05 The first test of the day is a servo-controlled, 4.5m x 4.5m x 6.1m reverse taper. There are seven channels being used - the first six as shown below, and the LVDT 1040 in Channel 6. All gains and slopes are as shown below. The test will be run for 30 seconds at 1000 Hz. From the crack tip to the edge, the gauges are as follows: 2810-JPB, 2310-1u 23103u and LVDT.

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-BP	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 5	Ramp output	5.000 V FS	SSH-4 Gain = 1
Chn 6	LVDT 1020	5.000 V FS	102mV/mm SSH-4 Gain = 1 49.02mm FS at 5V
Chn 7	LVDT 1019	5.000 V FS	105mV/mm SSH-4 Gain = 1 47.86mm FS at 5V
Chn 8	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 1 28.57mm FS at 5V
Chn 9	LVDT 1036	5.000 V FS	186mV/mm SSH-4 Gain = 1 26.94mm FS at 5V

Continued...

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3-4	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 5	Slope = 1 V/V	
Ch 6	Slope = 9804 uM/V	One AD Step = 49.02 uM
Ch 7	Slope = 9571 uM/V	One AD Step = 47.86 uM
Ch 8	Slope = 5714 uM/V	One AD Step = 28.57 uM
Ch 9	Slope = 5388 uM/V	One AD Step = 26.94 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output.

First, Second and Third Loadings

14:30 Three tests were done on the same beam, with data called D0126Ax.VDT, where x is 1,2 or 3, depending on the test. There was stable fracture. For the first two tests, loop gain on the Kaman gauges was x5 and the dial read 1000. For the last test, the gain was x5 and the dial read 25. Neither of the 2310 Kaman gauges were working.

Test RT-8

15:25 Another servo-control test will be done on the same size beam. The test will only run for 3 seconds, since we are using a 500ms ramp instead of a 5 second ramp. The sampling rate will be 10 kHz. The gain and dial reading in the feedback loop will again be x5 and 100.

First, Second and Third Loadings

16:30 Three tests have been run, all at 10 kHz, with ramps of different time span. The gain in the feedback loop was always x5 and the dial reading was at 100, 25 and 10 for tests 1, 2, and 3 respectively. They are saved in files D0126Bx.VDT, with x being 1, 2 or 3. A fourth test is being set-up, with the Kaman 2310-1u being used as the feedback gauge.

Fourth Loading

17:00 In the fourth test, the ramp generator was not set correctly so the pressure stayed at one rate. The data for this test was saved in D0126B4.VDT. One more test will be done, with the same settings, and the data for this test will be saved in D0126B5.VDT.

Fifth Loading

17:05 The test ran and the specimen broke before there was any data acquired. The settings on the feedback were x5, 100 on the dial.

January 27, 1992

11:45 The first test today is a large RT: 40.5m x 40.5m x 57.3m. It is being loaded with the gas system. The gauges to be used are shown below and are, from the crack tip to the edge, the 2810-JPD, 2310-1u, 2310-3u, and LVDT. These readings will last for 240 seconds at a scan rate of 300 Hz.

Continued...

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2310-1u	0.400 V FS	400mV/mm SSH-4 Gain = 10 1mm FS at 4V
Chn 2	Kaman 2310-3u	1.200 V FS	400mV/mm SSH-4 Gain = 10 2.5mm FS at 10V
Chn 3	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V
Chn 4	LVDT 1040	5.000 V FS	175mV/mm SSH-4 Gain = 10 2.857mm FS at 5V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 2	Slope = 250 uM/V	One AD Step = 1.25 uM
Ch 3	Slope = 2.5 uM/V	One AD Step = 0.0125 uM
Ch 4	Slope = 571.4 uM/V	One AD Step = 2.857 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output.

Test RT-9 *First Loading* *Second Loading*	12:10	Two tests are to be run on this beam. First, the beam will be loaded and unloaded, which will also give a check if all gauges are working. The data for this test will be in D0127A1.VDT. The second test will crack the beam. Data for this test will be in D0127A2.VDT.
	13:00	The first test was successful. During the second, the flatjack slipped out, so it was essentially another load/unload test.
Third Loading	14:45	Another test will be attempted. Data for it is in D0127A3.VDT.
	15:15	Another test has been done. The load only went up to 7 psi. Another test will be conducted shortly. Data not saved.
Fourth Loading	15:55	The beam did not crack. Maximum pressure was 12 psi. The data for this test is in D0127A4.VDT. A fifth test produced nothing and the data was not saved. A new test will be performed shortly.
	16:15	Still no success, but the problem apparently has been found: a small leak. The beam should now crack as a new pressure line has been installed.
Fifth Loading	16:21	Beam cracked. Data in D0127A5.VDT.

