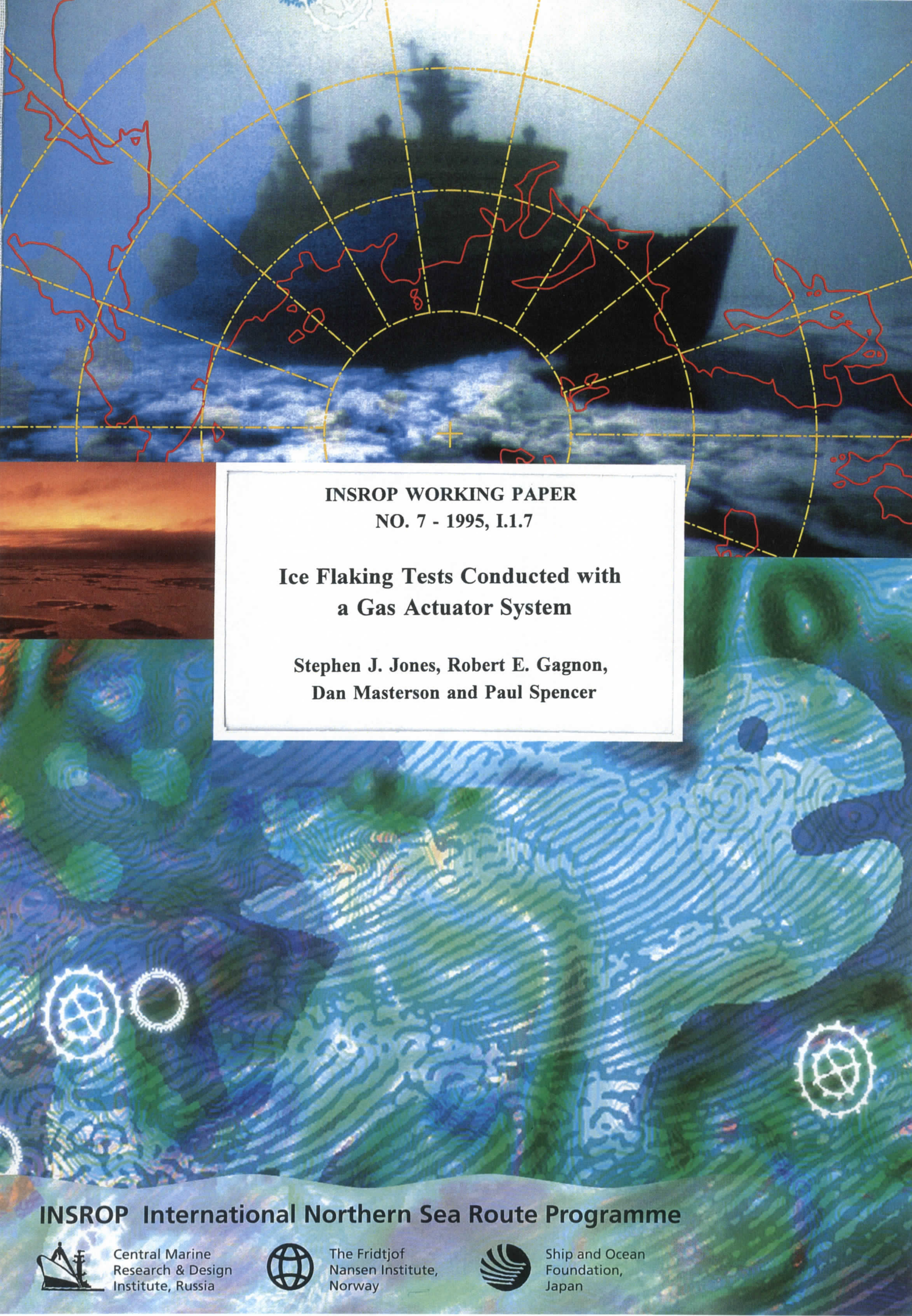

INSROP WORKING PAPER
NO. 7 - 1995, I.1.7

Ice Flaking Tests Conducted with a Gas Actuator System

Stephen J. Jones, Robert E. Gagnon,
Dan Masterson and Paul Spencer

INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

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Title: Ice Flaking Tests Conducted with a Gas Actuator System

Sub-programme I: Natural Conditions and Ice Navigation

Project I.1.7: Large Scale Hull Loading of First Year Ice. Phase 1.

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Reviewed by: Dr. Kaj Riska, Helsinki University of Technology

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FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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ICE FLAKING TESTS CONDUCTED WITH A GAS ACTUATOR SYSTEM

Final Report

CR-1994-03

Sandwell Inc.

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KEY WORDS: ice / ice loads / ice flaking	PAGES	FIGS.	TABLES

SUMMARY:

The object of the tests was (a) to determine if gas actuated flat jacks, rather than liquid activated, could be used safely in the field and (b) to investigate whether the presence of a rigid indentor alongside the flat jack, affected the measured loads significantly.

Results showed that the rigid indentor had little effect in undamged ice giving failure pressures about 65% of those obtained without a rigid indentor. Pre-damaged ice, however, gave significantly lower pressures.

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EXECUTIVE SUMMARY

Since 1969 when Esso first conducted tests on the first-year ice in Tuktoytaktuk Harbour, NWT by pushing pairs of steel piles against the full ice sheet thickness (the "Nutcracker Tests") to determine the pressure ice could exert on offshore structures, there have been efforts to devise methods of deriving global ice loads on structures by means of small or medium scale tests. Since the time of the early tests, gravity base structures have been placed in the Beaufort Sea and full scale load measurements have been made. Large scale data has also been obtained from ship trials wherein load measurements have been made while ramming thick multi-year ice. Forces were also measured at Hans Island when southward drifting multi-year ice impacted the island.

While these measurements have contributed considerably to our knowledge of the global forces on structures and ship hulls, the constraints of the measurement programs result in sufficient uncertainty to cast doubt on the accuracy of the measurements, limiting their reliability for use in design. There is still much controversy over the magnitude of loads experienced by the Molikpaq and the loads measured at Hans Island are considered to be lower bound. Thus there is still a need to develop and utilize methods which will lead to an understanding of the processes at work in ice/structure or ice/hull interaction which will also yield large scale values of ice pressure and load.

A technique for testing ice strength was developed in the 1970's which consisted of using the walls of pits excavated in the ice along with a hydraulic ram and load plates. The ice itself formed the "load frame" with the ram reacting against one wall with a larger plate and the other wall with a smaller plate, under which failure of the ice would occur. These tests were small scale but the plates could be shaped to model structural sections or the entire structure itself. Since the tests could only be reasonably conducted at small or medium scale, it was not possible to model large scale interactions.

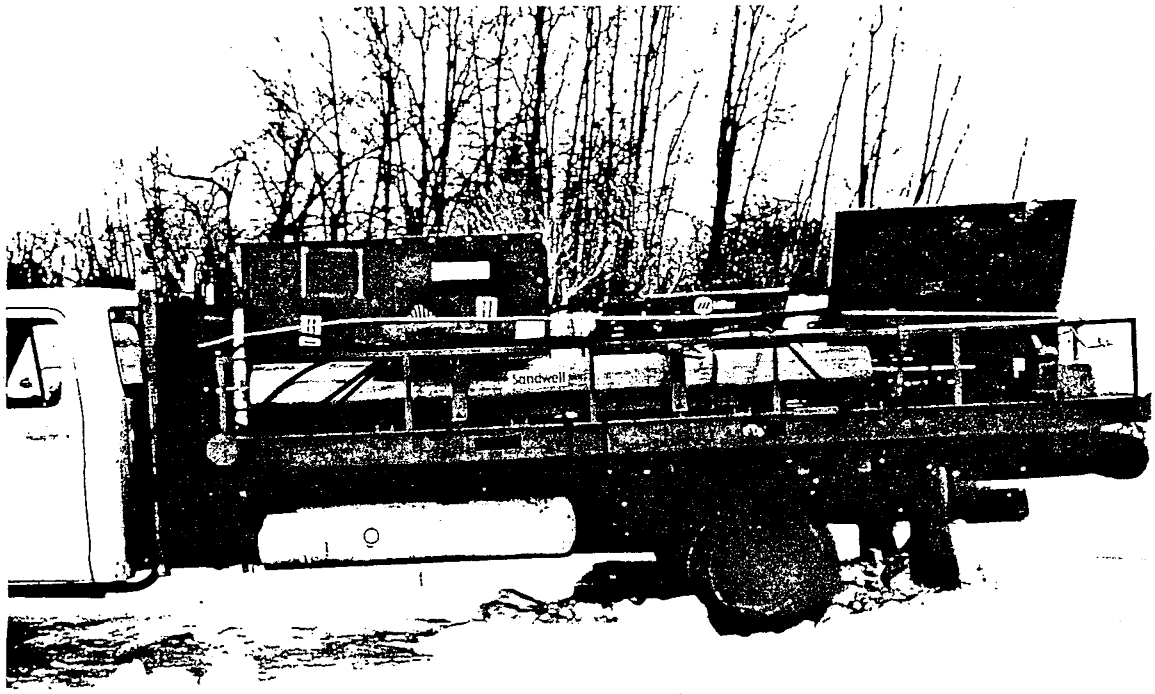
The use of the flat jack, a thin walled, flat envelope of steel which is fitted into an ice slot and into which fluid is pumped to achieve the failure load of the ice, made it possible to load much larger areas of the ice at relatively low cost. Tests conducted with these flat jacks to areas of 4.5 m^2 showed that the strength of competent, intact ice did not change significantly with the size of loaded area. The compliant flat jacks themselves provided a perfect loading with no stress concentrations over the loaded area, allowing the ice to fail uniformly and to deform visco-elastically. This was conclusively demonstrated in 1993 during the Resolute Bay tests. In most cases the ice did not fail but deformed sufficiently to allow the flat jack to burst or else the ice was able to simply resist the available pressure from the accumulator.

It was reasoned that if a stiff plate were placed in the ice slot alongside the flatjack, then the resulting stress concentrations from the stiff plate would result in a lower failure pressure more reasonably approximating that measured on large structures and ships. This past program outside Calgary in February, 1994 used a 76 mm thick aluminum plate. However, so perfect are the saw cuts made using a specially built guide, that the pressures, while reduced somewhat, still resembled those measured in the laboratory. An aluminum plate 1.5 m by 0.2 m by 76 mm thick was able to produce pressures of around 5.5 MPa. Meanwhile, average pressures on large structures due to global loading of 1 to 2 MPa have been measured. The overall testing program is illustrated in the photographs provided in this section.

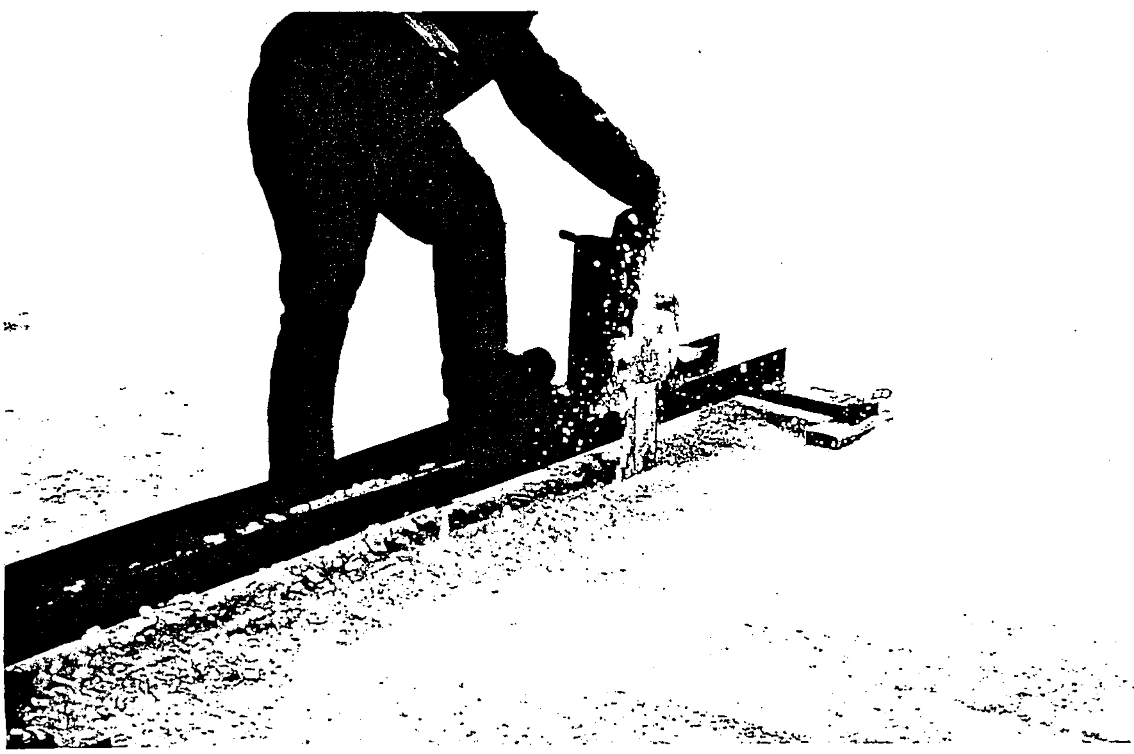
Some of the tests during this program had been conducted, as at Resolute, with no rigid plate and in some tests the ice had been deformed and damaged but had not flaked. Two additional tests with the rigid indentor were run in this pre-damaged ice and the pressures obtained averaged 1.5 MPa, a value in line with global pressure measured on large structures. This constitutes a very important observation and provides concrete direction for tests aimed at determining global loads on large structures in the future.

When an ice feature approaches and impacts an offshore structure, the edge of the ice is not uniform and contact between the ice and the structure occurs locally while there is no contact at other areas. Locally the pressure on the ice builds to a high value and the ice is damaged or failed. Meanwhile, contact at other spots along the width of the structure is beginning or is in process and pressure builds at these spots, resulting in damage to or failure of the ice. Finally, the ice across the width of the structure is all in a state of "damage" and when global failure occurs, if it does crush simultaneously the pressure is much lower than would be obtained from intact, undamaged ice.

While the above scenario is simplified and omits possibilities such as non-simultaneous failure and varying failure modes, it is still realistic and was observed at the Molikpaq when crushing and extrusion occurred in 1986. Thus this methodology, allowing one to predamage the ice with control on the maximum pressure and load duration and then to load the ice to failure with an indentor resembling the wall of a structure, is a very powerful tool for studying ice/structure or ice/hull interaction and quantifying the loads.



ACCUMULATOR, AIR COMPRESSOR AND AC POWER GENERATOR



CUTTING SLOTS

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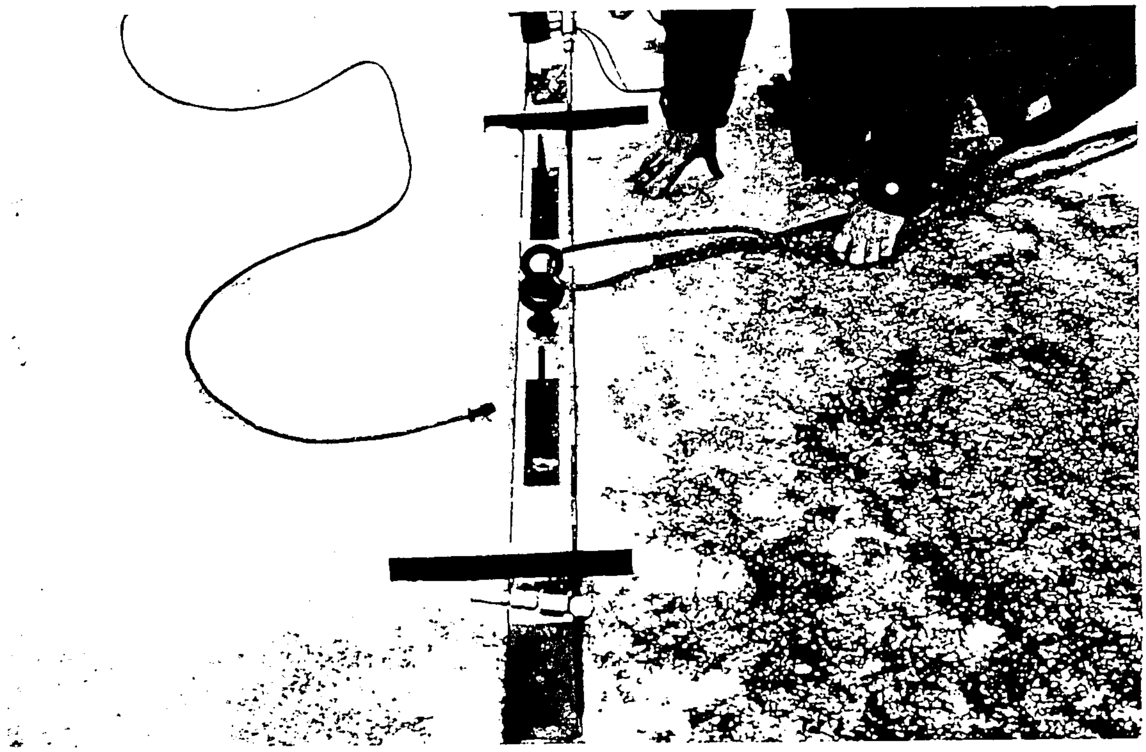
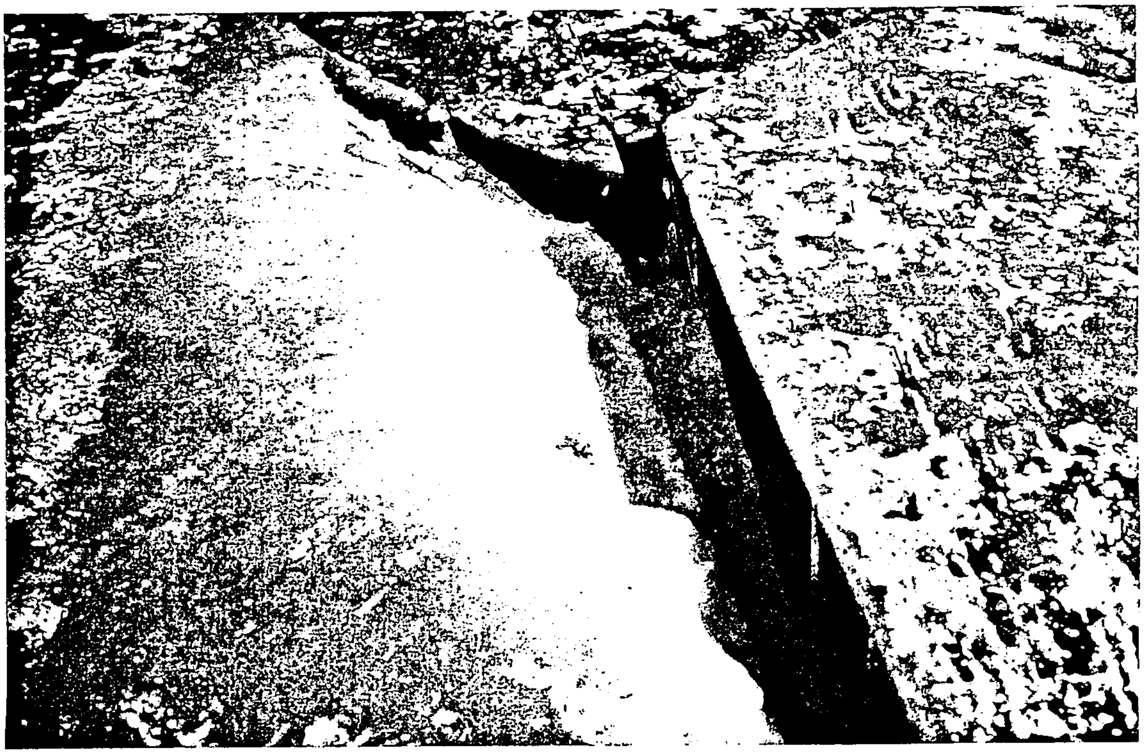


SETTING UP FOR TEST USING AN INDENTOR



FLAKING AFTER TEST 1 USING INDENTOR

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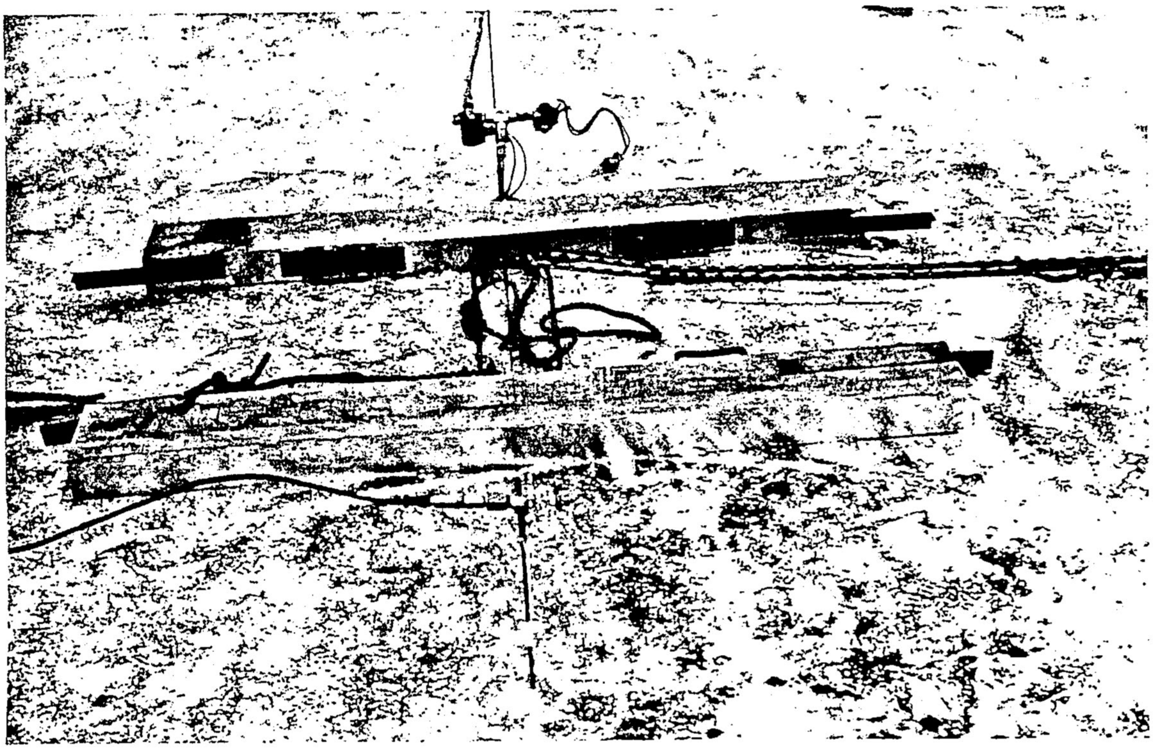
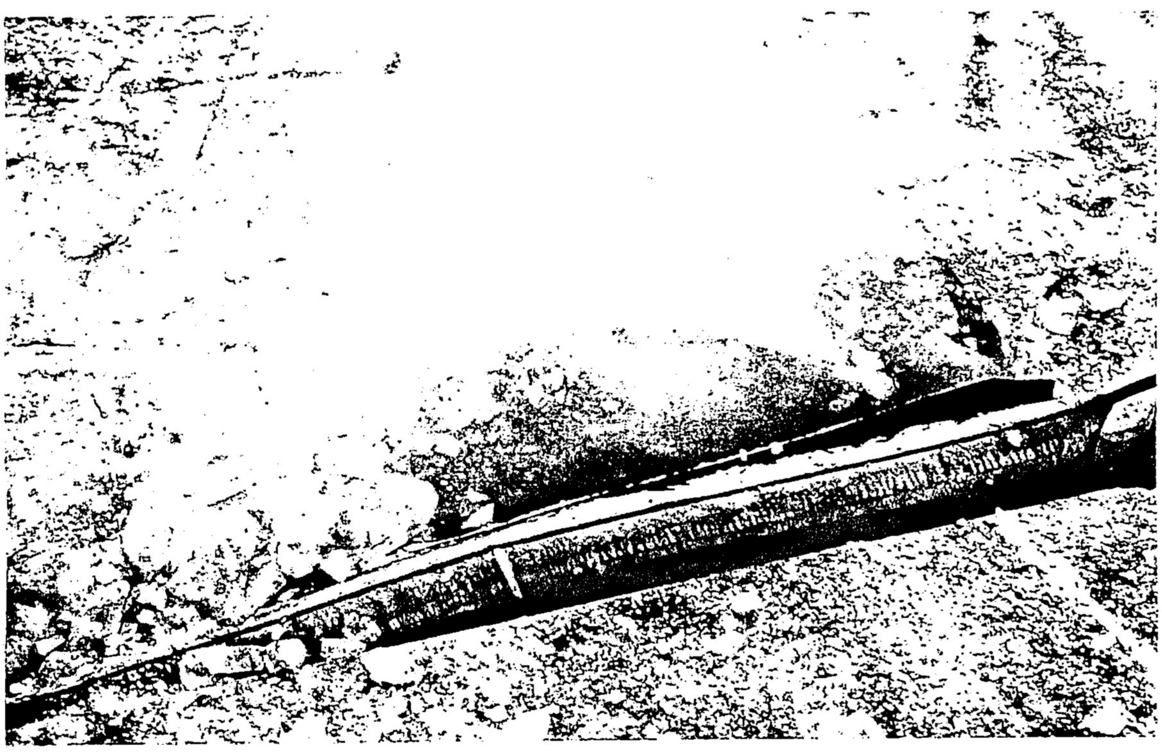


SETUP FOR FLATJACK TEST



EXPANDED FLATJACK AND FLAKING AFTER TEST 6

1.0 PROJECT BACKGROUND

In Arctic waters, ice loads on offshore structures and ice going vessels are usually the design load case. Other loadings, for example wave, tectonic or thermal exist but are often of lower magnitude. For this reason, there is an ongoing desire to quantify and understand global ice loads on ship hulls and structures. In an attempt to achieve these aims Sandwell Inc. conducted a test series for the National Research Council "Medium Scale Uniform Pressure Tests on First-Year Sea Ice at Resolute Bay, N.W.T. 1993", in which flatjacks were used to load segments of the level first-year ice sheet. Flatjacks are constructed from thin sheets of stainless steel, welded around the edge and hydraulic connections made. By pumping a fluid into the flatjack a uniform pressure can be generated. By inserting the flatjack into a thin slot cut into the ice the uniform pressure is then applied to the ice sheet. From these tests it was found that laboratory scale pressures (5 - 15 MPa) could be sustained by the ice sheet even though the contact area ranged from 0.15 to 4.5 m^2. There was not any strong evidence of a size or aspect ratio dependence for the maximum pressures but there was strong evidence for edge effects. The more free edges the flatjack was adjacent to, the lower was the maximum pressure. The 1993 project results were presented at the OTC meeting during May 1994 in Houston, Texas (Masterson et al, 1994).