January 28, 1992

10:30 Today, cantilever beam tests with a load and unload cycle. There will be no fracture. Since the beam is small, only two channels will be used as shown below. The test length will be 120 seconds at a sample rate of 1 kHz.

Chn 0	Pressure	0-10 VDC	100 PSI/V SSH-4 Gain = 1 689.476 kPa/V
Chn 1	Kaman 2810-JPD	1.000 V FS	40mV/um SSH-4 Gain = 10 25um FS at 10V

Ch 0	Slope = 689.476 kPa/Volt	One AD Step = 3.45 kPa
Ch 1	Slope = 2.5 uM/V	One AD Step = 0.0125 uM

Pressure Transducer: Validyne model DP-15-60, 0-1000psig, 0-10 V output
Built in power supply, 5Vrms excitation.
Pin-out: red - positive output; black - negative output.

Test CB-1 11:05 The test was successful. Data in D920128A.VDT.

12:15 The next beam will be tested shortly. The sample rate and test length will be the same as for the first test.

Test CB-2 12:30 The second test was successful. Data stored in D920128B.VDT.

Test CB-3 14:30 The third and final test will be starting soon. This beam is the largest of the three samples. Data for this test is in D920128C.VDT. The sequence is the same as above.

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Appendix C
Daily Log Summary

DATE	WEATHER		ACTIVITIES	TESTINGNOTES
January 15	Overcast a.m. Wind moderate	+9C	Equipment mobilization and set-up; DitchWitch trenching; computer checks; Griffith's crack slot with chainsaw	First Griffith's Crack test (G-1); reciprocating crack scribing saw tested and performed well; water on ice from trenching operations; gauges on metal mounts melting into the ice
January 16	Clear and sunny Winds light	-5C	Refurbishment of Test G-1 slot for more testing; more beam trenching; DitchWitch down p.m.; spikes from UPS	Griffith's test G-2 (using G-1 slot); digital D.A. system not used dur to UPS problem; all data on analogue system; Griffith's test G-3 prepared and tested at 5:00 p.m.
January 17	Overcast Winds light	-2C	Bug found in Viewdac D.A. software; UPS sensitive to voltage regulation; DitchWitch under repair all day	Rectangular beam specimen B-1 prepared and tested; nitrogen regulated loading system used, i.e., not servo-controlled; test very successful
January 18	Overcast Winds light	0C	DitchWitch operational; beam sites roped, slots cleared and filled with styrofoam to prevent refreezing	Beam test B-2 prepared for servo-control loading; full day needed to prepare (readied by 7:00 p.m.; CTOD control yielded stable crack; beam split in test B2-B; left site at 9:00 p.m.
January 19	Sunny Chinook winds	+13C	Trenching halted due to flooding and melting caused by high temp.; ice melting; all equip. off ice by 4:30 p.m.	Test preparations halted; warm weather forecasted for remainder of week; decided that January 20 would be downtime; contigency plans put into effect on January 20
January 20	Sunny Chinook winds	+15C	Forecast warm all week; Bearspaw evening opearations considered; site change preferred but must be approved	
January 21	Overcast Chinook winds	+15C	Access to Spray Lakes arranged through offical channels; mobilization of personnel/equipment; onsite by 7:00 p.m.	
January 22	Partly cloudy Winds light	-3C	Trenching operations; full day set-up of equipment and site surveys; good access to site; limited cracking in ice	Several beams prepared but not tested
January 23	Overcast Winds moderate	-1C	Backup computer now onsite; temperatures consistently cold; two small beam tests prepared	Tests B-3 and B-4 prepared and tested successfully; appears that slot between flatjack and beam refroze before test; slot will be closely monitored
January 24	Snow a.m. Flurries p.m.	0C	Noted that day old slots melted at the bottom, creating an unsuitable bearing face for flatjacks; new slots cut	Reverse taper (RT) geometry adopted to alleviate problems with slot melting; flatjack placed in crack; beams quickly cut and set up; tests RT-1, RT-2 and RT-3 successful; all nitrogen
January 25	Overcast Winds moderate	-2C	Concentrating on preparing many RT geometries; scale effect in RT beams top priority; flexure test now unlikely	Three more RT beams tested with nitrogen regulated loading system; RT-4, RT-5 and RT-6 all tested successfully; servo-controlled RT tests planned
January 26	Clear and sunny Winds moderate	-1C	Set-up for servo-control RT tests; visitors from Canmar to observe tests; largest RT geometry being trenched	Test RT-7 propagated stably on three loadings; ice near crack removed for thin sectioning and analysis; test RT-8 loaded 5 times
January 27	Snow a.m. Winds strong	-1C	Little refreezing of large RT beam; beam ensures as free-floating; large ice block removed to ship to Clarkson	Test RT-9 loaded twice; double-flatjack system prepared to give required load; beam cracked eventuallyl ice block trucked to Calgary and stored ovenight at Alberta Ice
January 28	Heavy snow Winds strong	-1C	Preparation for cantilever beam tests; testing hampered by bad weather; windbreak constructed; full day of testing	Three cantillever tests set up and performed to estimate full-thickness elastic modulus of ice; flatjack loading with nitrogen gas; tests appeared successful
January 29	Overcast Flurries a.m.	-2C	Demobilization of equipment and shipment to Calgary; site well signed and hazardous areas roped and flagged	