One hypothesis for the large pressures found during the 1993 field tests, was that the compliant flatjacks did not produce stress concentrations in the loaded surface (i.e. end effects). A rigid indentor would presumably cause local ice failure resulting in lower maximum pressures. Thus for the current project a rigid indentor was placed in the ice adjacent to the flatjack to determine its effect.

The 1993 field tests were conducted in the Arctic at Resolute Bay, N.W.T. using oil and a hydraulic servo-controller. The budget for the current project did not allow for a project to be undertaken in the Arctic and a field project adjacent to Calgary was proposed. To further reduce the field costs it was proposed to use compressed air rather than oil and to dispense with the servo control mechanism. The use of air would also be expected to reduce site clean-up compared with oil. The 1993 field project indicated that rupture of the flatjacks with the resulting fluid loss was a liklihood.

The current project was thus to demonstrate the use of rigid indentors in conjunction with flatjacks and to investigate the use of air as the active medium.

2.0 PROJECT PARTICIPANTS

Sandwell Inc. conducted this project under a contract for the National Research Council Canada with Dr. Stephen Jones of the Institute of Marine Dynamics (IMD), St. Johns, Newfoundland as Scientific Authority. Funding was provided by INSROP and by the Canadian National Energy Board (NEB). Canadian Marine Drilling Ltd. (CANMAR) of Calgary were a project sponsor and contributed in-kind support by providing the hardware and the professional manpower required for the on-site data acquisition system. Kelly Mamer of Canmar configured and operated the data acquisition system in the field. Dr. Robert Gagnon and Ms. Michelle Johnston of IMD supplied and operated a high speed video recording system and conducted a crystallographic and thin sections analysis of the lake ice. The tests were conducted on a small lake on the property of Mr. Jim Minty and Mr. Brown of Strathmore, Alberta. Dr. Paul Spencer of Sandwell was project director and Dr. Dan Masterson provided input on the indentor design and the test procedures. Bill Graham, John Robertson and Brian Brenner completed the field team.

3.0 SCHEDULE

The preparation and field schedule was compressed due to length of time required to obtain the funding for the project and the need to be able to conduct tests before the winter season ended.

System development and shop testing was performed from January 21 up to February 11 at the Sandwell facilities in Calgary. Activities included manufacture of flatjacks, assembly and modifications of hydraulic sub system, manufacture of chain saw mounts, manufacture of indentor plates, electrical assembly and construction of electronics. On February 12 most equipment was trucked out to the test site and a thermistor string was installed in the ice. On February 14 the remainder of the equipment was trucked to the site and two tests conducted. Testing continued until Friday, February 18 by which time 16 tests had been successfully completed. Bob Gagnon and Michelle Johnston of the Institute of Marine Dynamic (I.M.D.) from St. Johns arrived on site on Wednesday, February 16. Site clean-up occurred on February 21. A progress report was submitted in March 1994 and data reduction and analysis performed in May and June 1994.

4.0 TEST LOCATION

The test site was located approximately 50 km east of Calgary, Alberta, south of the town of Strathmore and was on a small freshwater lake (50° 59' 30" N, 113° 25' W). The lake was situated on private property with the permission of the property owners. Ice thickness was between about 0.47 m and 0.52 m with about 0.1 m of snow cover. The property owners indicated that water flow (from north to south) in the lake stopped during December 1993 and that the ice was snow free until the beginning of February 1994. The general site layout is illustrated in Figure 4.1.

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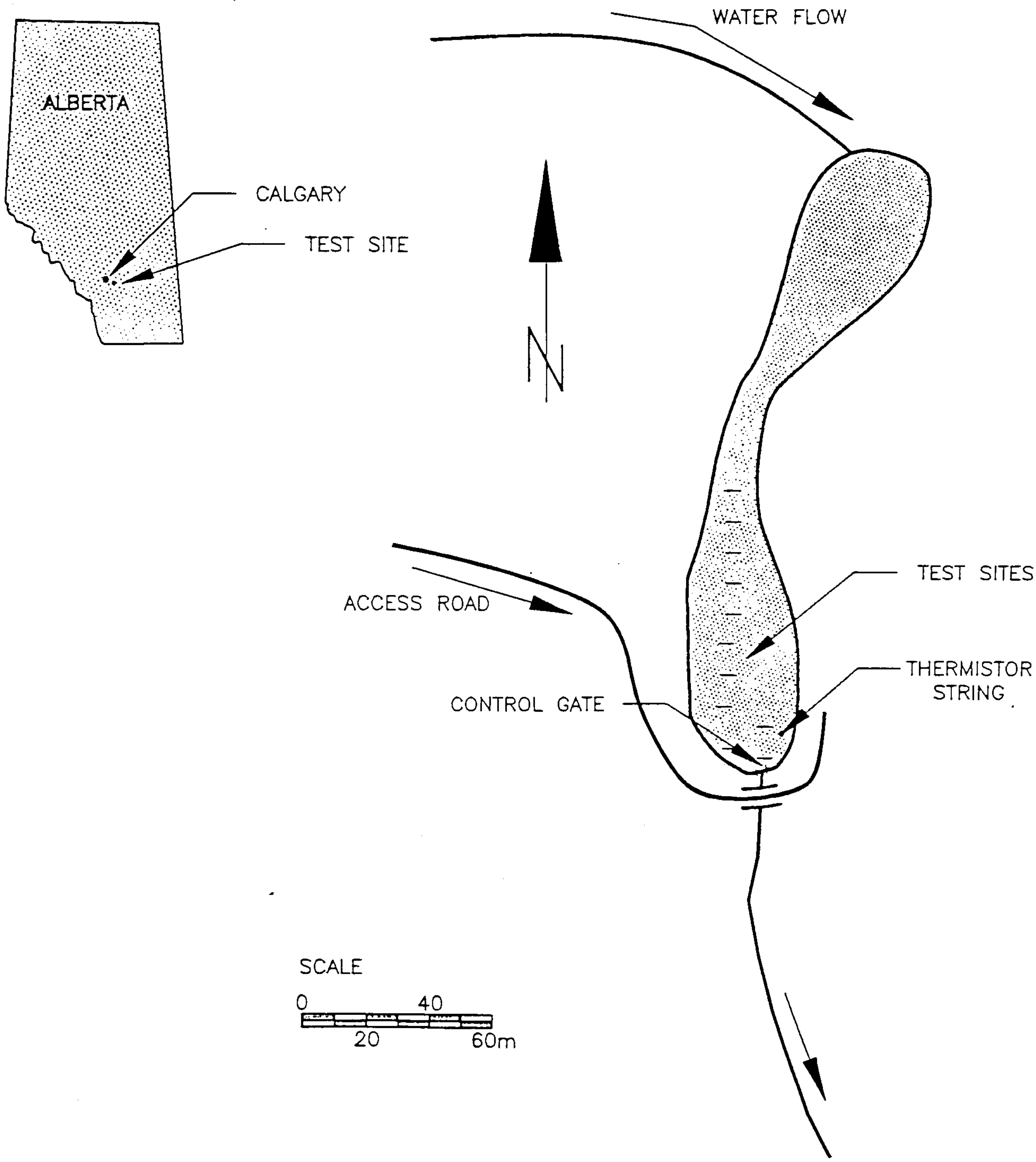

TEST SITE LOCATION

FIGURE 4.1

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5.0 FIELD OPERATION

The loading system used an air reservoir and electrically operated solenoid valves and is illustrated in Figure 5.1. This proved to be satisfactory as a field device. The air reservoir system allowed for the measurement of supplied air volume plus it limited the volume of air which would be supplied in the event of flatjack failure. The vertical slots in the ice were made using a chain saw mounted on rails. This allowed straight parallel and reproducible cuts to be made. The 1.5 x 0.2 m flatjack was then vertically mounted adjacent to the upper surface. The indentor was an aluminum plate 1.5 x 0.2 m by 0.076 m thick mounted adjacent to the flatjack. (See Figure 5.2)

The use of a compressed gas within the flatjack had the consequence that on the occurrence of a large ice flake, the expansion of the flatjack could impart considerable kinetic energy to the indentor. Calculations indicated that the range of an unrestrained indentor could be up to about 100 m. Thus the indentor must be restrained.

The tie-downs for the indentor used lengths of 11 mm dynamic climbing rope with a tensile strength of 3000 kg and a 5% elongation with a 80 kg load. Dynamic climbing rope was chosen because of its suitable tensile characteristics and the ease of handling in the field situation. The lengths of rope used were a compromise between the maximum force applied to the rope and the ice-anchors and the ability to limit the motion of the indentor after the failure of the ice.

The tie-downs were configured as indicated in Figure 5.2. The two shorter lines provided the main restraint and the single longer line provided for back-up. The configuration allowed for a straight pull on the restraint ropes. The restraint system worked well with no failures in any of the ropes or ice anchors. After a number of tests the rope had become rigid due to the plastic work and new sections of rope were used. The ice anchors were lengths of 50 mm diameter pipe driven into 50 mm diameter holes augured through the ice sheet. The holes were offset from the vertical by about 20°.

The design of the indentor was based on considerations of stiffness, strength, cost and weight. Initial calculations treating the indentor as a beam on an elastic foundation indicated that the depth of the beam should be about 1 m for it to be considered "stiff" relative to the foundation. This was obviously not practical and so the depth of the beam was designed on strength considerations with the maximum extreme fibre flexural stress being limited to less than yield. It was assumed that an ice segment equal to the width of the indentor would flake at the end of the beam leaving the indentor cantilevered. Because there was a desire to keep the weight of the beam (indentor) to less than about 90 kg for ease of handling 6061-T6 aluminum was chosen over steel. An aluminum indentor 1.5 m by 0.2 m by 76 mm thick was used for the tests. Two of these indentors were constructed. There was not any sign of structural damage to the indentor after the whole test program. Eye bolts were mounted on the indentors for use with the safety tie-downs.

Calculations of the flow of gas through orifices and along pipes indicated that piping and valves sized to 12.7 mm would provide for a flatjack filling time between 1 and 5 seconds. Solenoid valves available within the short lead time were rated at 10 MPa which was suitable for the current application.

The video system operated by IMD provided useful information on the time and spatial characteristics of the ice failure. The video system installation, operation or analysis was not within the scope of operation of Sandwell Inc. The I.M.D. personnel should be contacted regarding overall comments on the video system or for any analysis conducted on the video images.

Fluid pressures and supplied air volume was recorded on a data acquisition system supplied and operated by Canmar, a project partner. Data were recorded at 1000 Hz/channel with a 12 bit A/D resolution. No low pass filtering was incorporated in the data acquisition system. The sample rate was chosen based on experience gained by Sandwell and Canmar during similar field projects. Data were recorded by the computer for 30 (s) and the segment of interest selected for subsequent analysis.

Access to the lake was excellent via a 200 m ploughed road. The data acquisition system and support electronics were installed in a camper on the back of a 500 kg capacity pick-up truck. The accumulator, air compressor and 110V AC power generator were installed on a 3,000 kg capacity truck. The use of these two vehicles allowed for economic transport of equipment to and from the test site and, the easy and efficient movement from test site to test site. Both vehicles were driven onto the ice.

As is typical of fresh water lakes, there was extensive thermal cracking of the ice with cracks 1 mm to 15 mm wide spaced about 10 m to 15 m; the cracks had refrozen. Testing locations direction relative to the lake.

The general procedure was to map out the thermal cracks by removing the snow to find a suitable testing location. The snow cover was then removed by hand from the immediate vicinity of the test location and the slot(s) cut in the ice as required. The two vehicles were then driven to the new testing location and the various hydraulic and electrical connection made. The compressor was used to charge the accumulator for each test. Air pressures used were in the 9 - 10.5 MPa range. The accumulator had been designed during an earlier project (Masterson et al 1992) for a working pressure of 35 MPa. The high speed video was likewise set up adjacent to the test site. Once the various pre-test procedures had been conducted, personnel moved to a safe distance. The valve at the outlet of the accumulator was opened and then the data acquisition system started. An electrical switch box allowed an operator to charge the flatjacks. When the flaking event occurred the switch box was used to stop the loading and allow for the release of the internal flatjack pressure. The status of the control switch was monitored with the data acquisition system.

While restrained by the ice, the flatjacks were able to sustain 9.5 MPa internal pressure. However, once the ice failed and the flatjacks were allowed to expand, failure of the seam weld of the flatjack often occurred. With the indentor in place, failure of the flatjack was less common than with the bare flatjack. A review of the video recordings and an inspection of the failed flatjacks suggested that with the bare flatjack, ice adjacent to one end of the flatjack would flake. This would then allow the flatjack to expand in that location with only a small reduction in internal pressure. With the indentor in place the expansion occurred over the whole or majority of the flatjack allowing for a larger reduction in internal pressure and subsequent lower probability of flatjack failure.

When failure of the flatjack did occur, on many occasions the pressure transducer attached to the flatjack was destroyed. A total of six transducers were destroyed in the 16 tests conducted. The pressure rating of the devices were either 35 MPa or 70 MPa and so it is unlikely that the devices were overpressured. A more likely explanation is that the rapid pressure unloading caused by the flatjack failure resulted in a stress wave travelling along the connecting piping resulting in shock failure of the transducer. In future test programs measures should be adopted to reduce the liklihood of destroying the relatively expensive pressure transducers.

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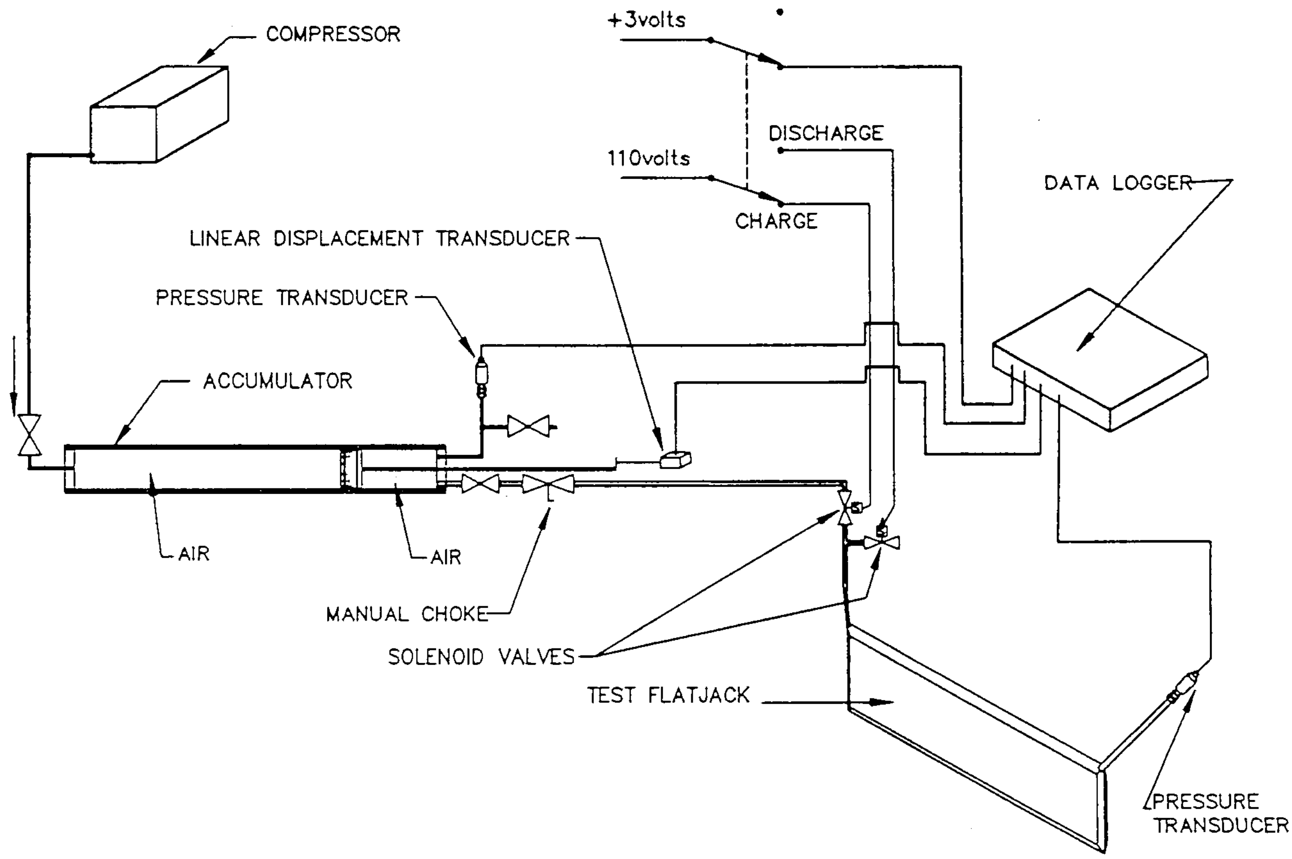

GAS LOADING SYSTEM
FIGURE 5.1

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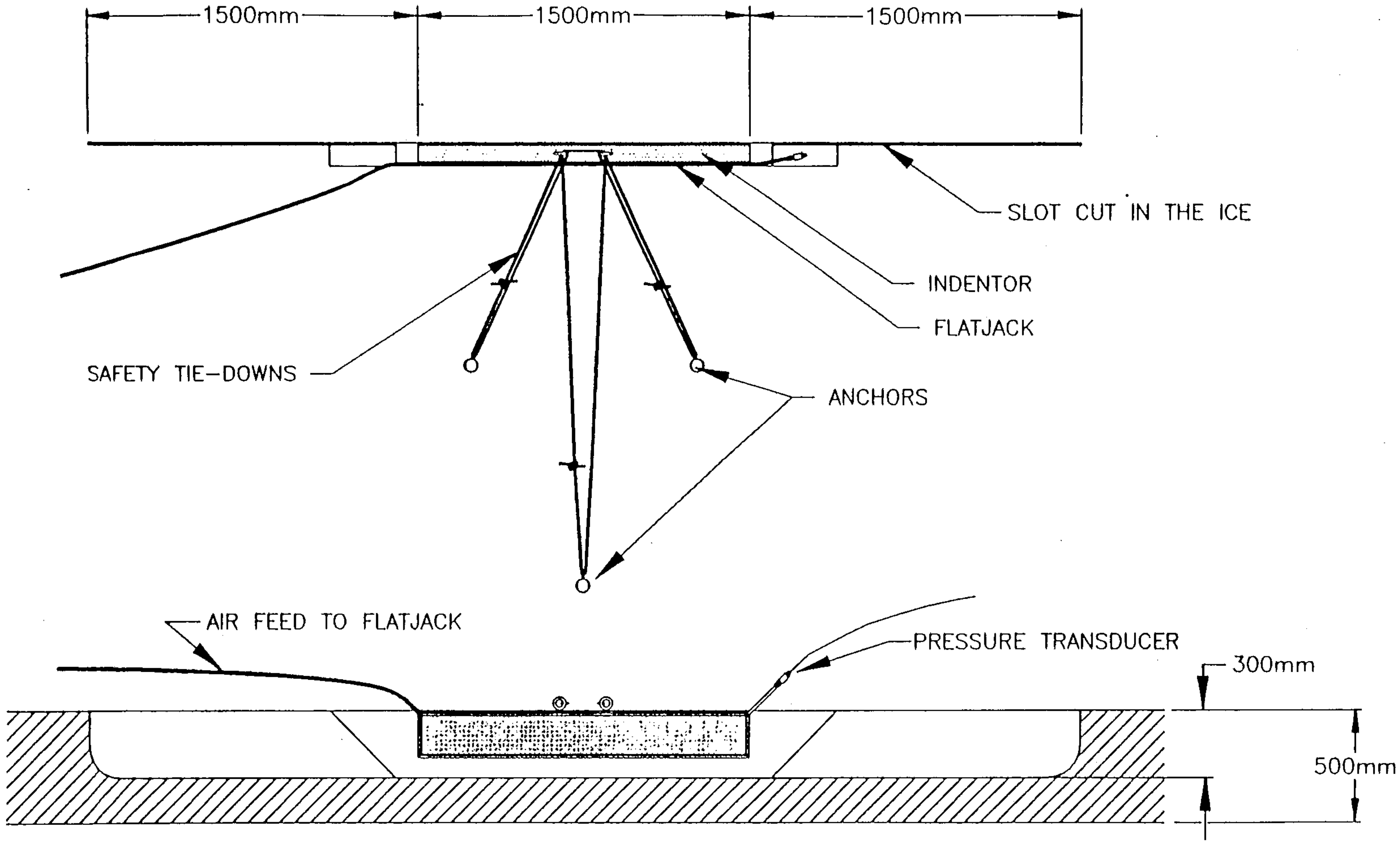

FLATJACK AND INDENTOR 200mm X 1500mm

TEST LAYOUT
FIGURE 5.2

6.0 ENVIRONMENTAL CONDITIONS

The weather was excellent for conducting ice tests with air temperatures in the -10 to -20° C range, except for the 15th of February when a Chinook caused +8° C temperatures (see Figure 6.1). The mean monthly temperature for Calgary during February is -7.3° C and the tests were conducted during a colder than normal period. The data from the installed thermistor string are given in Figure 6.2. Note that at the thermistor string location, there was an undisturbed snow layer approximately 0.1 m thick. The thermistor string was mounted in a 50 mm diameter hole augered through the ice which was then packed with ice chips to reduce the freeze-in and thermal stabilization time.

FIGURE 6.1 : AIR TEMPERATURE FEBRUARY 1994, STRATHMORE

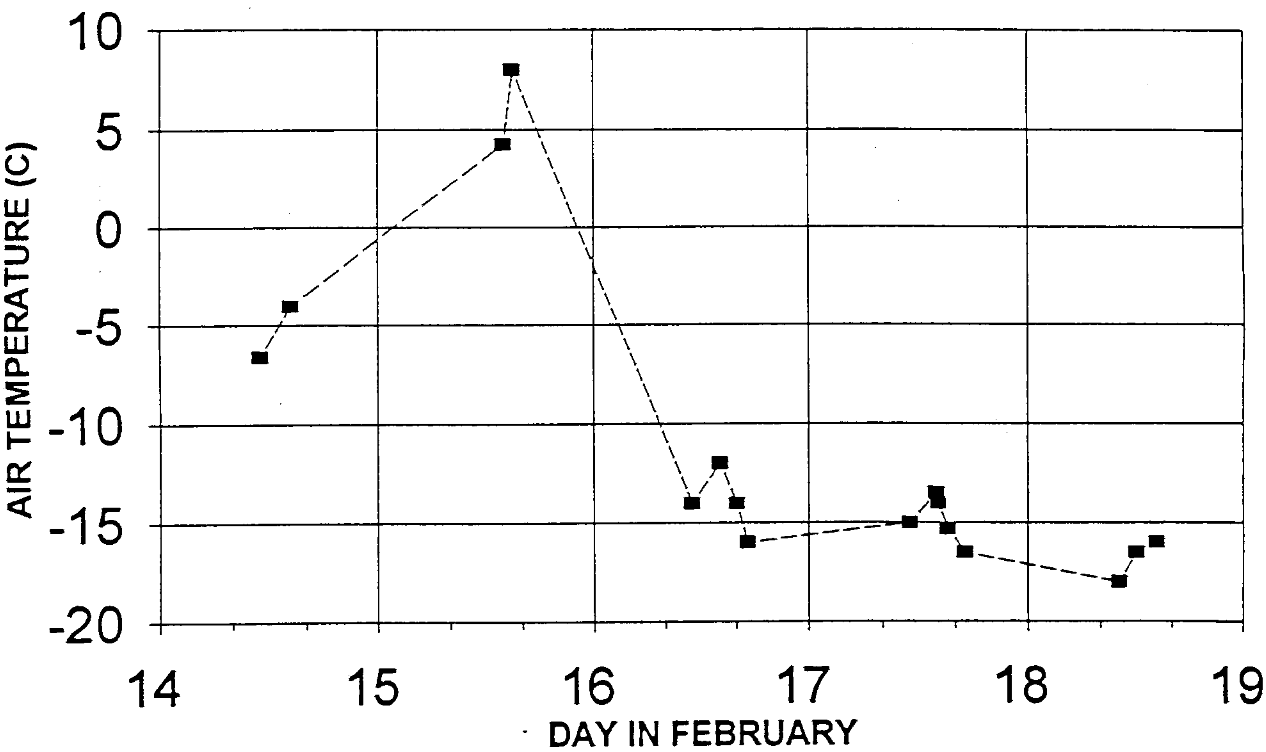

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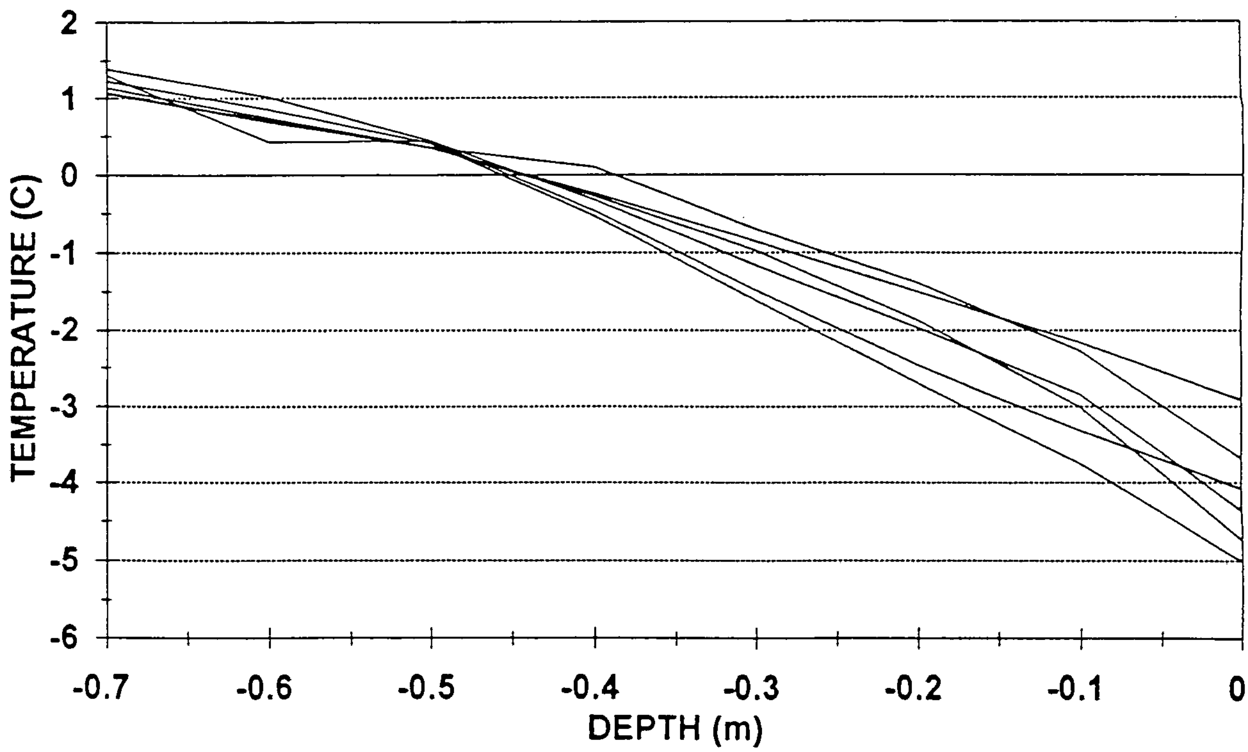
FIGURE 6.2 : ICE TEMPERATURE RANGE
FEBRUARY 1994, STRATHMORE



7.0 TEST MATRIX

The test matrix is given in Table 7.1 and sketches for the various tests provided in Appendix B.

At the beginning of the field test program a major aim was to investigate the affect of an indentor plate on the indentation pressures. Therefore tests with and without indentor plates were generally alternated in order to reduce any systematic error associated with differing ice conditions during the test period. However, during the test period it became apparent that the reduction is flatjack pressure due to the presence of the indentor plate was relatively small. In addition the consistency in the collected pressure data were good. The effect of testing damaged ice was therefore investigated during the last few tests.

A brief description of the tests is provided below:

7.1 Test 1

First test using an indentor. Maximum flatjack pressure of 5.53 MPa achieved in 2.22 (s). Flaking of ice occurred adjacent to indentor. Cracking of ice adjacent to flatjack but not flaking. Manual flow choke set to limit the loading rate. The motion of indentor after the ice flaking indicated that the indentor tie-downs are important.

7.2 Test 2

First test using a bare flatjack. The pressure reached 4.38 MPa causing extensive cracking but no flaking. The flatjack came out of the slot resulting in flatjack failure. Loading time was 0.53 (s). Because of the low stiffness of the gas within the flatjack the surface flaking events prior to general flaking failure of the ice face are indicated by pressure transients rather than by large pressure drops.

7.3 Test 3

Another test using the rigid indentor plate. Extensive flaking and cracking adjacent to indentor, cracking only adjacent to flatjack. To reduce the possibility of the flatjack coming out of the ice, friction tape was applied to both sides of the flatjack. Friction tape was used in all subsequent tests. Air temperature +4.3° C at test time. The crack pattern after the test is shown in Figure 6.

7.4 Test 4

A bare flatjack test, air temperature had reached +8.0° C by test time. The flatjack reached maximum pressure in approximately 3 (s) causing extensive cracking and uplifting of ice adjacent to flatjack. No flaking occurred and air supply switch maintained at open. At about 20 (s) into the event flaking occurred resulting in the failure of the flatjack.

7.5 Test 5

An test conducted using an air temperature -14.0° C. IMD personnel now on site to record the ice failure using monochrome 1000 frame/second video camera system. Approximately 2.8 (s) loading time with flaking adjacent to indentor.

7.6 Test 6

Test conducting with bare flatjack. However, used the two indentor plates across the flatjack to act as inertial ballast. Loading time 1.9 (s) prior to final failure. Two or three flaking events were observed in video.

7.7 Test 7

An indentor test with flaking adjacent to indentor. No failure occurred in the flatjack.

7.8 Test 8

A test conducted using an indentor, flaking occurred at 5.5 MPa. Test conducted late in the day at 5:45 PM and the ambient light levels were only sufficient to allow high speed video system to record at 500 or 250 frames/second even with illumination.

7.9 Test 9

For all subsequent tests the manual choke at the outlet of the accumulator was set fully open to increase the loading rate. Test conducted using an indentor with pressure reaching 8.43 MPa in 2.33 (s) with flaking adjacent to indentor.

7.10 Test 10

Bare flatjack test. Reached the maximum supply pressure with cracking but no flaking. The supply pressure was removed after 3 - 4 (s) rather than allowing the ice to creep to failure.

7.11 Test 11

Second loading with bare flatjack using same set-up as Test 10. No flaking occurred but some additional cracking. Again removed pressure after about 4 (s). The flatjack was removed for later use.

7.12 Test 12

Increased the accumulator pressure to approximately 10.8 MPa. Bare flatjack test reached 9.5 MPa in about 1 (s). The ice at one end of the flatjack flaked allowing the flatjack to expand and fail.

7.13 Test 13

Because of the good consistency between bare flatjack tests and because the reduction in flatjack pressure at failure due to the presence of the indentor was only about 20 - 30%, it was decided to investigate damaging the ice prior to a test with an indentor. In this test a series of vertical saw cuts (5 mm wide, 10 mm deep, 100 mm spacing) were made in the ice adjacent to the indentor. Flaking flatjack pressure of 6.8 MPa in 0.84 (s) reached so no large reduction in pressures due to the presence of the saw cuts.

7.14 Test 14

A continuation of the damaged ice investigation. Used the ice previously loaded during Test 2, to conduct this test using an indentor. The results from Tests 10 and 11 showed that re-loading with the flatjack in exactly the same location resulted in no significant change in maximum pressures, indicating that, while damaged, the ice was not "failed". As illustrated cracks emanate from near the end of the flatjack or indentor. For this test the centre of the indentor was arranged to be at these end cracks. The indentor and flatjack for this test were parallel to the slot for Test 2. Maximum flatjack pressure of 2.08 MPa only reached in this test!

7.15 Test 15

An indentor test using the predamaged ice from Test 12 location. Similar geometrical arrangement as for Test 14. Only reached 1.54 MPa flatjack pressure before flaking occurred.

7.16 Test 16

A larger 1.5 x 0.5 m flatjack used for full thickness test with bare flatjack. Reached 6.24 MPa pressure and flaking allowed flatjack to expand and fail at both ends. Flatjack landed about 2 m away from test.

TABLE 7.1: TEST MATRIX				
Test	**Date**	**Time**	**Configuration**	**Comments**
1	14 Feb.	11:00	1.5 x 0.2m + Indentor	Indentor Test
2	14 Feb.	14:43	1.3 x 0.2m Flatjack	Bare Flatjack
3	15 Feb.	14:00	1.5 x 0.2m + Indentor	Indentor
4	15 Feb.	13:00	1.5 x 0.2m Flatjack	Bare Flatjack
5	16 Feb.	11:15	1.5 x 0.2m + indentor	Indentor Test
6	16 Feb.	14:30	1.5 x 0.2m Flatjack	Bare Flatjack
7	16 Feb.	16:10	1.5 x 0.2m + Indentor	Indentor Test
8	16 Feb.	17:45	1.5 x 0.2m + Indentor	Indentor Test
9	17 Feb.	11:15	1.5 x 0.2m + Indentor	Indentor Test
10	17 Feb.	14:00	1.5 x 0.2m Flatjack	Bare Flatjack
11	17 Feb.	14:30	1.5 x 0.2m Flatjack	Same location as 10
12	17 Feb.	15:40	1.5 x 0.2m Flatjack	Bare Flatjack
13	17 Feb.	17:30	1.5 x 0.2m + Indentor	Indentor Test Notched Face
14	18 Feb.	10:30	1.5 x 0.2m + Indentor	Damaged Ice Test Same location as 2
15	18 Feb.	12:15	1.5 x 0.2 m + Indentor	Damaged Ice Test Same location as 12
16	18 Feb.	14:50	1.5 x 0.5m Flatjack	Full Thickness Test

8.0 DATA REDUCTION

The data reduction was performed using the Quatro-Pro™ spreadsheet program. The field data were stored as ASCII files in engineering units. Each file contained the extracted portion of one signal, for example, trigger or displacement. The various files for a particular test were then input into the spreadsheet. The trigger signal was used to identify when the switch was closed and used as the zero for the time axis.

Various "glitches" in the data were identified and removed. For example when the switch was open or closed it usually caused a transient which was recorded on other channels. This transient was removed from the data. Also, for the cases when a pressure transducer was destroyed in a test, the data is obviously invalid and so that portion of the data was removed. For Tests 1 and 2 the ground reference for the differential input to the data-acquisition system was missing. This caused additional transients in the data which were identified and removed. For some tests the extracted files were too long to be able to be imported in the spreadsheet. A special Quatro-Pro Macro was written to allow for data filtering and decimation. The various data were baseline corrected and reformatted and used to generate time series data plots. A second special Quatro-Pro Macro was written to allow selected sections of the spreadsheet data to be output in comma-delimited ASCII format. This latter format was chosen to allow for the easy importing into various spreadsheets or easy import into a mainframe computer system.

Data plots for tests 1 through 16 are presented in Appendix A. The ASCII output files are provided in DOS format along with a Readme file for explanation.

8.1 Indentor Pressure

The mean indentor pressure was estimated from the flatjack pressure. Tests and experience with flatjacks by Sandwell has indicated that the overall efficiency of load transfer of a flatjack can be represented by an edge effect. Calibration data indicated that the effective contact size of the flatjack is approximately 15 mm per edge less than the nominal flatjack size. Thus for the 1.5 x 0.2 m flatjacks used in this test program and the 1.5 x 0.2 m indentors used, the mean indentor pressure was taken to be 0.833 times the flatjack pressure. Maximum test pressures are provided in Table 8.1

Visual observations of the ice failure indicated that in all cases where an indentor was installed, failure occurred on the indentor side rather than the flatjack side. Thus it is appropriate to express the peak pressure over the indentor rather than the flatjack. This visual observation alone indicates that the existence of the indentor allows ice failure at lower loads. One of the reasons for installing an indentor on one side rather than both sides was to allow such observations.

8.2 Ice Displacements

Budgeting considerations and the intention of the project to demonstrate the overall techniques, no on-ice displacement transducers were deployed. Some initial assessment on using the flatjacks pressure supply pressure and reservoir displacements to calculate flatjack expansions have been conducted.

We have assumed that the compressed air can be treated as a perfect gas. For a perfect gas the internal energy is a function of the temperature only. Thus, for expansion with no work done against the surroundings, the usual isothermal relationship hold between pressure p and Volume V.

$$p_1 V_1 = p_2 V_2 \qquad 8.1$$

However, when work is being done against the surroundings and there is no heat transfer, the adiabatic conditions relationship is given by:

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} \qquad 8.2$$

Where the exponent γ is the ratio of the specific heats and for air = 1.40.

The expansion of the flatjack may be approximated by two stages. The first stage is pressure rise in the pre-expanded flatjack using Equation 8.1. The second stage would be an expansion as the ice restraining wall expands, a process described by Equation 8.2.

For the initial analysis we assumed that the whole expansion would be described by Equation 8.1. This has the result that the calculated flatjack expansion over-estimates the actual ice displacement. Examples of the analysis conducted for Tests 1 and 2 are given in Appendix A.

To obtain accurate ice displacement measurements from the data, further analysis would be required. In any future field programs it is recommended that on-ice displacement transducers be installed to directly measure the ice movement.

8.3 Flaking

An inspection of the flatjack pressure time series data (Appendix A) revealed the presence of the large scale ice cracking. Because of the low stiffness of the air within the flatjack as compared with oil for example, the presence of the cracks is detected mainly by pressure transients rather than large pressure drops. The pressure at which these cracks occurred are listed in Table 8.1.

A histogram of the pressures at which cracks were detected, including the final failure, are given in Figure 8.1. Note that for the tests using a rigid indentor the governing pressures are those applied by the indentor to the ice. For tests using the bare flatjacks, the governing pressures are the effective pressures applied to the ice by the flatjack. The mean and standard deviation for the pressure for the bare flatjack tests is 7.82 ± 0.71 MPa and for the indentor tests 5.45 ± 1.15 MPa. As well as providing lower pressures the standard deviation for the indentor tests is larger.

TABLE 8.1: TEST DATA						
Test	Ice Temperature (° C)	Maximum Flatjack Pressure (MPa)	Cracks Detected At Pressure (MPa)	Indentor Pressure (MPa)	Loading Time (s)	Loading Rate (MPa/s)
1	-5.6	5.53		4.61	2.22	2.49
2	-4.1	4.38			0.53	8.26
3	-0.8	6.82		5.68	4.21	1.62
4	-0.5	8.01	7.16, 7.5, 8.0		2.19	3.66
5	-8.0	6.81		5.67	2.78	2.45
6	-7.0	8.32	6.57, 7.08, 7.42		1.89	4.40
7	-8.0	7.56	7.07	6.30	1.81	4.18
8	-8.0	4.95	4.0	4.12	1.26	3.93
9	-9.2	8.43	7.95, 8.35	7.02	2.33	3.62
10	-10.0	8.47	7.07, 8.37		1.33	6.37
11	-10.0	8.98			2.33	3.79
12	-9.3	8.71			0.83	10.49
13	-9.8	6.18	4.93	5.15	0.84	7.36
14	-14.0	2.08		1.73	0.26	8.00
15	-13.0	1.54		1.38	0.27	5.70
16	-13.6	6.24			1.56	4.00

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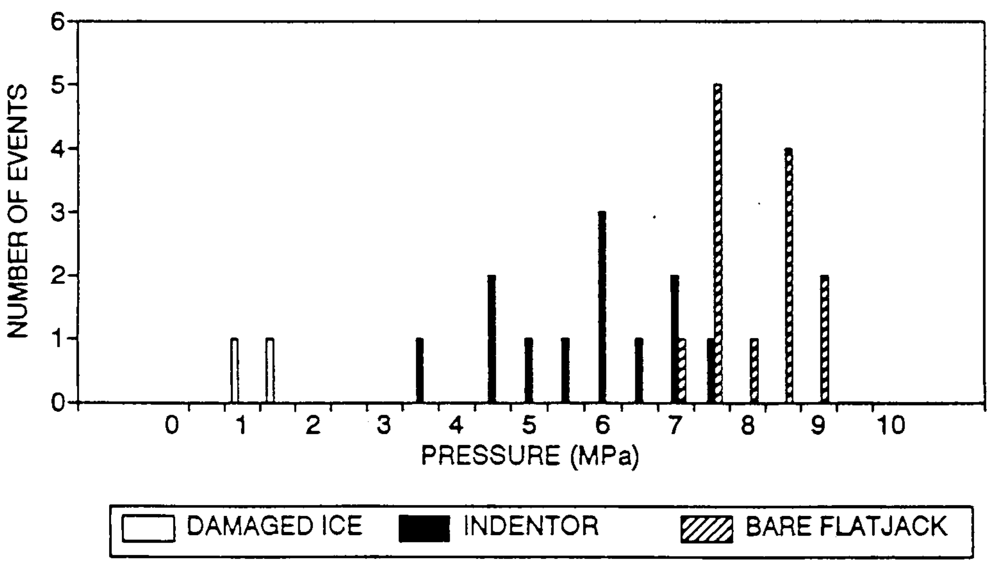
FIGURE 8.1 : HISTOGRAM OF PRESSURE
AT WHICH CRACKS DETECTED



9.0 DATA INTERPRETATION

The mean flatjack pressure for tests without an indentor excluding Tests 2 and 16 was 8.50 MPa. Test 2 was excluded because the flatjack came out of the slot at a relatively low pressure and Test 16 was a full ice thickness test. The mean indentor pressure for the indentor tests excluding the damaged ice location Tests 14 and 15 was 5.50 MPa. Thus the presence of the indentor reduced the maximum pressure to 65% of the bare flatjack test data. The mean indentor pressure for the damaged ice locations is 1.54 MPa. The damaged ice location presented an indentation pressure approximately 27% of the undamaged indentor tests. The pressures observed in the damaged ice locations are in line with large scale pressures observed from offshore structures rather than laboratory scale uniaxial or nonaxial strength values.

The full thickness flatjack test with a contact area 2.5 times the other bare flatjack tests had a pressure of 6.2 MPa which is less than the other bare flatjack tests. The reduction in pressure could be due to an increase in flatjack area or a difference in the boundary conditions. In the 1993 tests [Masterson et al, 1993] it was found that the greater the number of free edge the lower was the maximum pressure. These data are summarized in Table 9.1.

If we use the following to characterize the ice strain rate $\dot{\varepsilon}$:

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} \ (s^{-1})$$

$$\dot{\sigma} = \textit{Loading Rate } (MPa/s)$$

$$E = \textit{Youngs modulus } (MPa)$$

then data from Table 8.1 and a Youngs modulus of 4,300 MPa (Cole 1987) provides a typical strain rate of about 10^{-3} s^{-1}. Peak uniaxial ice strength, often occur near a strain rate of 10^{-3} s^{-1}.

9.1 Damaged Ice Tests

Two tests were conducted using bare flatjacks at the same location (Tests 10 and 11). The first loading (Test 10) did not result in flaking even though cracking has occurred and the applied pressure was limited by the supply pressure. The second loading (Test 11) to essentially the same pressure also did not result in flaking or any large amount of new cracks. Thus although the ice was "damaged" the fact that the cracks were pre-aligned appears to be significant. In Test 13 the loading face was damaged by the series of chain saw cuts. They however, did not appear to provide for significantly lower pressures. Therefore for Test 14 using the pre-damaged ice from Test 2 the indentor plate was mounted so that the cracks occurred near the end of the flatjacks during Test 2 were on the indentor centre-line of Test 14. The same geometrical arrangement was employed during Test 15. Significant reduction in pressure was found in Tests 14 and 15.

A study was conducted by Timco (1987) in which indentation tests were conducted on ice sheets which had arrays of chain saw cuts. The chain saw cuts were to simulate ice damage by the presence of cracks. In that study the non-dimensional damage parameter D was used and was defined by:

$$D = n\left(\frac{L}{2}\right)^2 \qquad (9.1)$$

$$\text{Where } n = \text{Number of cracks per } m^2$$

$$L = \text{Cracks length } (m)$$

Timco (1987) found that large reduction in peak and mean indentation pressures occurred when the damage parameter was in the range $0.1 \leq D \leq 1$.

With this definition of damage proportional to L^2, a relatively few long cracks will contribute more damage than the same number of shorter cracks. Thus the longer cracks are more important.

For Tests 14 and 15 the peak pressures were about 25% of the pressures on undamaged ice. We assume that, for order-of-magnitude estimates the damage parameters for these two tests was unity and that the representative crack length was 2.0 m. Thus, using Equation 9.1, the crack density n is only 1 crack per square meter. This low crack density is certainly defensible for these two tests.

For the situation of Test 13 an estimate of the damage parameter close to the indentor face is $D \approx 10^{-3}$. Timco (1987) found that there were very little reduction in pressure for $D \leq 10^{-2}$, thus our observations for Test 13 are understandable.

TABLE 9.1: DATA SUMMARY		
	Mean Pressure (MPa)	**Number of Tests**
Bare flatjack maximum pressure	8.5	5
Undamaged ice with indentor	5.5	7
Damaged ice with indentor	1.5	2
Full thickness, flatjack	6.2	1

10.0 COMPARISONS WITH PREVIOUS MEASUREMENTS

In 1993 a series of tests were conducted in the first year sea-ice at Resolute Bay, N.W.T., Canada using flatjacks (Masterson et al, 1994). The geometrical arrangement was similar to that used in the current tests. The data were found to follow the regression model of Timco and Frederking, (1991) with corrections due to the number of free edges. A significant finding was that the collected contact pressure data did not show any dependence on contact area.

In a study by Gold (1991) on indentation tests, a trend of decreasing contact pressure with increasing indentor width was found. There thus appeared to be two incompatible trends, pressures a function of area/width, pressures independent of width. Some analysis has been conducted to investigate this aspect.

The major source of interaction data for the large interaction widths is from the APOA-93 tests reported by Taylor [1981] and are shown in Figure 10.1. A review of the data set indicated that, in general, lower penetration rates were associated with wider indentors. An adjustment for strain rate or stress rate effects has been applied and is given by:

$$p = P_{ref} \left[\frac{W}{\dot{\delta}} \right]^{0.22} \qquad (10.1)$$

Where W = *Indentor Width*

$\dot{\delta}$ = *Penetration Rate*

P_{ref} = *Pressure at Reference Conditions*

The value of the exponent in Equation 10.1 is that found by Timco and Frederking (1991).

The adjusted data are shown in Figure 10.2. There does not now appear to be any systematic trend of pressure with indentor width. The data were also plotted as a function of ice thickness and ice type/crystallographic orientation in Figure 10.3. The thicker ice tended to have a vertical orientation of the "C" axis whereas the thinner natural ice and the "pond" ice had horizontally oriented "C" axis. There is a significantly lower contact pressure for the vertical axis ice than the horizontal axis. It is difficult to separate an ice thickness effect from an ice crystallography effect.

In conclusion both the Eagle Lake tests conducted on fresh water ice using indentors and the tests at Resolute Bay conducted on first-year sea ice using bare flatjacks indicate that contact pressures were independent of contact width.