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Appendix D
Video-tape Annotation

TAPE COUNT	ELAPSED TIME	DATE	ACTIVITY	DESCRIPTION
0020	0:00:15	January 15	Bearspaw Reservoir	General view of site showing lake, Bearspaw Dam, shore approach and equipment.
0110	0:01:05	"	Griffith's Test Prep.	Chainsawing slot in preparation for Griffith's Test G-1.
0130	0:01:45	"	Residual Stress Meas.	M. Coon & S. Echert (Williamson & Associates) instrumentation and set-up for residual stress measurements; ice chainsawed out around gauges.
0290	0:04:15	"	D.A. Trailer Onsite	All computer equipment, power supply and servo-control electronics in trailer.
0363	0:05:20	"	Crack Scribing Saw	First use of reciprocating crack scribing saw; mounting of crack tip gauges.
0435	0:06:05	"	Griffith's Test Set-up	Final set-up for Test G-1, including view of nitrogen gas cylinder, flatjack and conducting strips at crack tip for crack velocity measurements (IMD/NRC).
0754	0:12:05	January 16	DitchWitch Trenching	Testing of steel bridges for beam trenching (to avoid placing DitchWitch wheels directly on beam); optimizing trenching speed and accuracy by trial and error.
1020	0:17:15	"	First DitchWitch Slot	Slot is not straight, but subsequent efforts at optimum chain and unit speeds yielded very good results; slot is about 100 cm wide.
1035	0:17:35	January 17	Beam Test B-1 Prep.	Short sides of beam cut free with chainsaws, slot cleared of cuttings, floating point supports inserted and D.A. trailer moved near beam site.
1242	0:22:20	"	Notch Preparation	Beam shored up with floating supports to aid in cutting notch; notch location marked, measured, cut and crack tip scribed with reciprocating saw.
1500	0:27:50	"	Beam Test B-1 Set-up	Test readied by evening (portable lighting system used); crack tip instrumented with Kaman gauges on wooden brackets and crack velocity measurment strips.
1590	0:30:05	"	Beam Test B-1	D.A. time exhausted before loading; test restarted at Tape Count (TC) ≈ 1665; flatjack pressure called out; unstable fracture at TC ≈ 1698 (0:32:35).
1710	0:32:50	January 18	Beam Test B-2	First test with servo-control loading skid; spooling noise as flatjack inflates; stable crack pops in at TC ≈ 1872 (white line from gauge cluster toward flatjack pipe) .