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FIGURE 10.1 : RAW DATA
EAGLE LAKE 1973

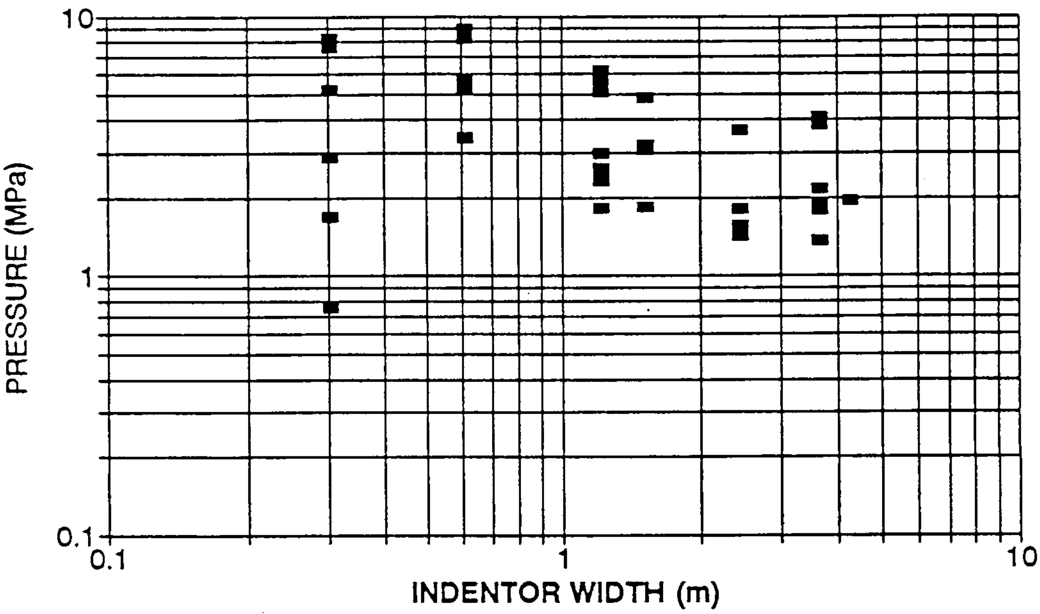

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FIGURE 10.2 : ADJUSTED DATA
EAGLE LAKE 1973

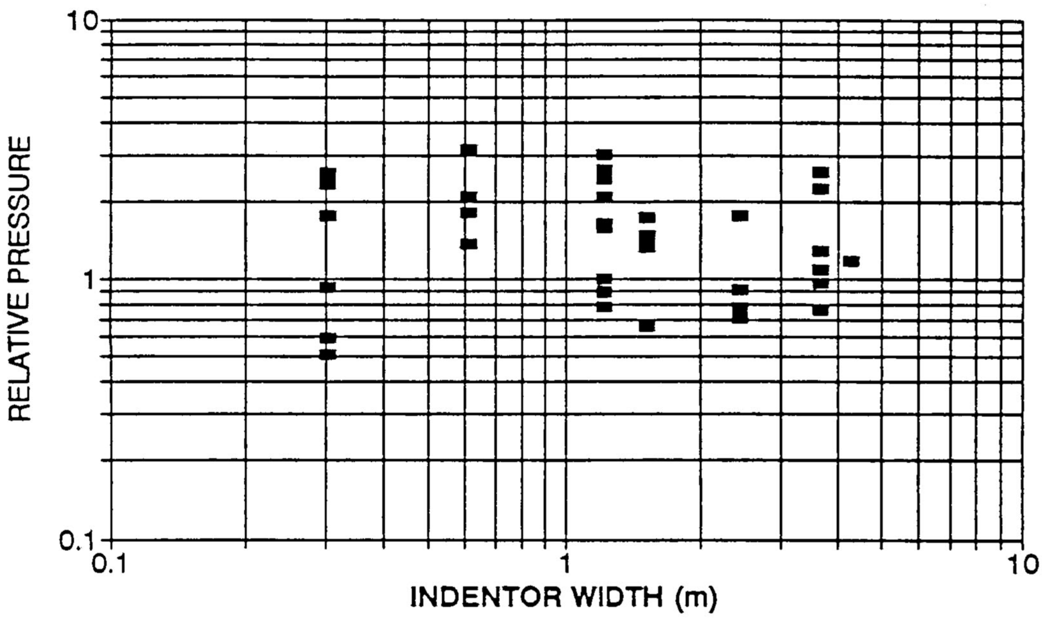

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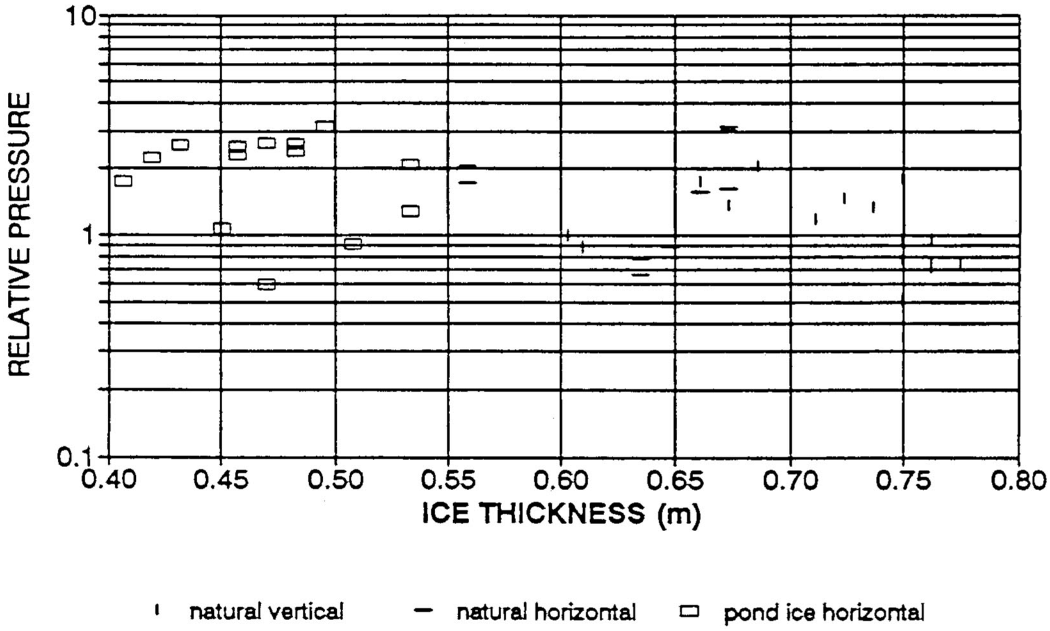
FIGURE 10.3 : ADJUSTED DATA
AS A FUNCTION OF ICE THICKNESS



11.0 CONCLUSIONS

The presence of the 1.5 x 0.2 m indentation plate resulted in failure pressures approximately 65% of pressures obtained with flatjacks. These indentation pressures were 5.5 MPa and higher than the 1 - 2 MPa experienced during ice interaction on offshore structures. By testing predamaged sections of ice, pressures of approximately 1.5 MPa were obtained.

The primary aims of the test program was met in that the presence of the rigid indentor was investigated. It was found however, that the reduction in interaction pressure was smaller than anticipated. It thus appeared that the stress concentrations caused by the indentation plate may not be a sufficient mechanism to allow for pressures in the 1 - 2 MPa range. The observation that pre-damaged ice leads to much lower pressures is not completely unexpected. However, the technique used here does appear to replicate some important aspects of ice-structure or ice-ship interaction with real-world ice sheets rather than idiolized laboratory situations.

The second aim of the test program was also met in that the use of air as the active medium was investigated. Compared with using a hydraulic fluid, the use of air provided for a cleaner work-site. The additional dangers due to the kinetic energy of the indentors etc. appear to be manageable. The experience gained from the current program will be valuable in the planning and execution of future similar programs.

12.0 RECOMMENDATIONS

The techniques used in this project to investigate interaction pressures were successful. They furthermore can be adapted and expanded for the further investigation of damage effects in ice. Systematic tests including different degrees of damage could be conducted at a scale larger than attainable in a laboratory. One approach would be to pre-damage the ice using bare flatjacks. The quantity of damage could be varied by controlling the pressure within the flatjack and the duration of the loading. A second part of the test would then be conducted by using an indentor plate along with a flatjack. The location of the indentor plate relative to the first flatjack could then be systematically varied over a series of tests. The output of such a test series would be quantification of the relationship between the damage and applied loading. The second output would be the quantification of the interaction pressures sustained by the damaged ice. This is illustrated in Figure 12.1.

During the pre-loading phase there will be micro-cracking in the area of contact and macro-cracking from the region near to the end of the flatjack. At this point it is difficult to say which ultimately dominate or determine the lower interaction pressure. By varying the location of the indentor in the second part of the test, this aspect can be investigated.

The advantage of performing the tests at field scale is that the geometry appropriate for ice/structure or ship/structure interaction can be achieved. The size of the ice sheet can be large enough so that the only significant boundary effects or conditions would occur at the indentation face. The required section of the predamaged or post damaged ice will be harvested for laboratory investigation and/or thin section analysis.

It is furthermore recommended that such a test program could be conducted on fresh water ice at a southern Canadian location more economically than in the Arctic. More project funds could be allocated to project execution rather than to project logistics. The collected data would still be of great value in the understanding of the processes at work.

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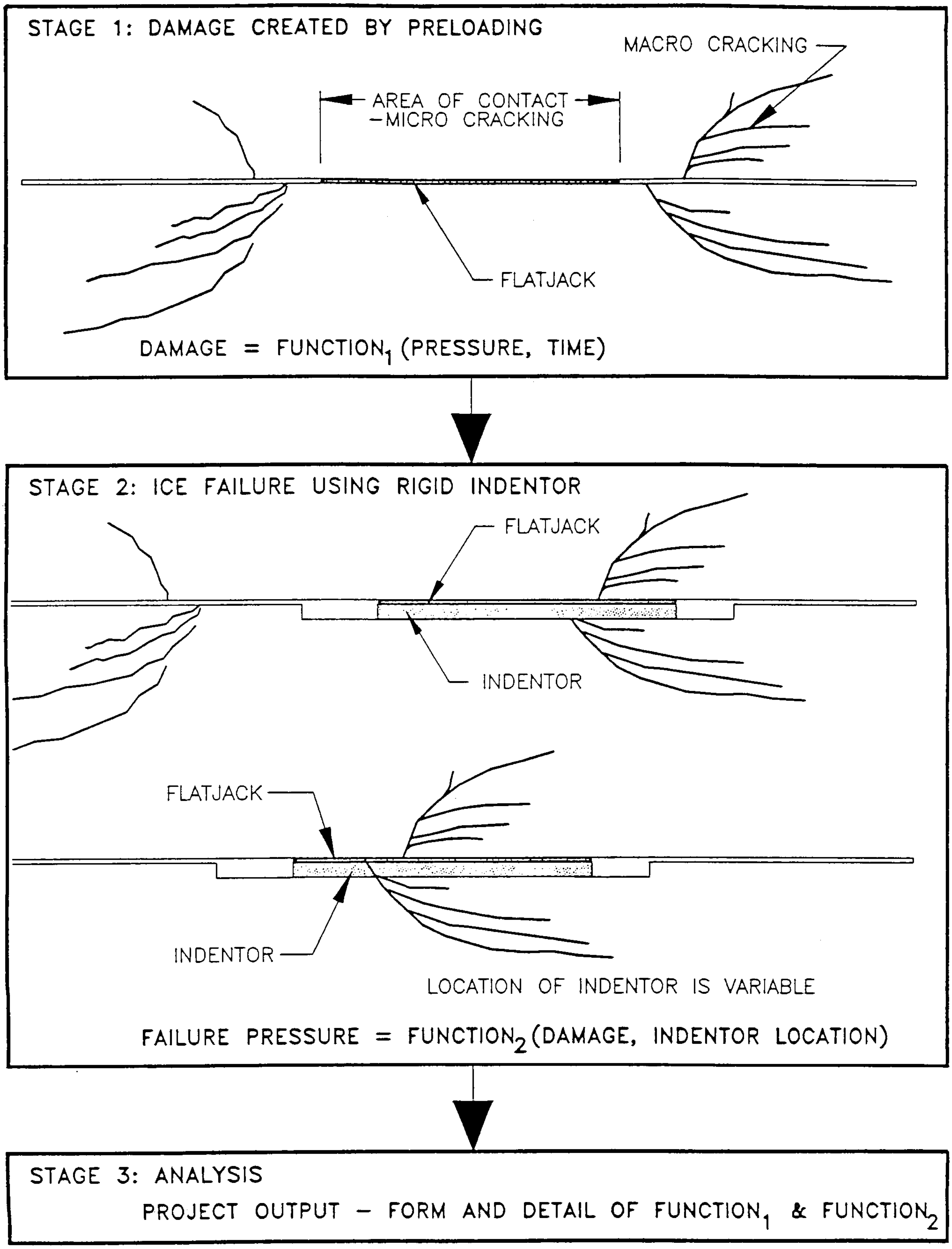

PROPOSED TEST SERIES
FIGURE 12.1

3281C017.DWG

13.0 ACKNOWLEDGEMENTS

We wish to thank all the members of the team for their excellent work during the project. We also thank Dr. Stephen Jones of the Institute of Marine Dynamics for his help and advice in the project and for arranging the funding. We thank the INSROP organization and the Canadian National Energy Board for funding. Canadian Marine Drilling (CANMAR) is also thanked for their valuable in-kind support for the project. We thank Mr. Brown and Mr. Minty for allowing the tests to be conducted on their property.

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APPENDIX A - Data Plots for Tests 1 : 16

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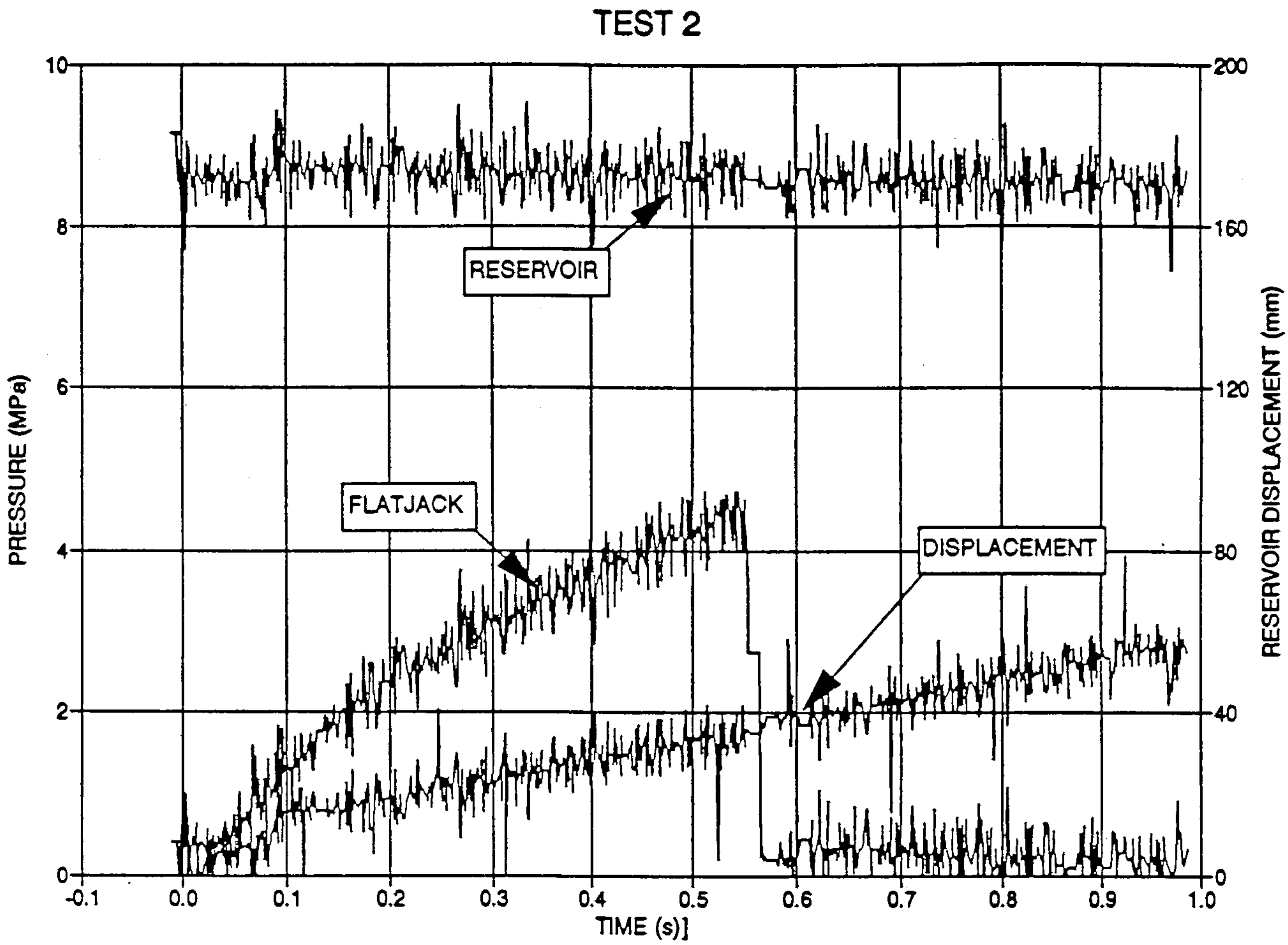
TEST 2
RESERVOIR
FLATJACK
DISPLACEMENT
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)]
10
8
6
4
2
0
200
160
120
80
40
0
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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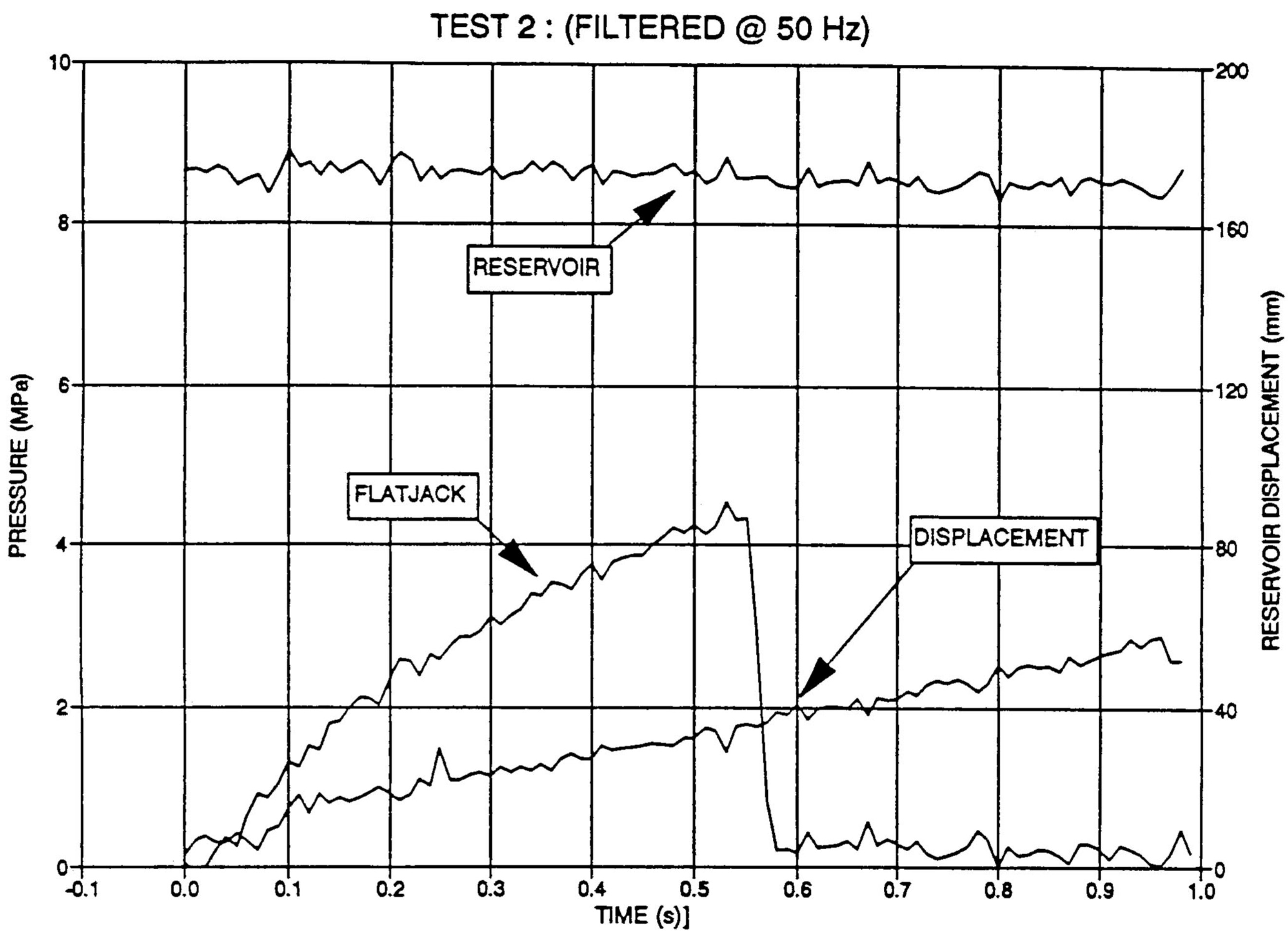

TEST 2 : (FILTERED @ 50 Hz)
10
8
6
4
2
0
PRESSURE (MPa)
200
160
120
80
40
0
RESERVOIR DISPLACEMENT (mm)
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TIME (s)]
RESERVOIR
FLATJACK
DISPLACEMENT

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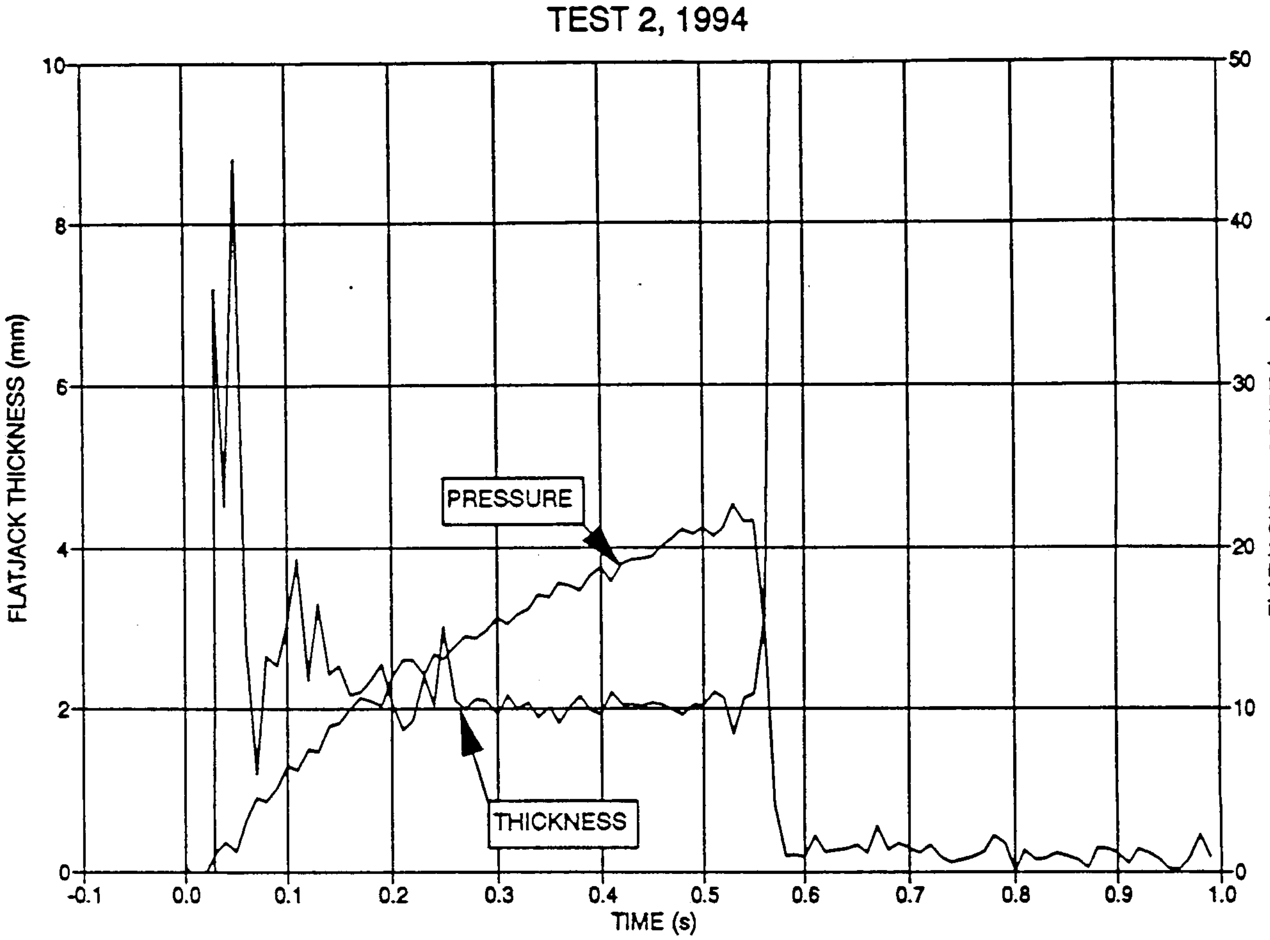
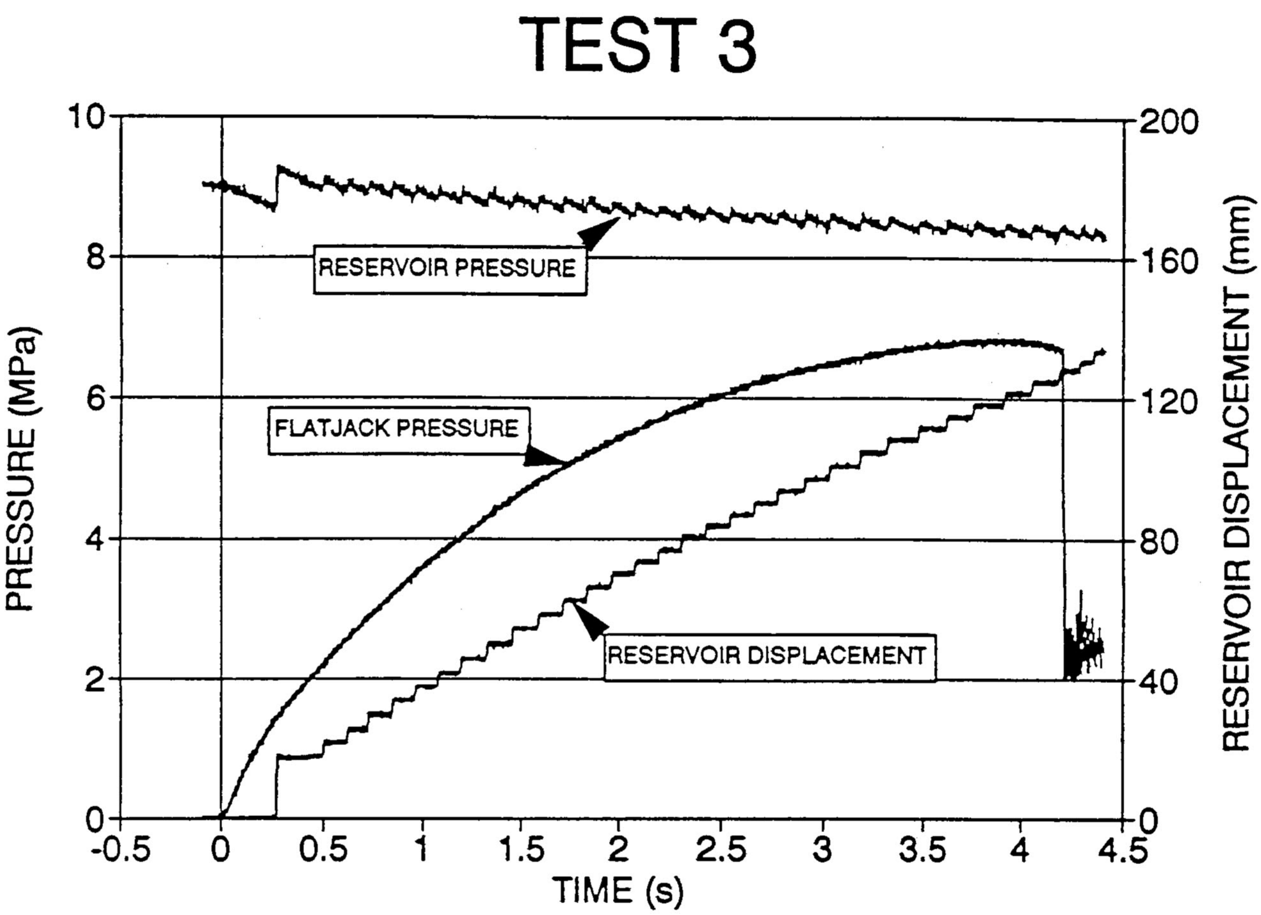


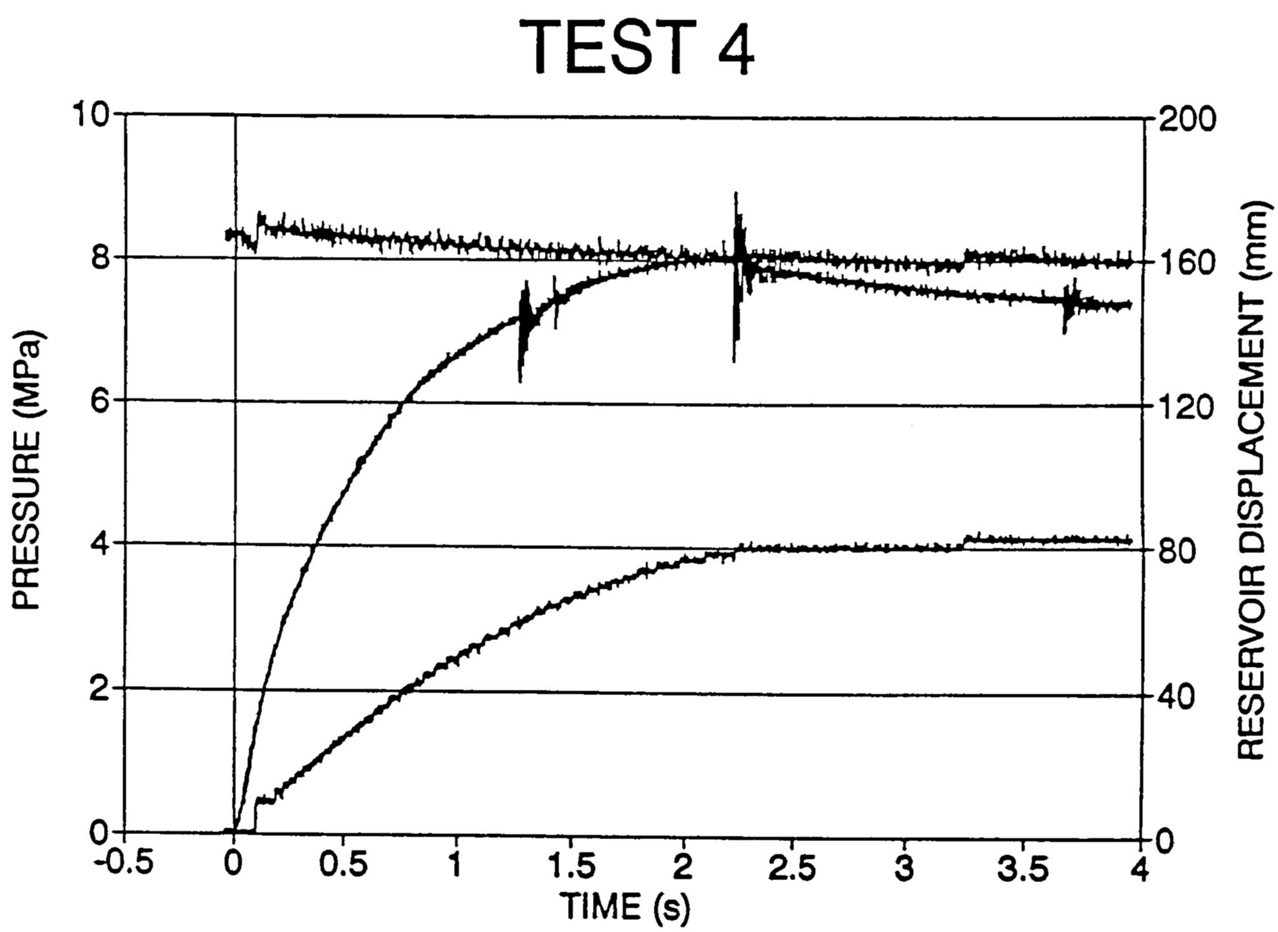
TEST 2, 1994
FLATJACK THICKNESS (mm)
FLATJACK PRESSURE (mm)
TIME (s)
PRESSURE
THICKNESS
0
2
4
6
8
10
10
20
30
40
50
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Sandwell

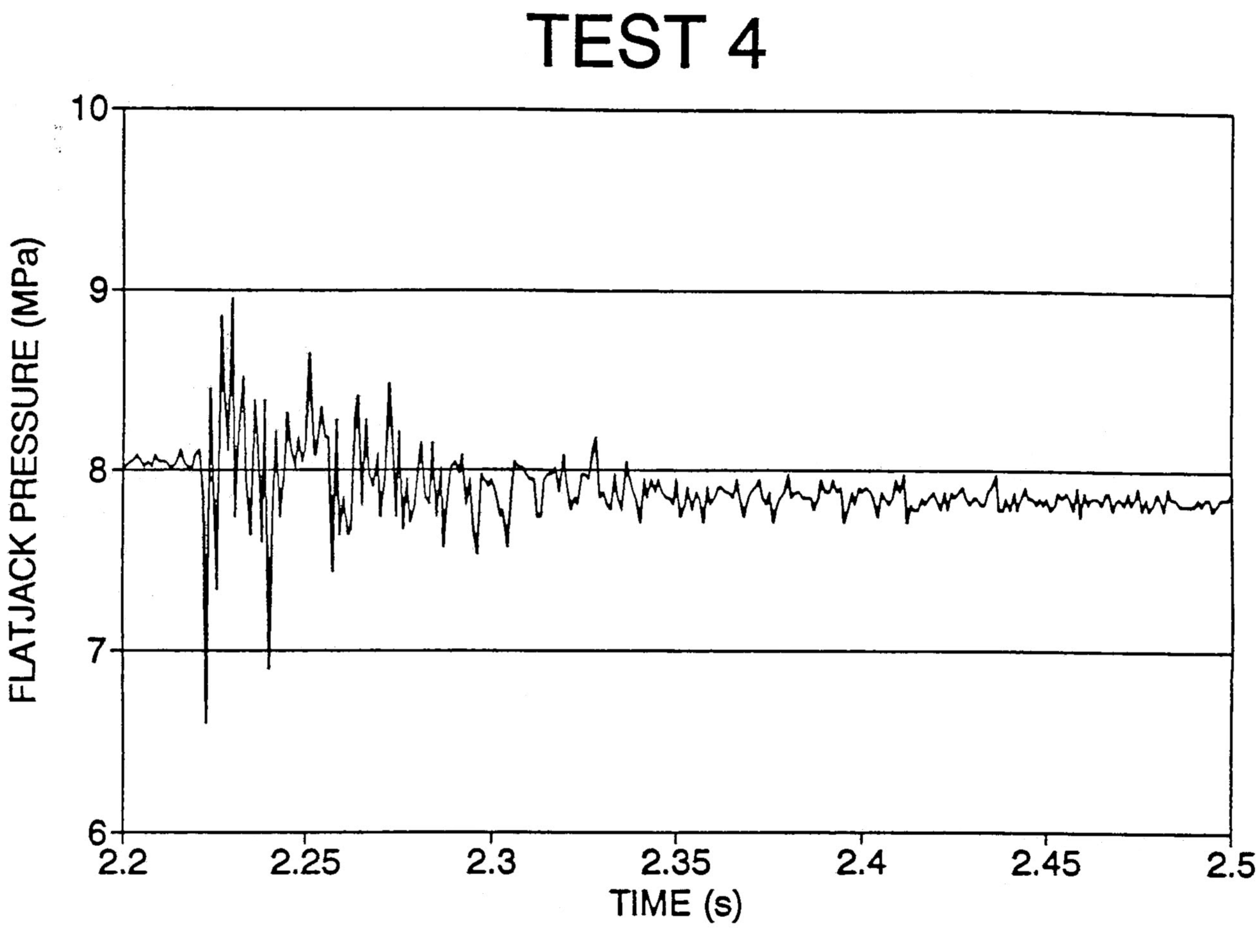


TEST 3
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
RESERVOIR PRESSURE
FLATJACK PRESSURE
RESERVOIR DISPLACEMENT
0
2
4
6
8
10
0
40
80
120
160
200
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

Sandwell

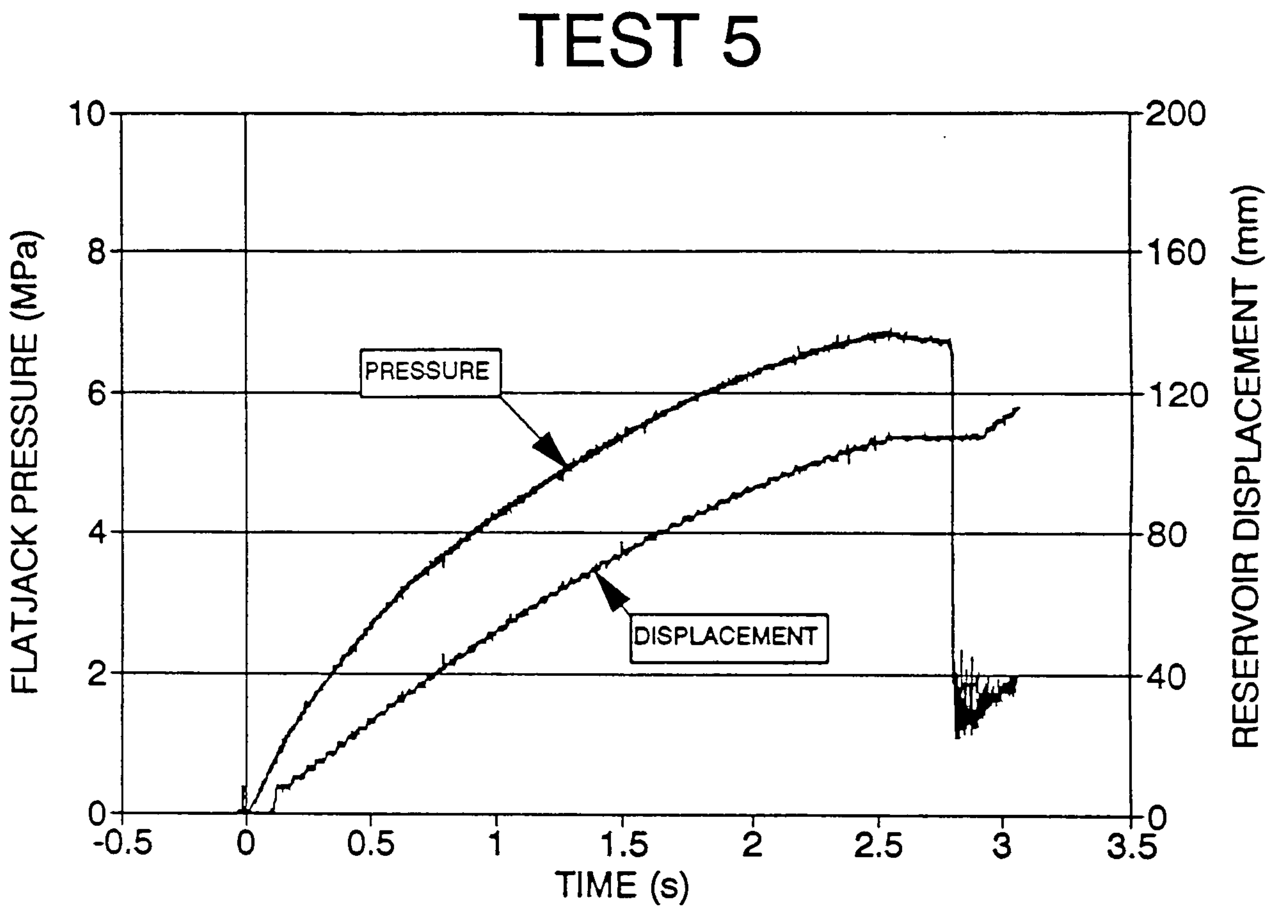

TEST 4
PRESSURE (MPa)
10
8
6
4
2
0
RESERVOIR DISPLACEMENT (mm)
200
160
120
80
40
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (s)

Sandwell



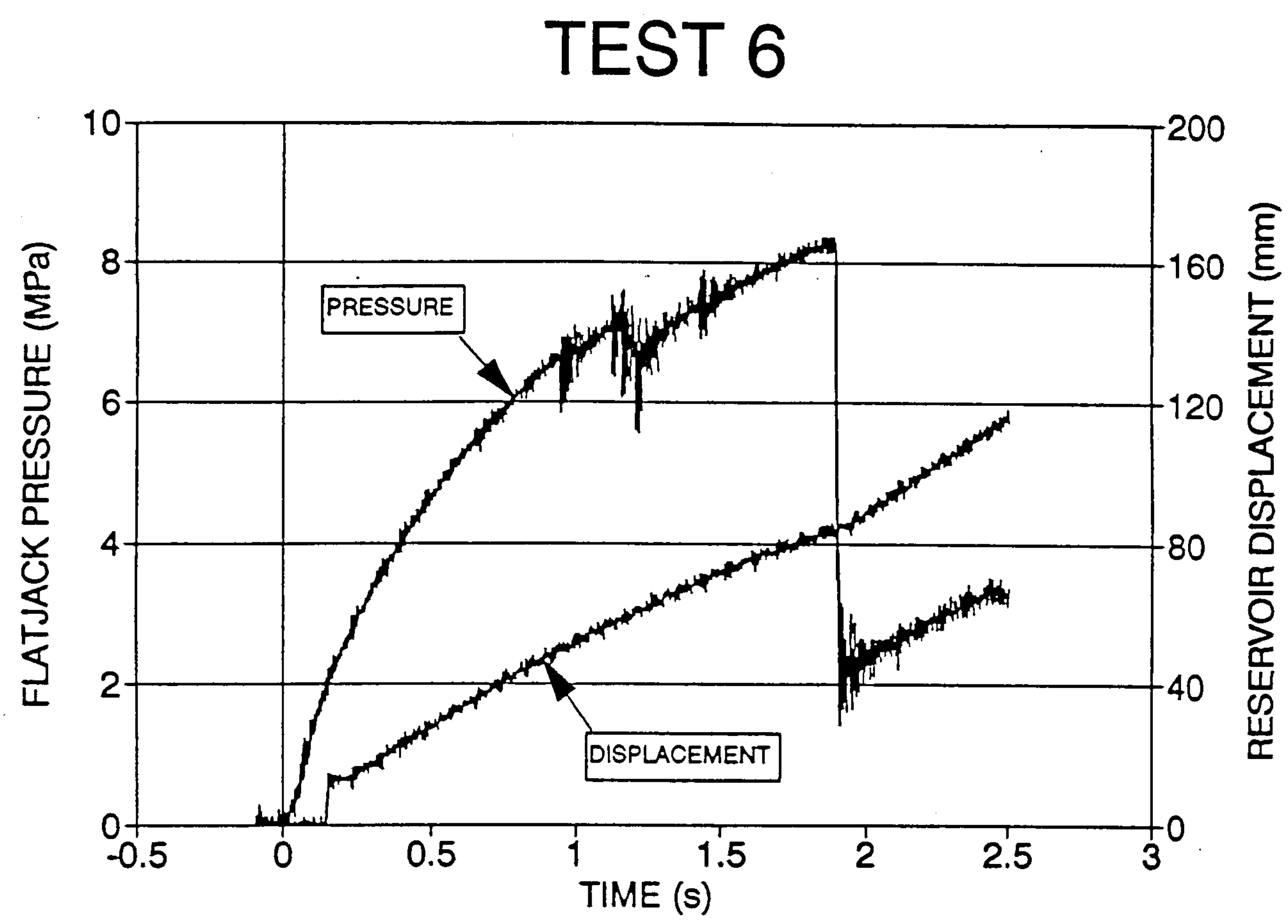
TEST 4
10
9
8
7
6
FLATJACK PRESSURE (MPa)
2.2
2.25
2.3
2.35
2.4
2.45
2.5
TIME (s)

Sandwell

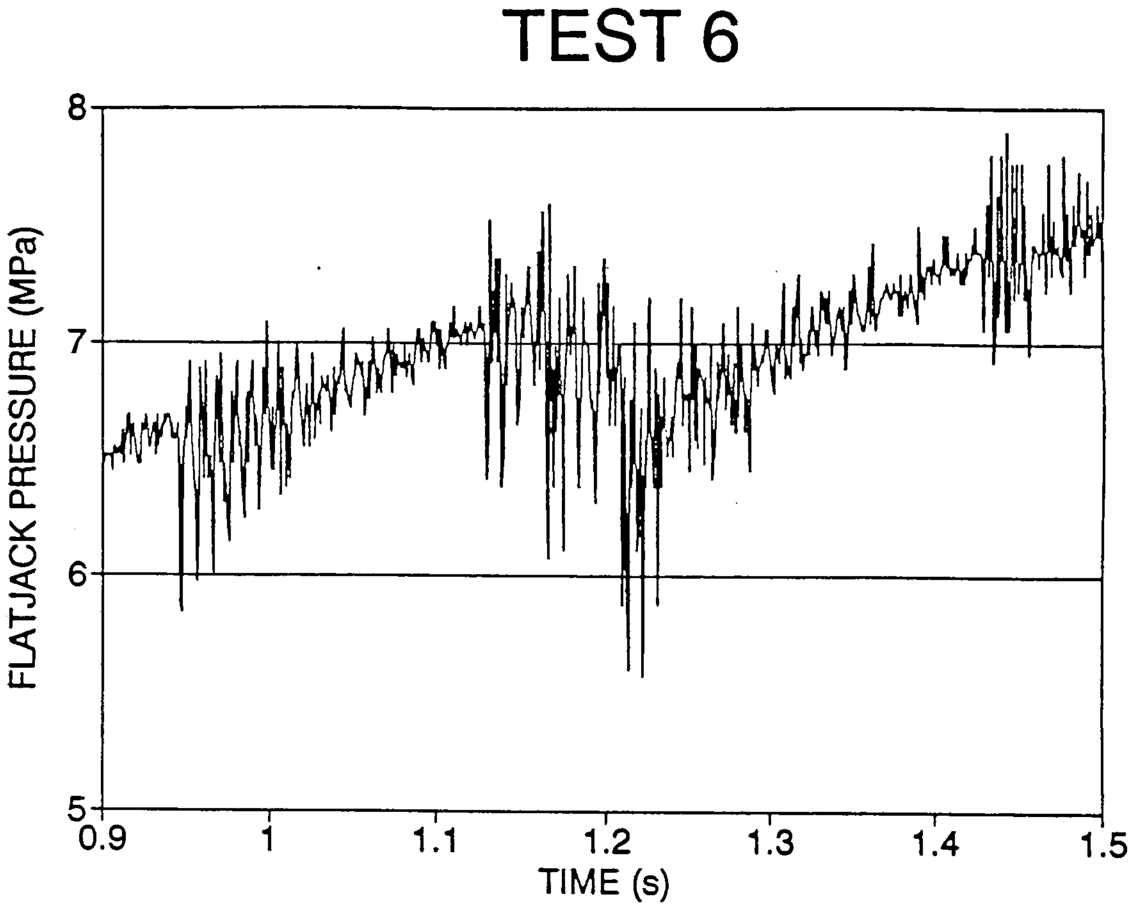


TEST 5
FLATJACK PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
PRESSURE
DISPLACEMENT
10
8
6
4
2
0
200
160
120
80
40
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5

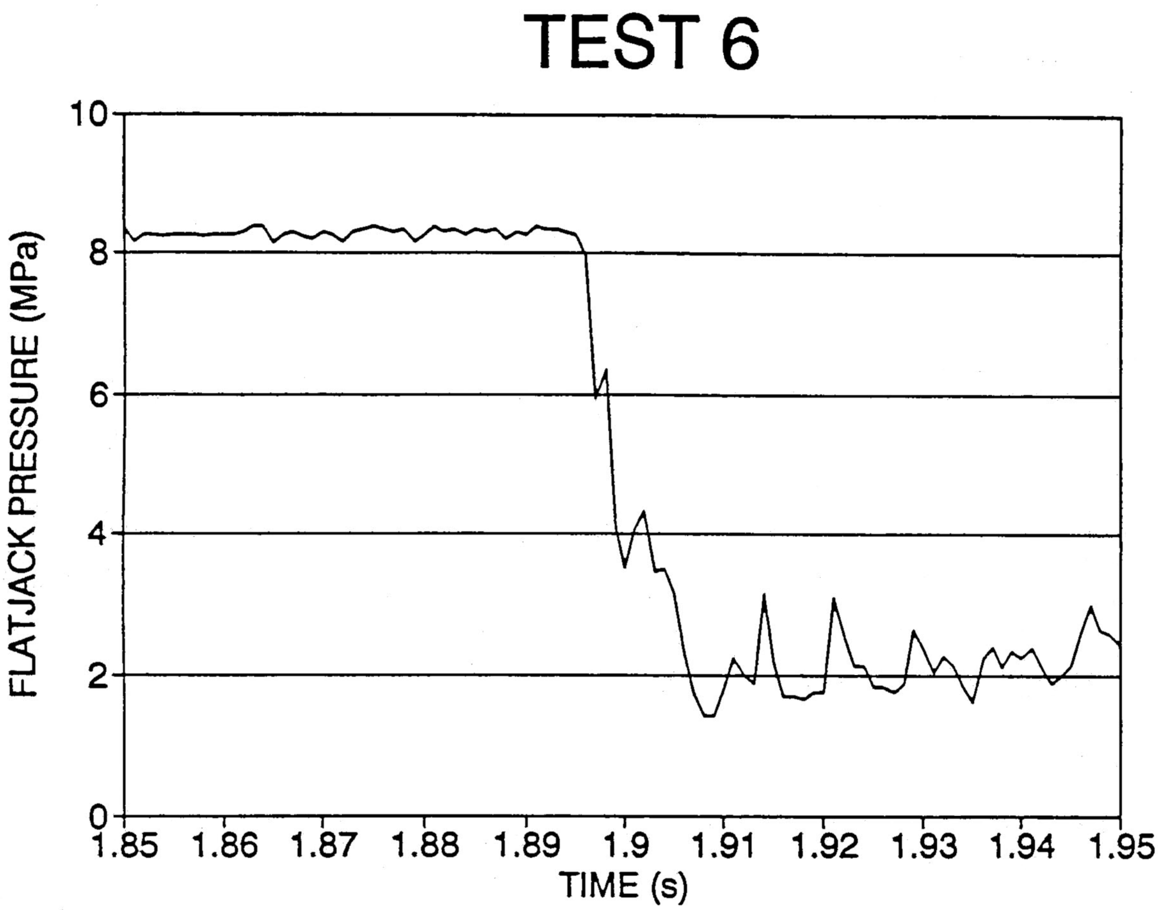
Sandwell


TEST 6
FLATJACK PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
PRESSURE
DISPLACEMENT
10
8
6
4
2
0
200
160
120
80
40
0
-0.5
0
0.5
1
1.5
2
2.5
3