TAPE COUNT	ELAPSED TIME	DATE	ACTIVITY	DESCRIPTION
1950	0:37:35	January 18	Beam Test B2-B	Close-up of stable crack; general discussions of observations; Test B2-B run to break the beam; specimen splits non-violently; J. Dempsey comments on test.
2070	0:42:15	January 22	Spray Lakes Reservoir	General view of site; Spray Lakes Reservoir, shore approach, equipment location.
2085	0:42:35	January 23	Beam Test B-3	LVDT's on wooden brackets to measure deflections for Elastic Modulus; crack tip scribed with sharp ruler; beam breaks cleanly at TC ≈ 2162; wind noise on tape.
2190	0:45:30	January 24	Beam Test RT-1	Geometry changed to reverse taper (RT); general views of site & safety signs; specimen tested and fails at TC ≈ 2272, just after pressure reading of "50".
2290	0:48:25	"	Beam Test RT-2	Crack scribing with reciprocating saw; chainsawing slots to ensure beam is free-floating; specimen fails at TC ≈ 2338, just after "20 pounds" pressure reading.
2345	0:49:55	"	Beam Test RT-3	View of large beam for RT-3; test preparations; specimen fails at TC ≈ 2468, just after "80" psi attained; post-test analysis (crack length, orientation).
2495	0:54:25	January 25	Beam Test RT-4	DitchWitch trenching largest RT-6 specimen in background; RT-4 specimen fails at TC ≈ 2564, immediately following "35" psi reading; surveying of RT-6 specimen.
2600	0:57:45	"	Rationale for RT	Discussion by J. Dempsey on Reverse Taper geometry (audio hampered by wind).
2630	0:58:30	"	Beam Test RT-5	Beam preparation and crack scribing; detailed video on crack tip instrumention; flatjack slippage on three loadings; failure on fourth at TC ≈ 3076, "70" psi.
3110	1:14:-5	"	Beam Test RT-6	Preparations and set-up; flatjack slippage on first loading; specimen failure on second loading at TC ≈ 3238, just after "55" psi reading; wind noise evident.
3315	1:21:05	January 26	Beam Test RT-7	DitchWitch trenching largest speimen, RT-9; test set-up with servo-control skid; spooling noise as flatjack fills; stable crack appears SW of notch @ TC ≈ 3402.
3450	1:22:00	"	Reloadings of RT-7	Spooling sound followed by stable crack growth (unclear in video); close-up of visible crack path; third loading to specimen failure (not clear).
3495	1:27:45	"	Beam Test RT-8	Preparations and set-up; stable crack growth at TC ≈ 3568 (unclear in video); wind noise; reloading and stable crack growth once again (unclear in video).
3770	1:37:55	January 27	Beam Test RT-9	Preparation and set-up; beam too large and snow-covered for useful video record; video camera also affected by poor weather conditions. ***END OF TAPE***

Appendix E
Phase I Budget

TABLE E-1

Large-Scale Ice Fracture Experiments
Phase I Total Expenditure

Contractor	Description	Expense	Totals
Canmar	Salaries and D.A. system	37,000.00	
	Incidentals (1)	1,925.00	
		38,925.00	$38,925.00
Clarkson	As per contract	39,117.65	
	Repair to gauges (2)	5,764.71	
		44,882.35	$44,882.35
Jessco	As per contract	43,000.00	
	Safety equipment (3)	1,500.00	
	Ice shipment (pre-test)	968.00	
	Ice shipment (post-test)	3,500.00	
	Move to Spray Lakes (4)	5,950.00	
		54,918.00	$54,918.00
Sandwell	As per contract	43,326.00	
	Field labour	23,370.00	
	Additional costs (5)	7,025.90	
		73,721.90	$73,721.90

TOTAL **$212,447.25**

Total project budget: 6 participants at
US $24,300 (CAN $28,588.24) plus D.A.
system purchased by Canmar

BUDGET	$182,791.76
Variance	$29,655.49
	+16%

All figures in Canadian dollars
CAN $1.00 = US $0.85

(1) Travel, video and miscellaneous expenses.
(2) Estimated: water damage to all Kaman gauges.
(3) Purchase of signs, lumber, rope, etc.
(4) Includes hauling fees and all accommodations.
(5) Travel, living expenses, bridge construction, bandsaw and function generator rental.

TABLE E-2

Large-Scale Ice Fracture Experiments

Phase I Baseline Expenditure

Contractor	Description	Expense	Totals
Canmar	Salaries and D.A. system	37,000.00	37,000.00
Clarkson	As per contract	39,117.65	39,117.65
Jessco	As per contract	43,000.00	43,000.00
Sandwell	As per contract	43,326.00	
	Field labour	23,370.00	
		66,696.00	66,696.00

TOTAL $185,813.65

Total project budget: 6 participants at
US $24,300 (CAN $28,588.24) plus D.A.
system purchased by Canmar

BUDGET	$182,791.76
Variance	$3,021.88
	+1.7%

All figures in Canadian dollars
CAN $1.00 = US $0.85