Sandwell

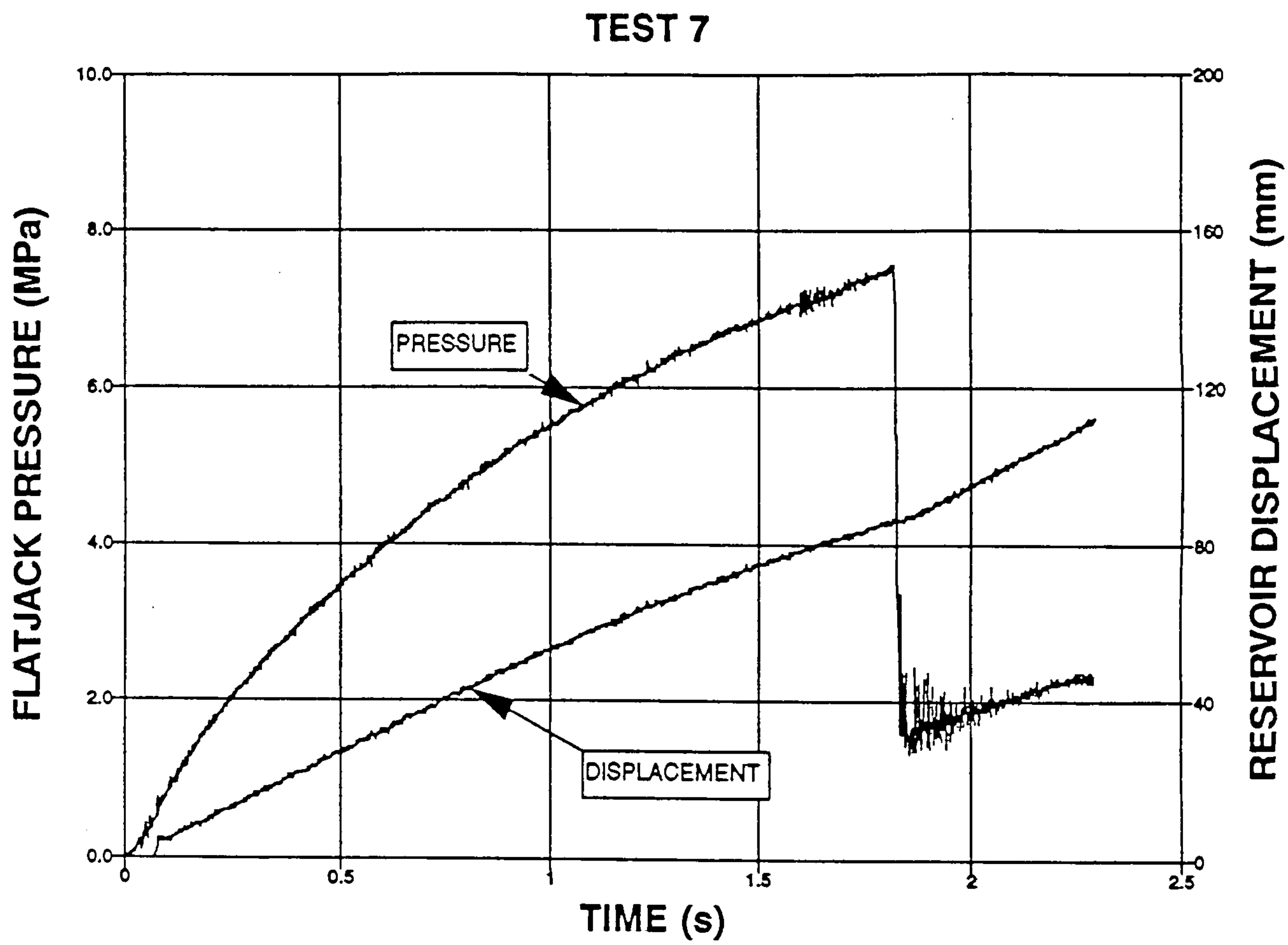


Sandwell

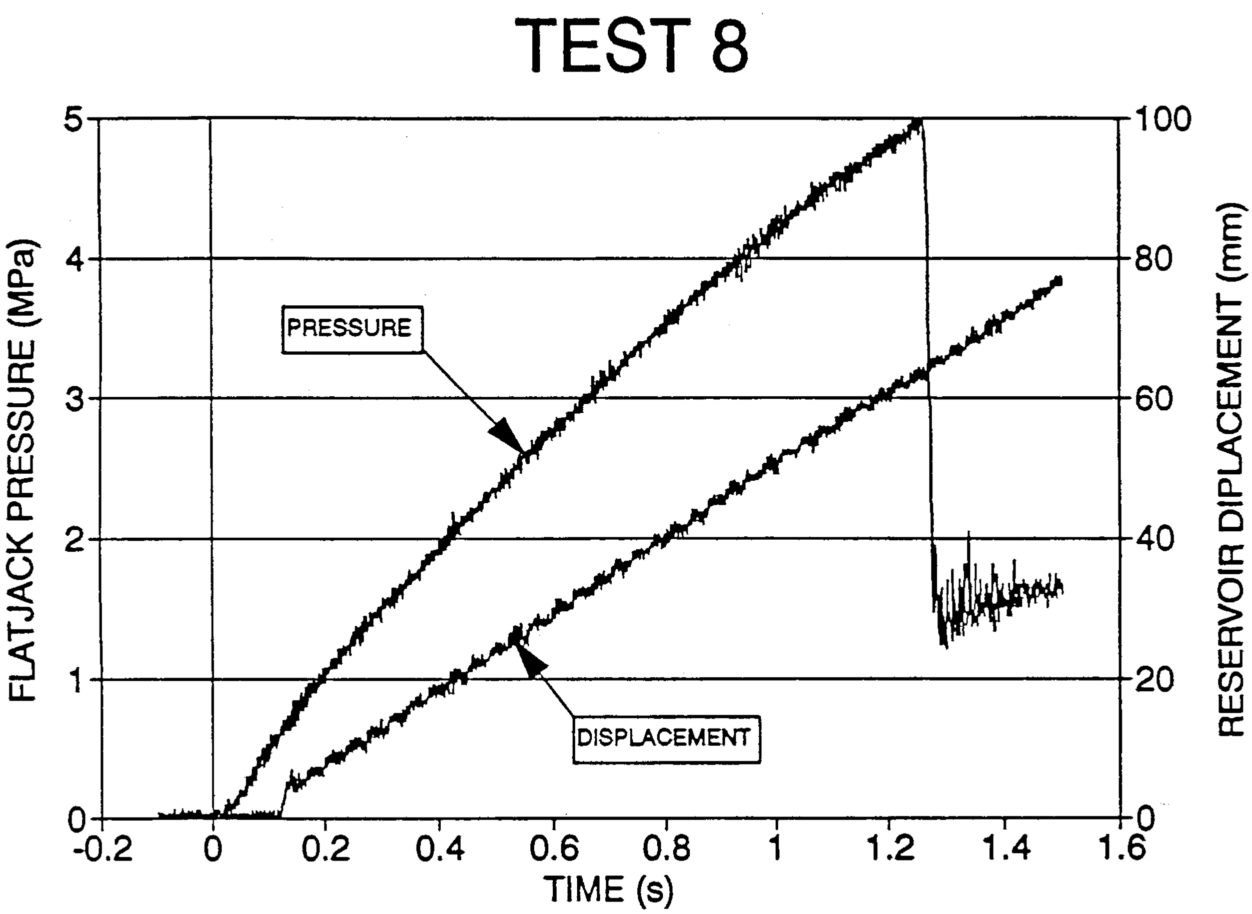


TEST 6
FLATJACK PRESSURE (MPa)
10
8
6
4
2
0
1.85
1.86
1.87
1.88
1.89
1.9
1.91
1.92
1.93
1.94
1.95
TIME (s)

Sandwell

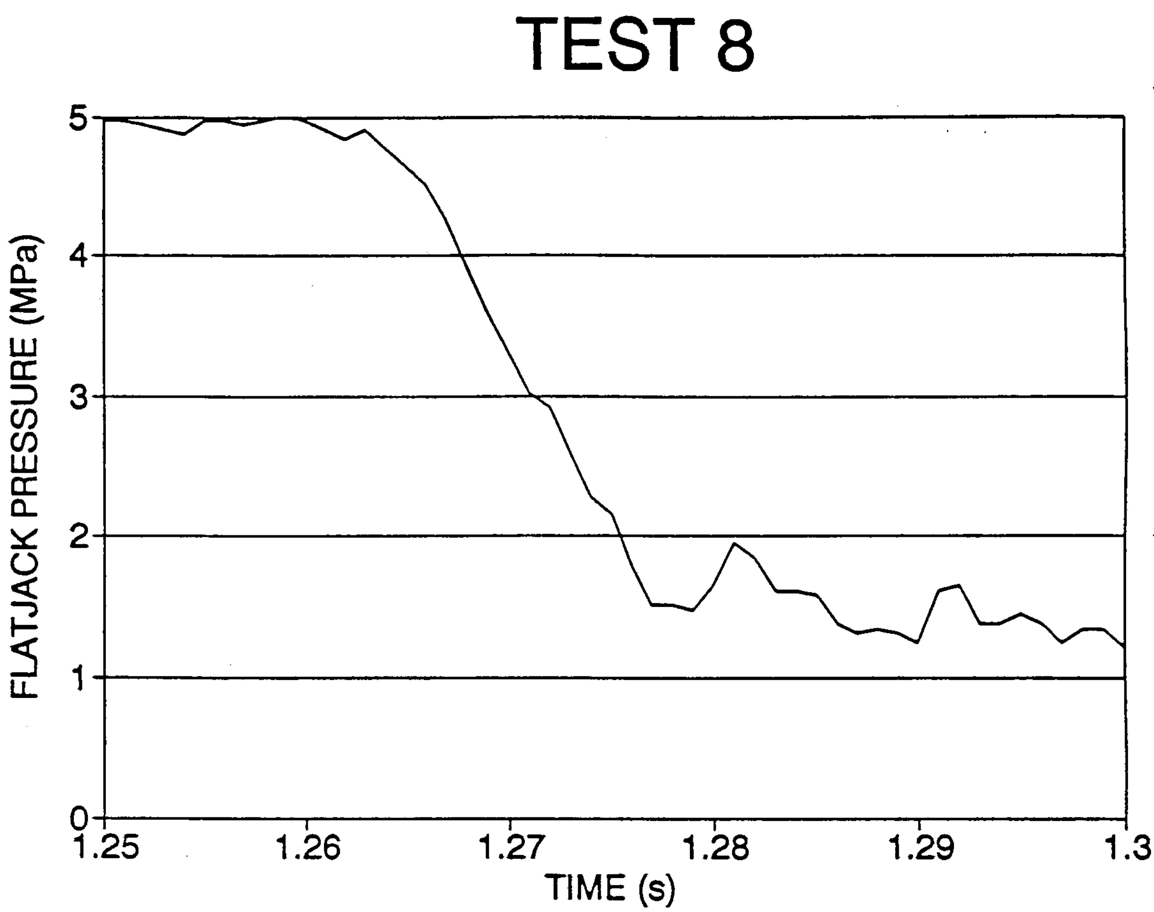

TEST 7
FLATJACK PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
PRESSURE
DISPLACEMENT
10.0
8.0
6.0
4.0
2.0
0.0
200
160
120
80
40
0
0
0.5
1
1.5
2
2.5

Sandwell



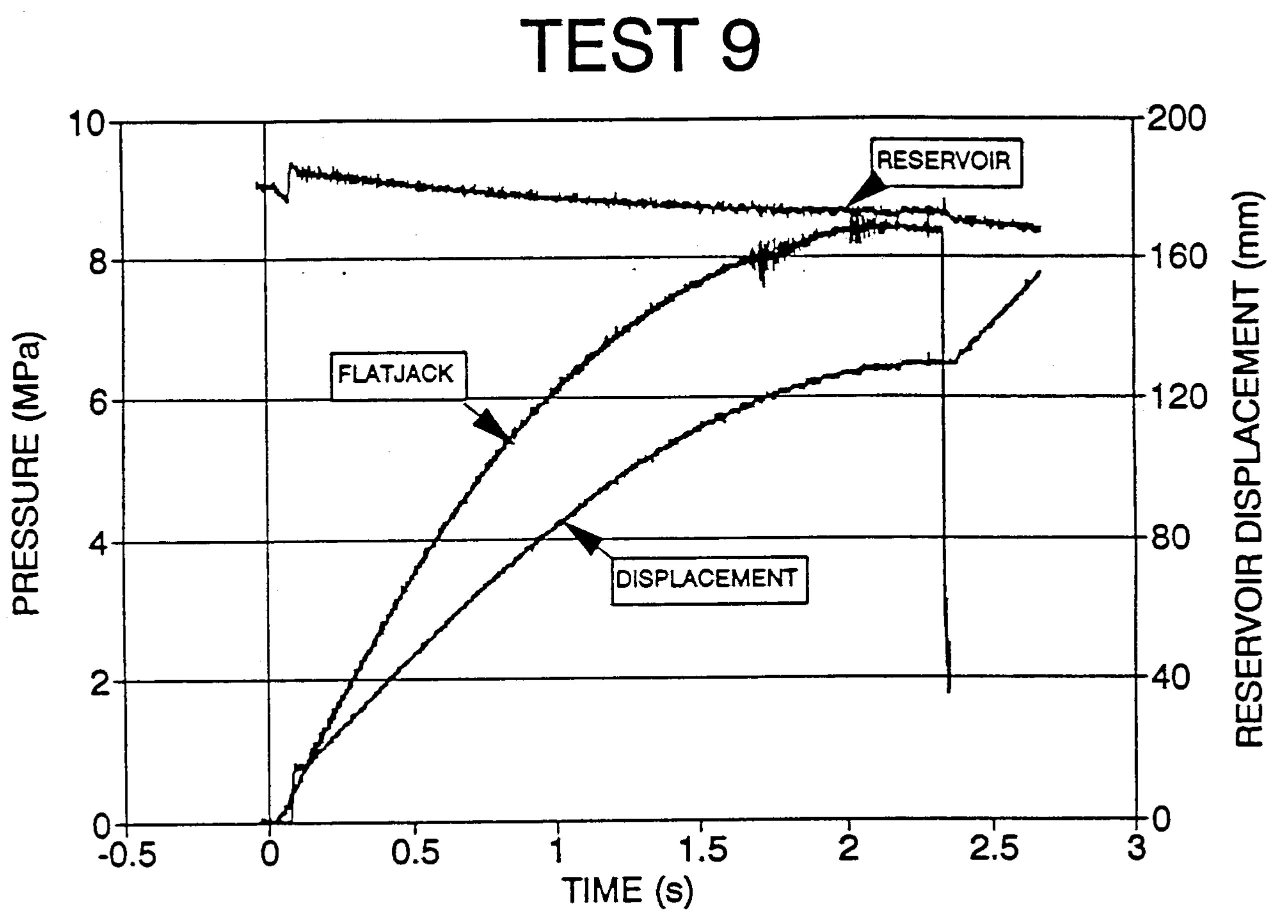
TEST 8
FLATJACK PRESSURE (MPa)
RESERVOIR DIPLACEMENT (mm)
TIME (s)
PRESSURE
DISPLACEMENT
5
4
3
2
1
0
100
80
60
40
20
0
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Sandwell



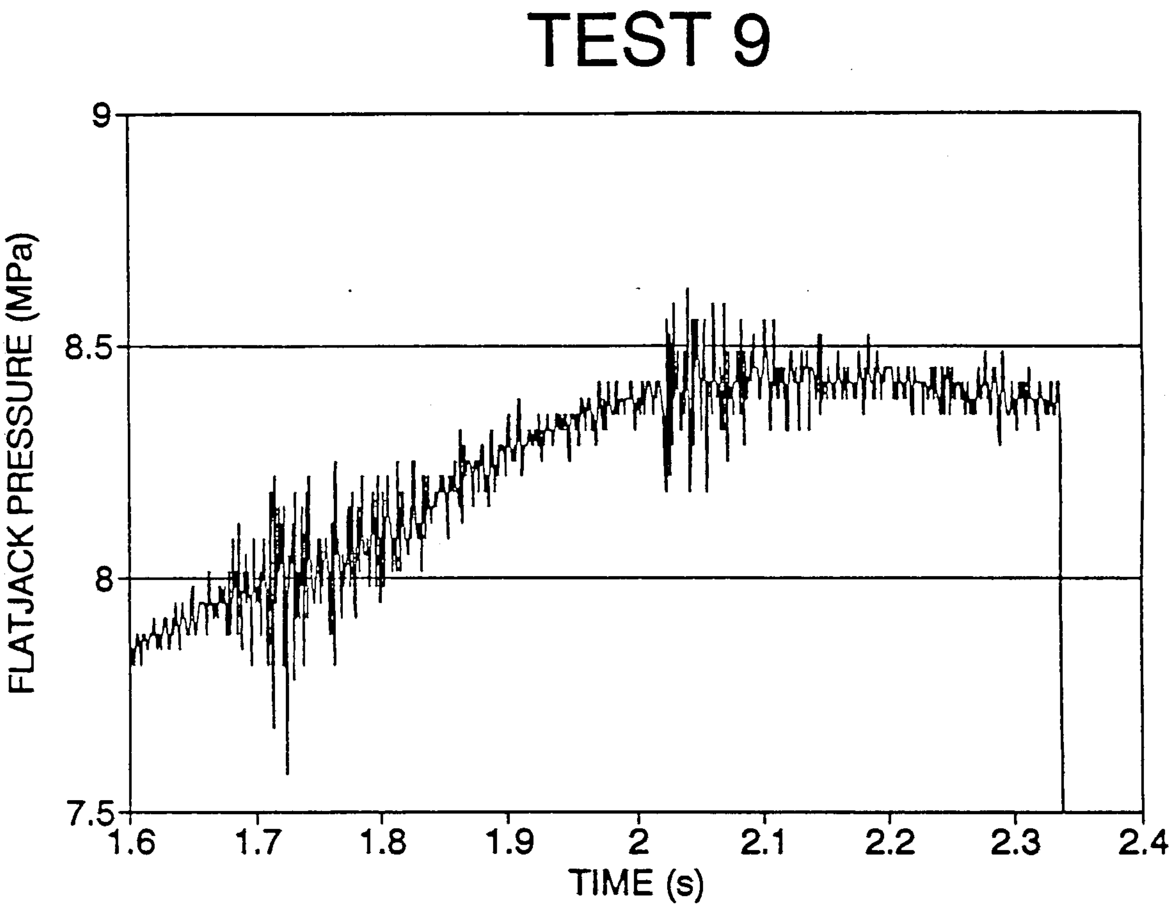
TEST 8
FLATJACK PRESSURE (MPa)
0
1
2
3
4
5
1.25
1.26
1.27
1.28
1.29
1.3
TIME (s)

Sandwell



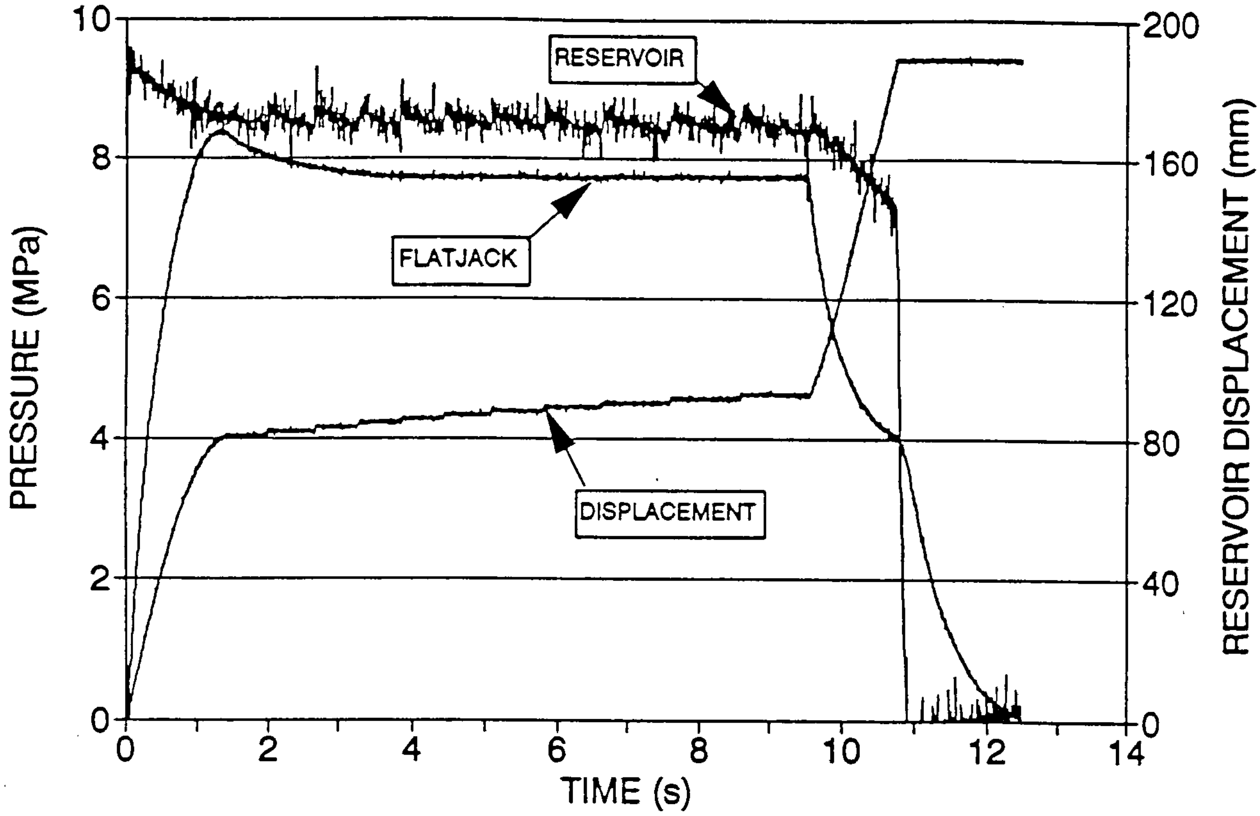
TEST 9
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
RESERVOIR
FLATJACK
DISPLACEMENT
10
8
6
4
2
0
200
160
120
80
40
0
-0.5
0
0.5
1
1.5
2
2.5
3

Sandwell

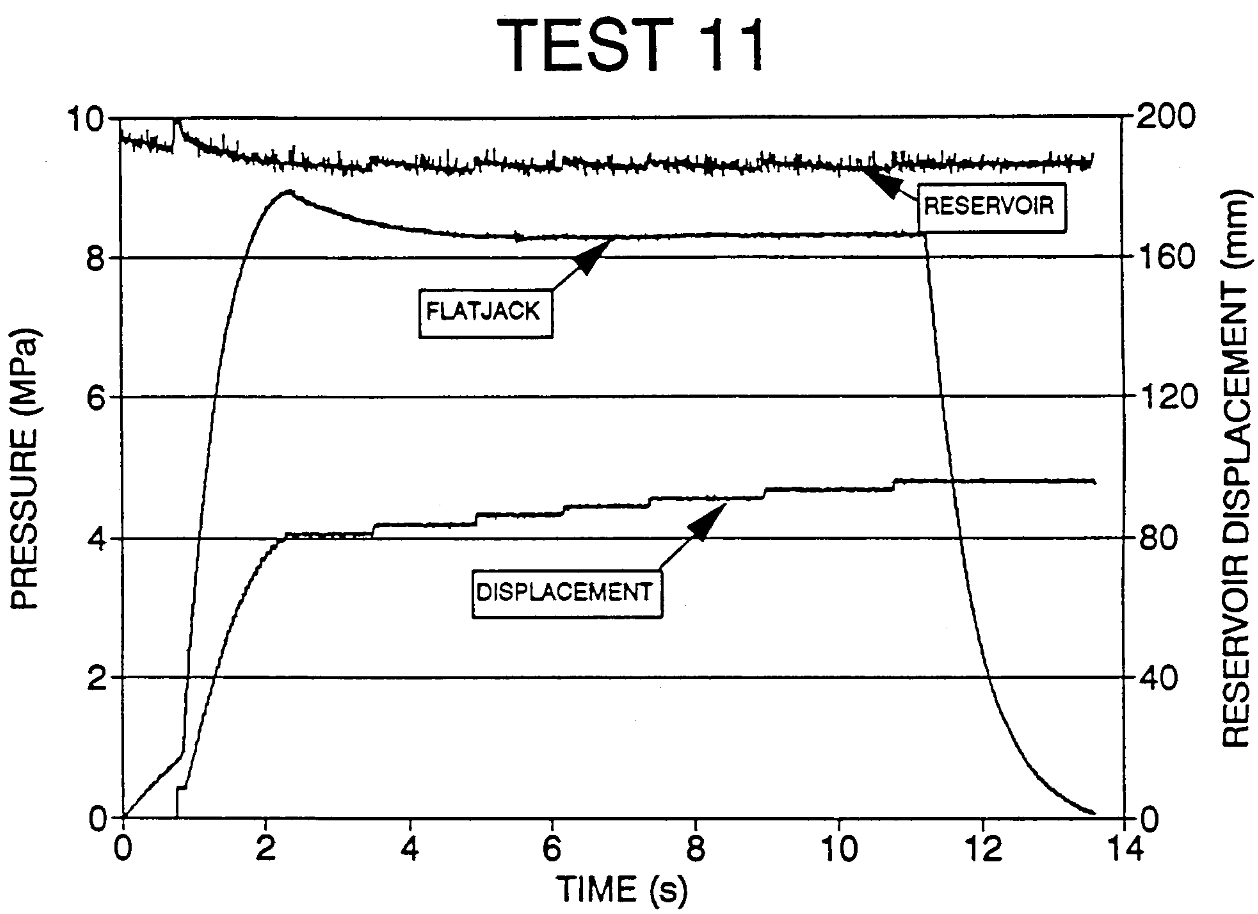

TEST 9
FLATJACK PRESSURE (MPa)
9
8.5
8
7.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
TIME (s)

Sandwell

TEST 10

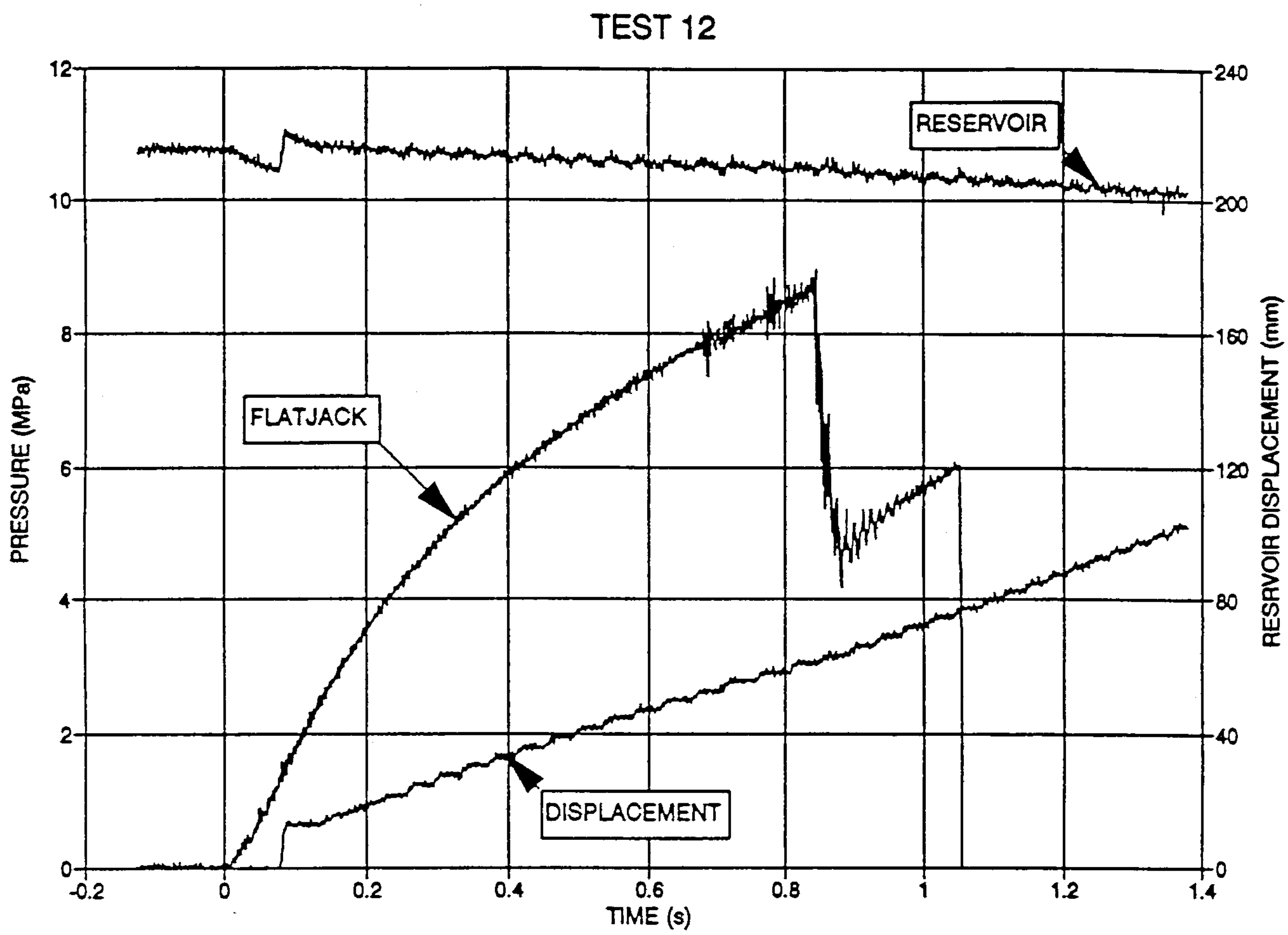


Sandwell

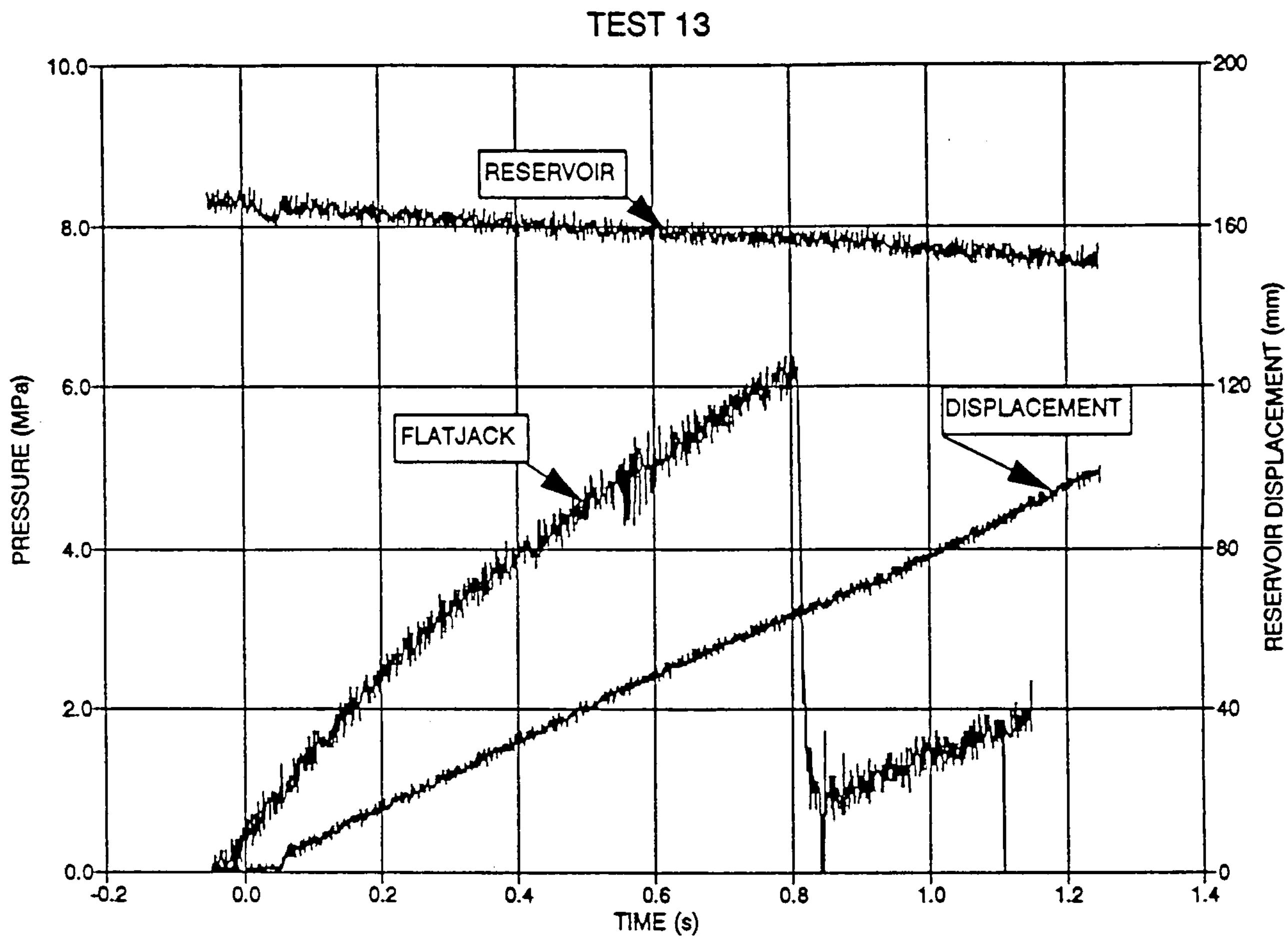


TEST 11
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
RESERVOIR
FLATJACK
DISPLACEMENT
0
2
4
6
8
10
200
160
120
80
40
0
0
2
4
6
8
10
12
14

Sandwell

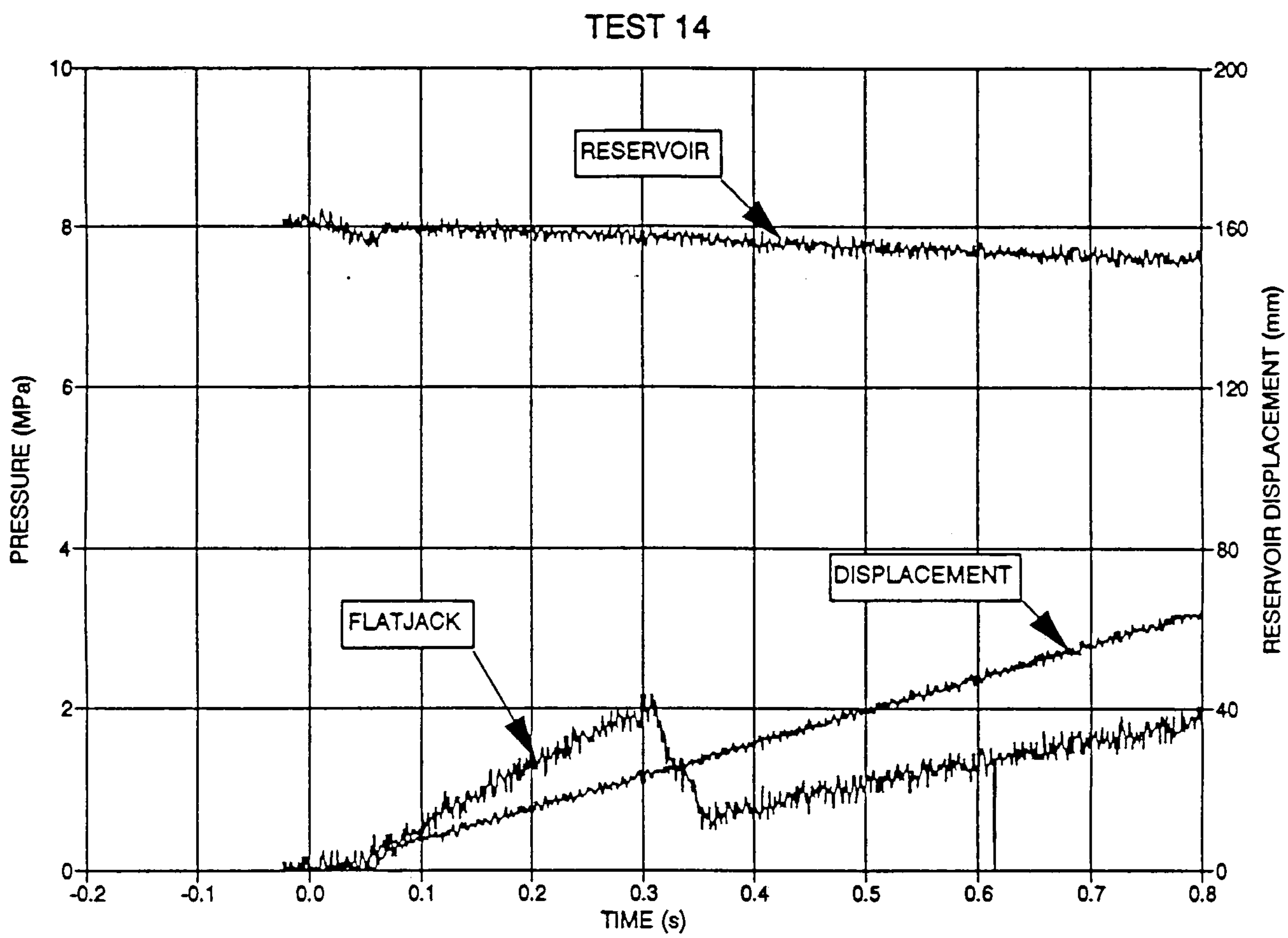

TEST 12
RESERVOIR
FLATJACK
DISPLACEMENT
PRESSURE (MPa)
RESRVOIR DISPLACEMENT (mm)
TIME (s)
12
10
8
6
4
2
0
240
200
160
120
80
40
0
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4

Sandwell



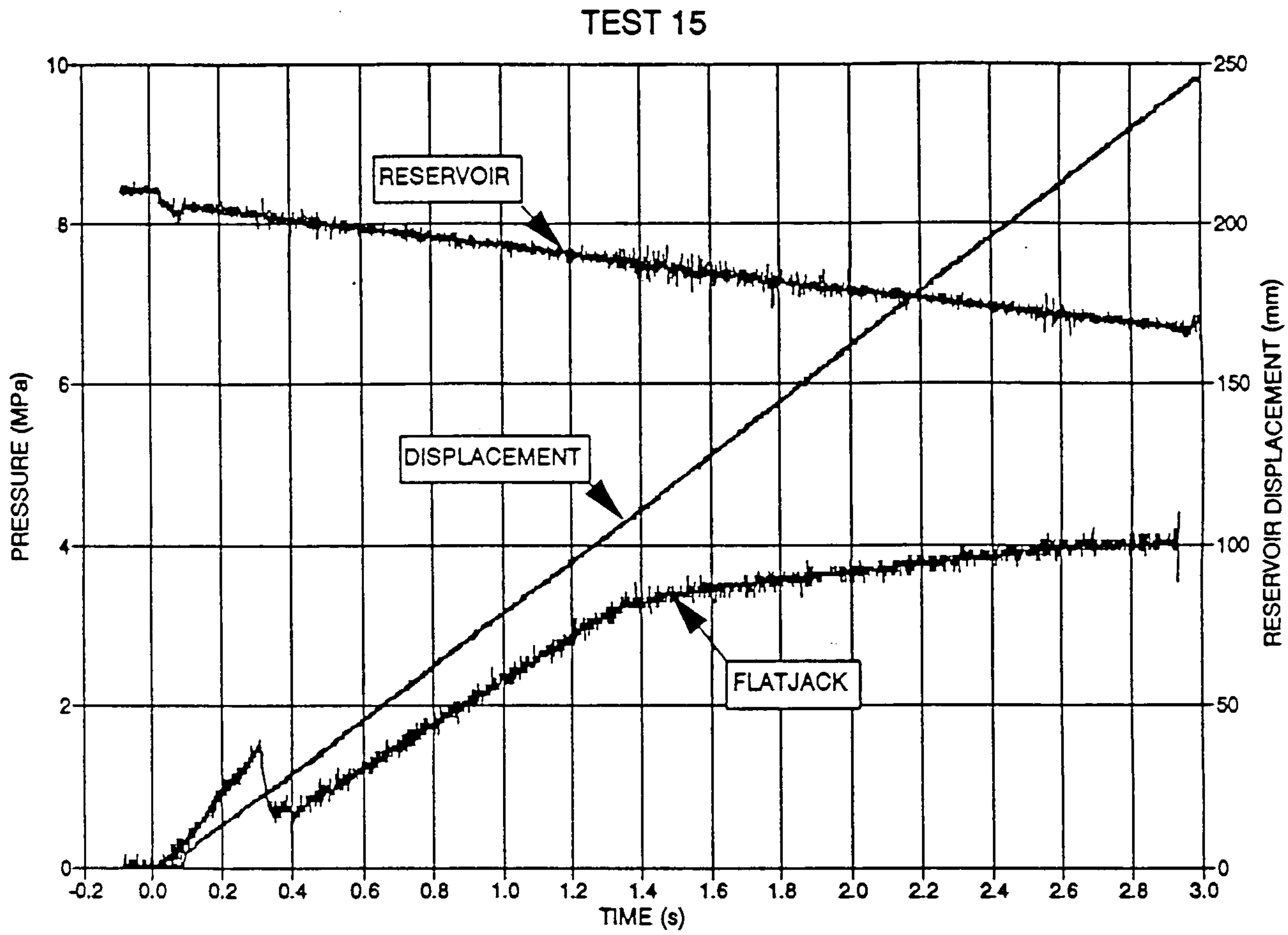
TEST 13
RESERVOIR
FLATJACK
DISPLACEMENT
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
10.0
8.0
6.0
4.0
2.0
0.0
200
160
120
80
40
0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Sandwell



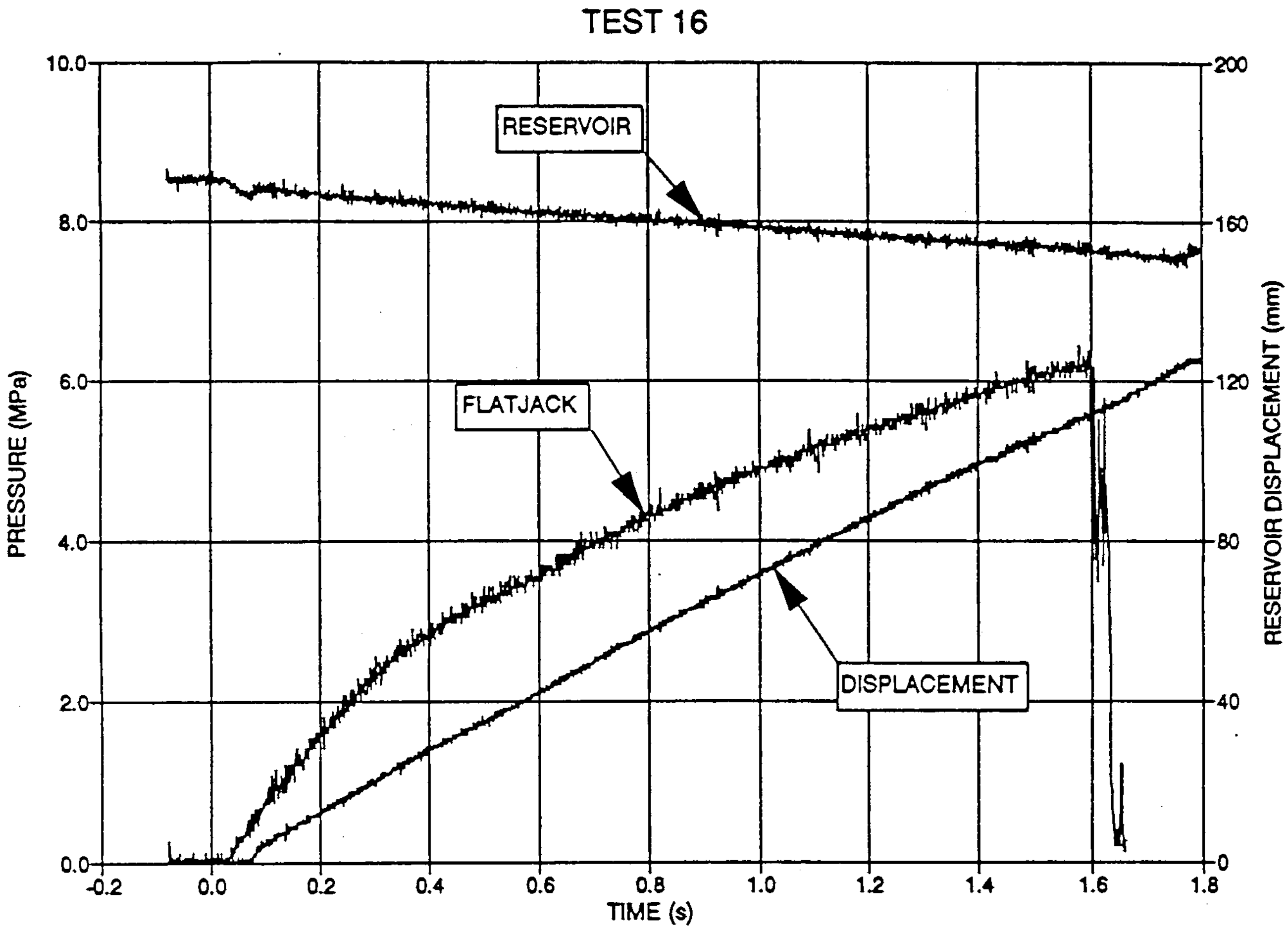
TEST 14
RESERVOIR
DISPLACEMENT
FLATJACK
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
0
2
4
6
8
10
0
40
80
120
160
200
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Sandwell



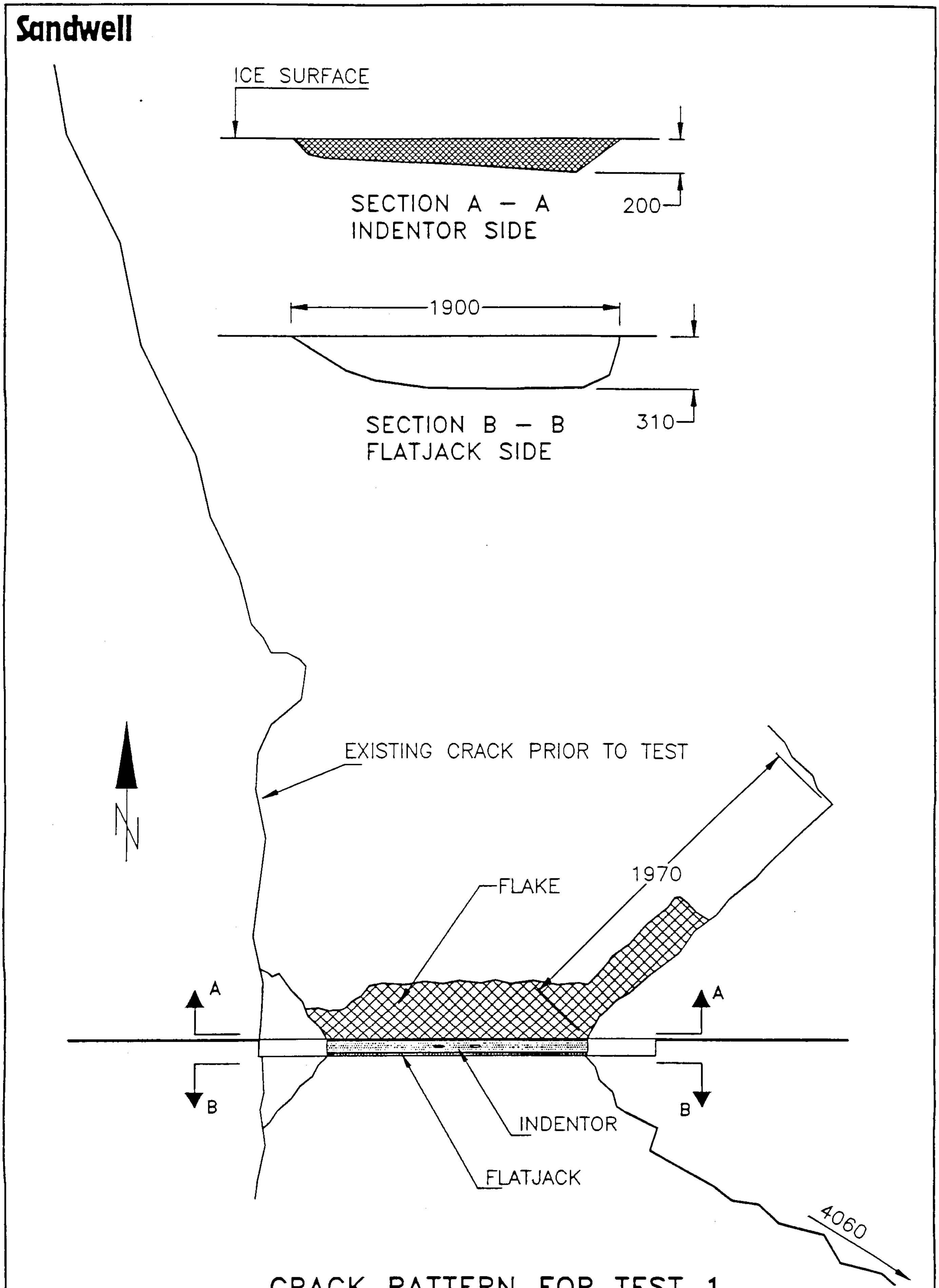
TEST 15
RESERVOIR
DISPLACEMENT
FLATJACK
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
0
2
4
6
8
10
0
50
100
150
200
250
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

Sandwell



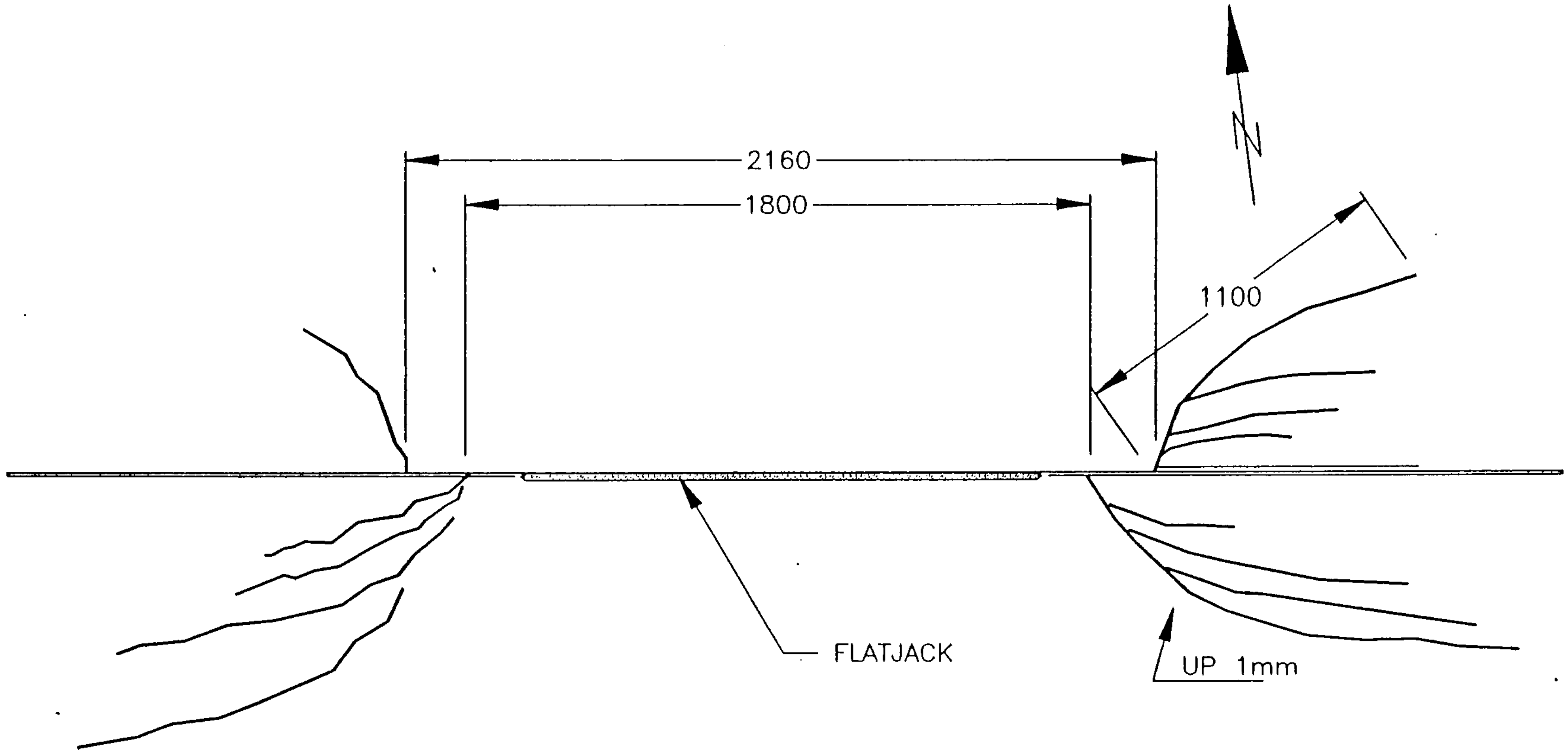
TEST 16
RESERVOIR
FLATJACK
DISPLACEMENT
PRESSURE (MPa)
RESERVOIR DISPLACEMENT (mm)
TIME (s)
10.0
8.0
6.0
4.0
2.0
0.0
200
160
120
80
40
0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

APPENDIX B - Crack Patterns



CRACK PATTERN FOR TEST 1

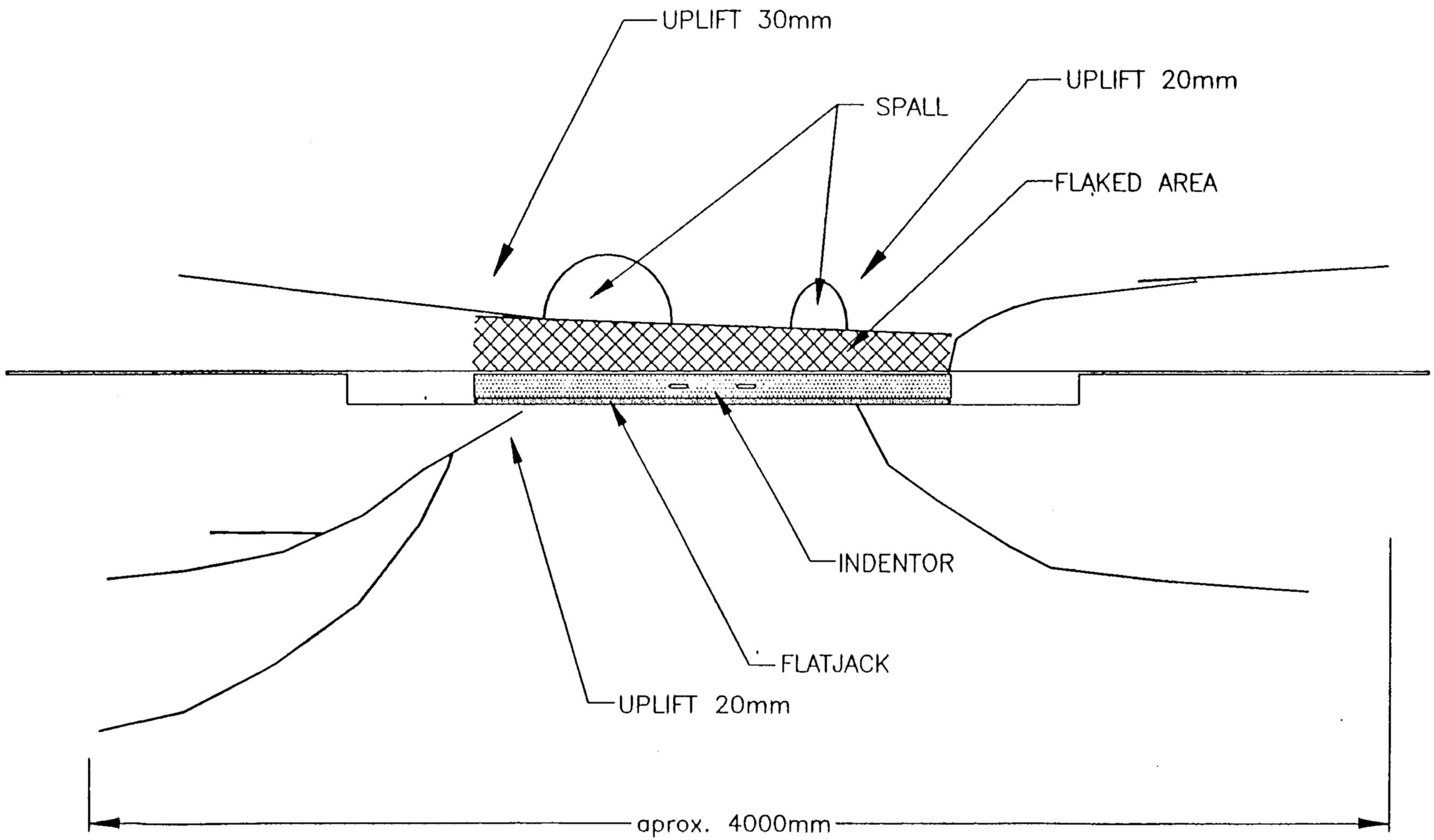
ACAD\3281C006



CRACK PATTERN FOR TEST 2

Sandwell

ACAD 3281C003.DWG

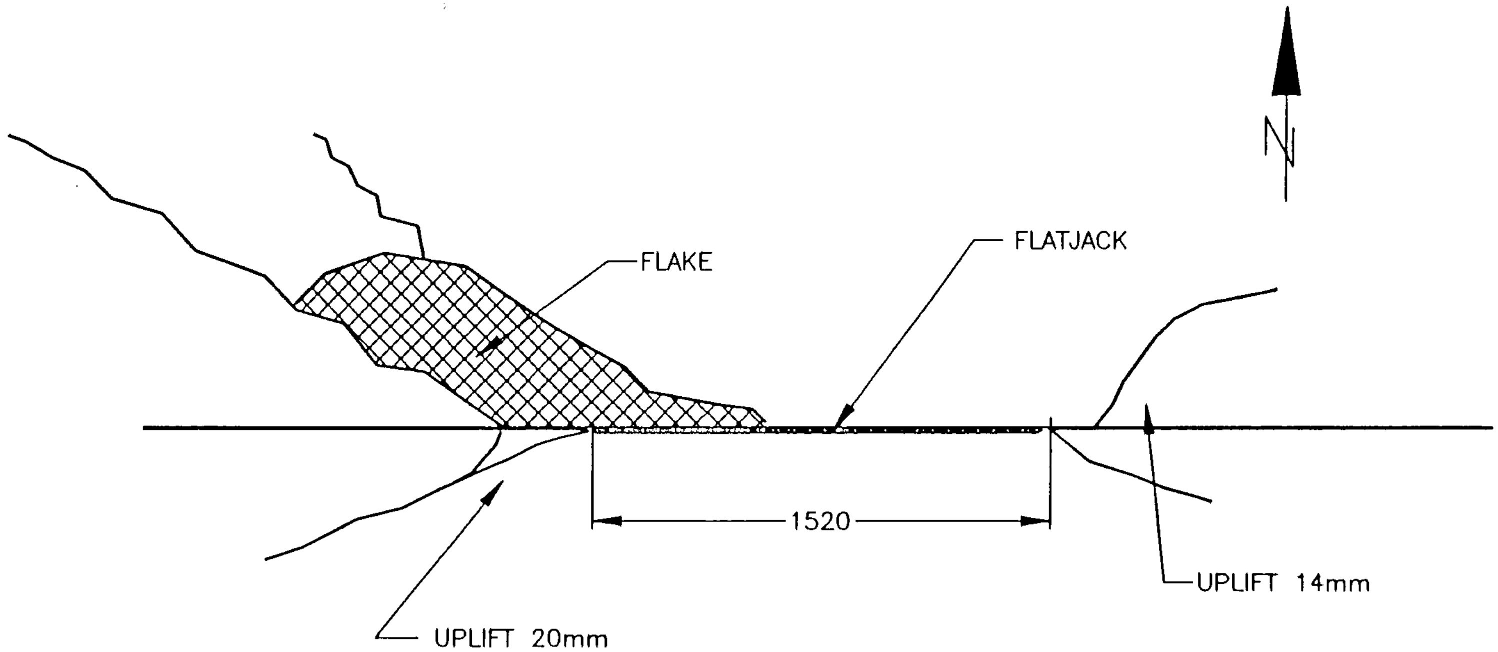


CRACK PATTERN FOR TEST 3

Sandwell

ACAD 3281C007.DWG

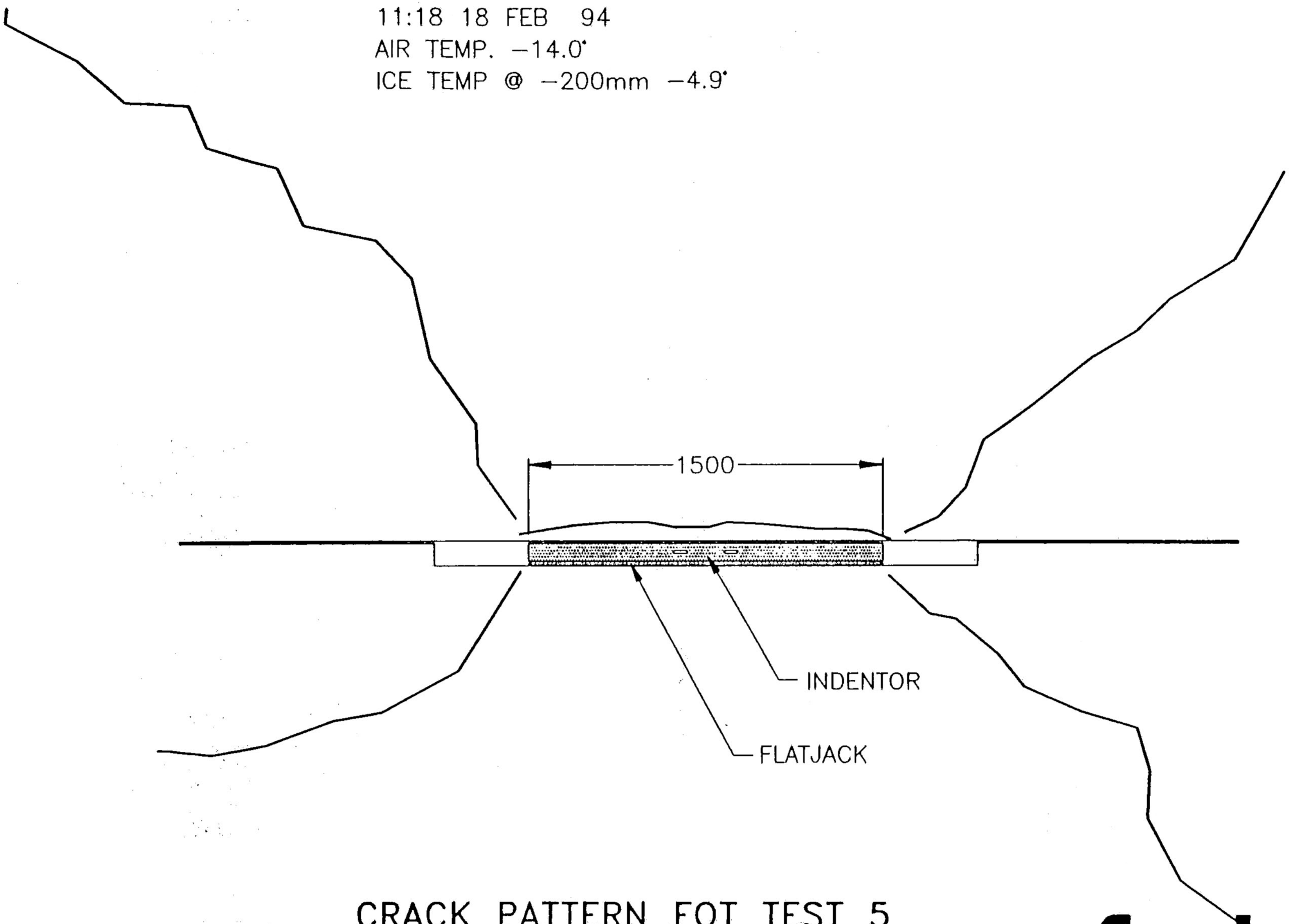
15:35 15 FEB 94
AIR TEMP. +8°



CRACK PATTERN FOR TEST 4

Sandwell

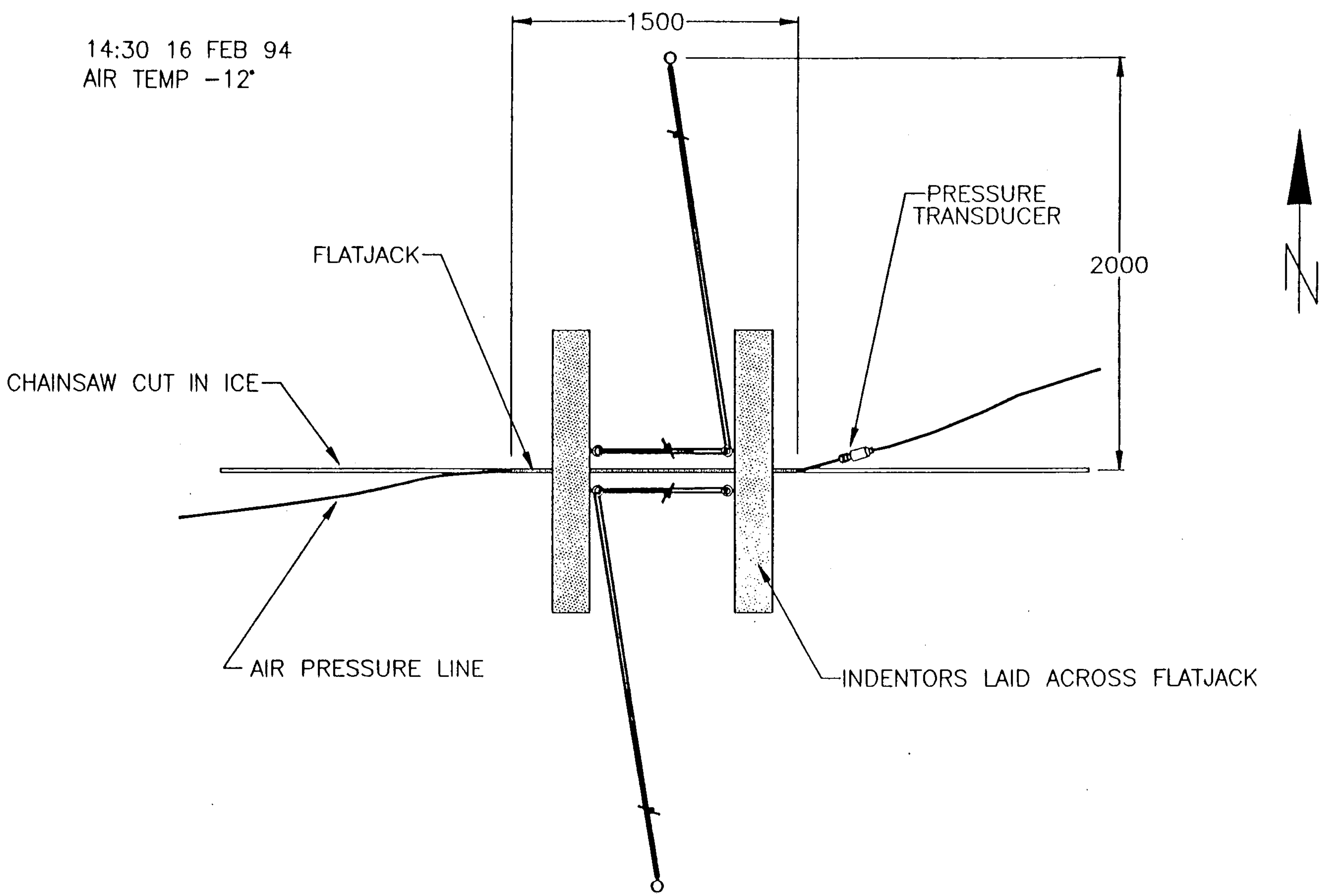
ACAD 3281c008.DWG



CRACK PATTERN FOT TEST 5

Sandwell

ACAD 3281C009.DWG

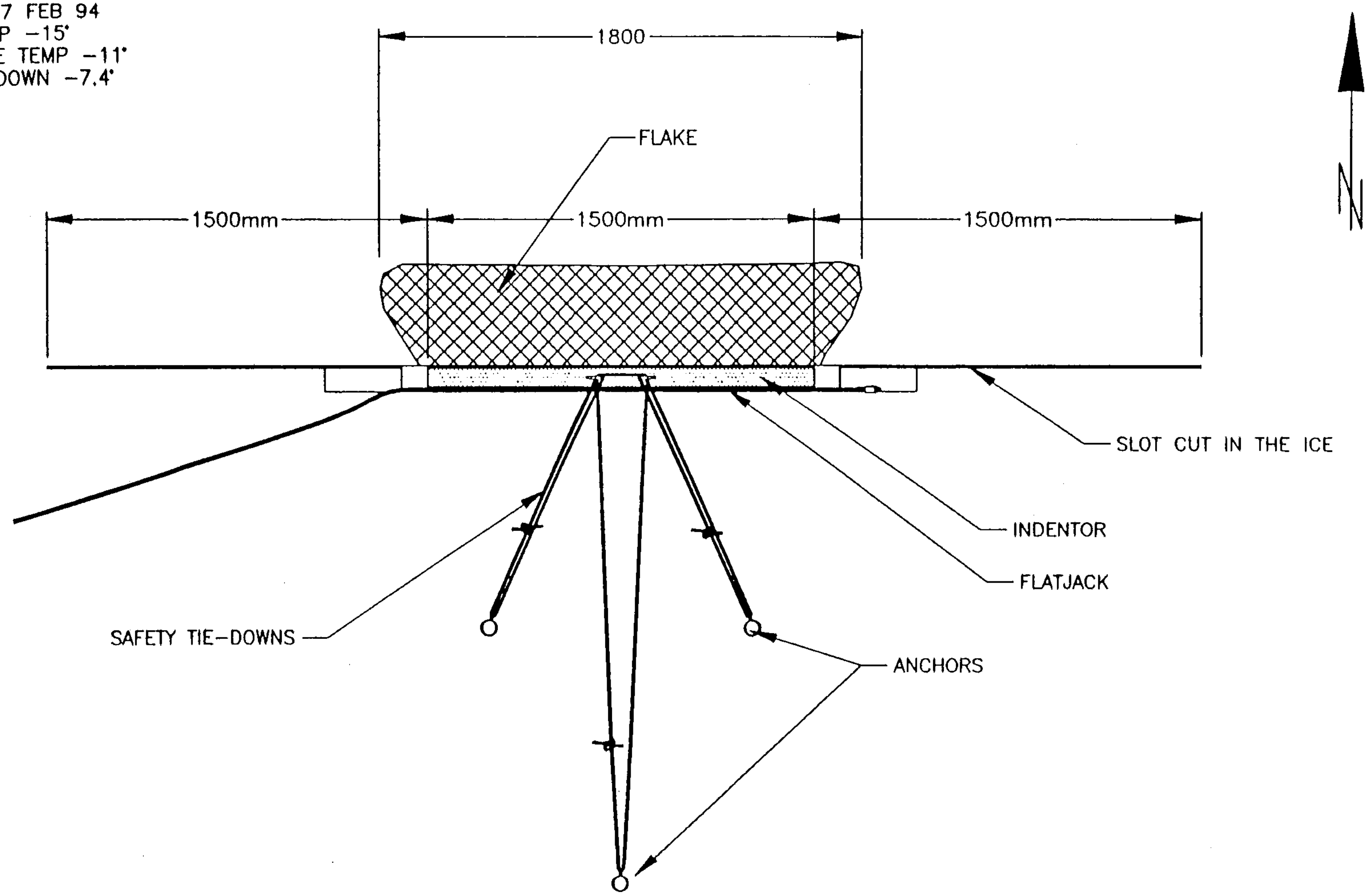


TEST SET-UP FOR TEST 6

Sandwell

ACAD 3281C010.DWG

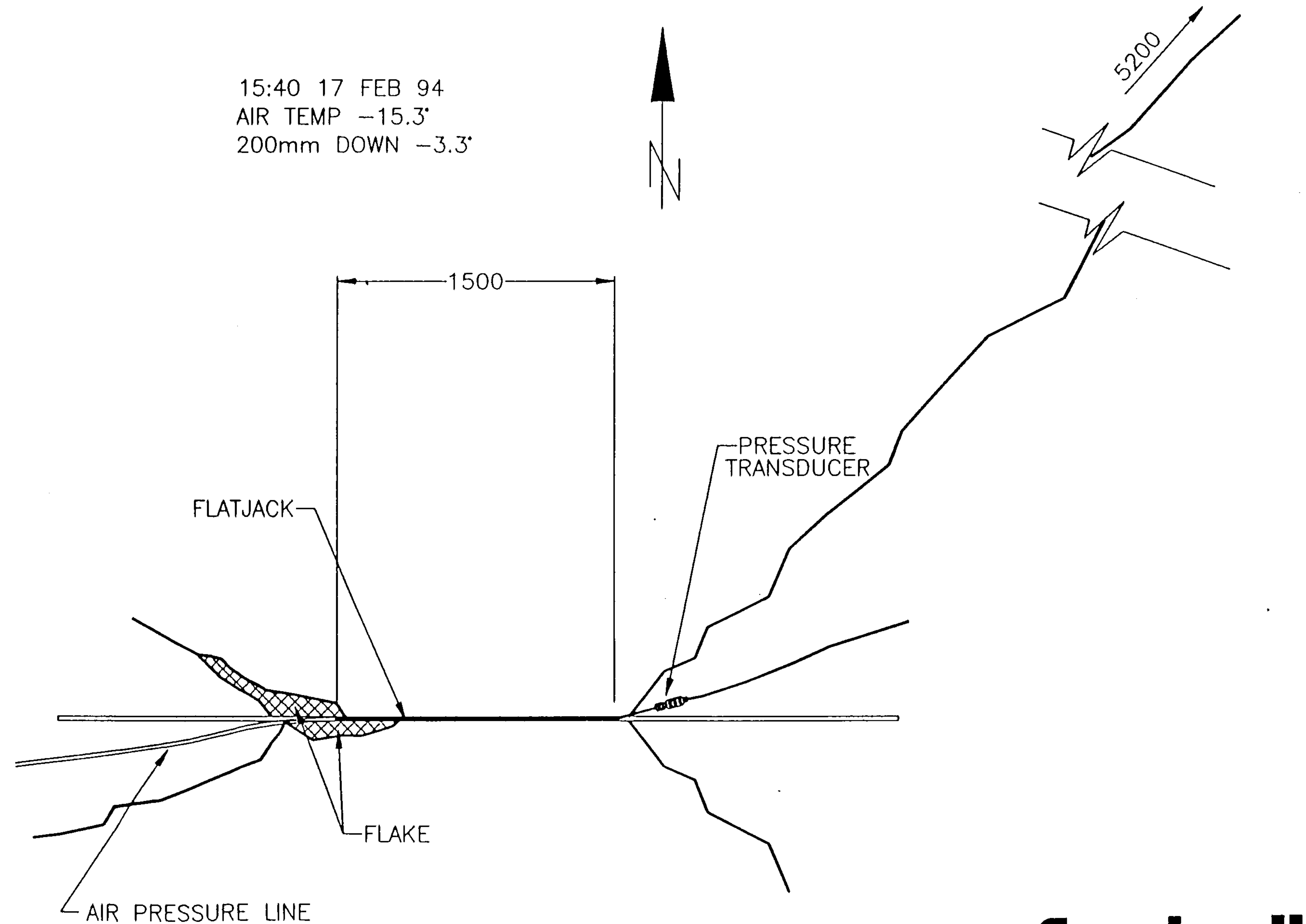
11:15 17 FEB 94
AIR TEMP -15°
SURFACE TEMP -11°
20mm DOWN -7.4°



FAILURE PATTERN FOR TEST 9

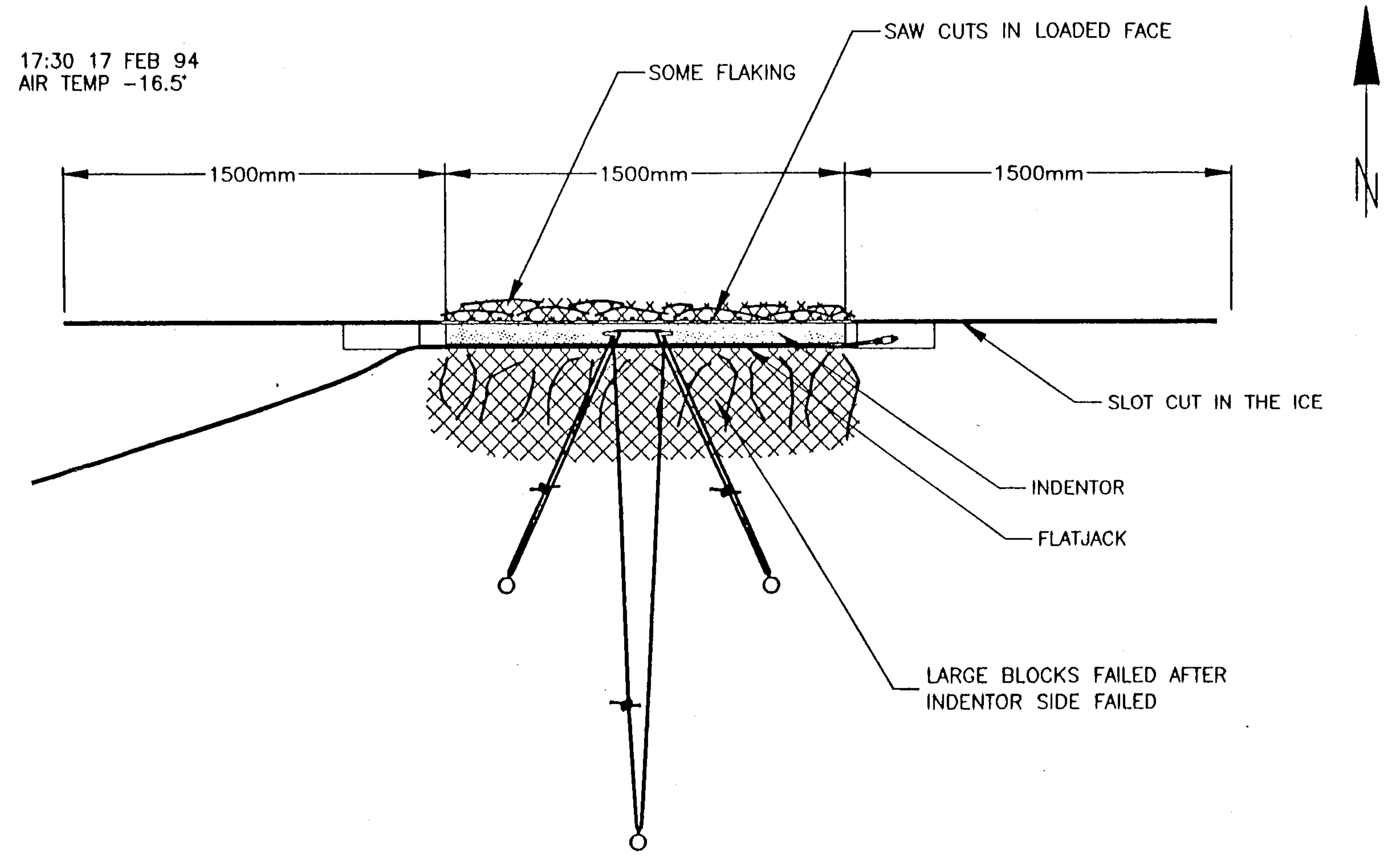
Sandwell

ACAD 3281C011.DWG



CRACK PATTERN FOR TEST 12

ACAD 3281C012.DWG

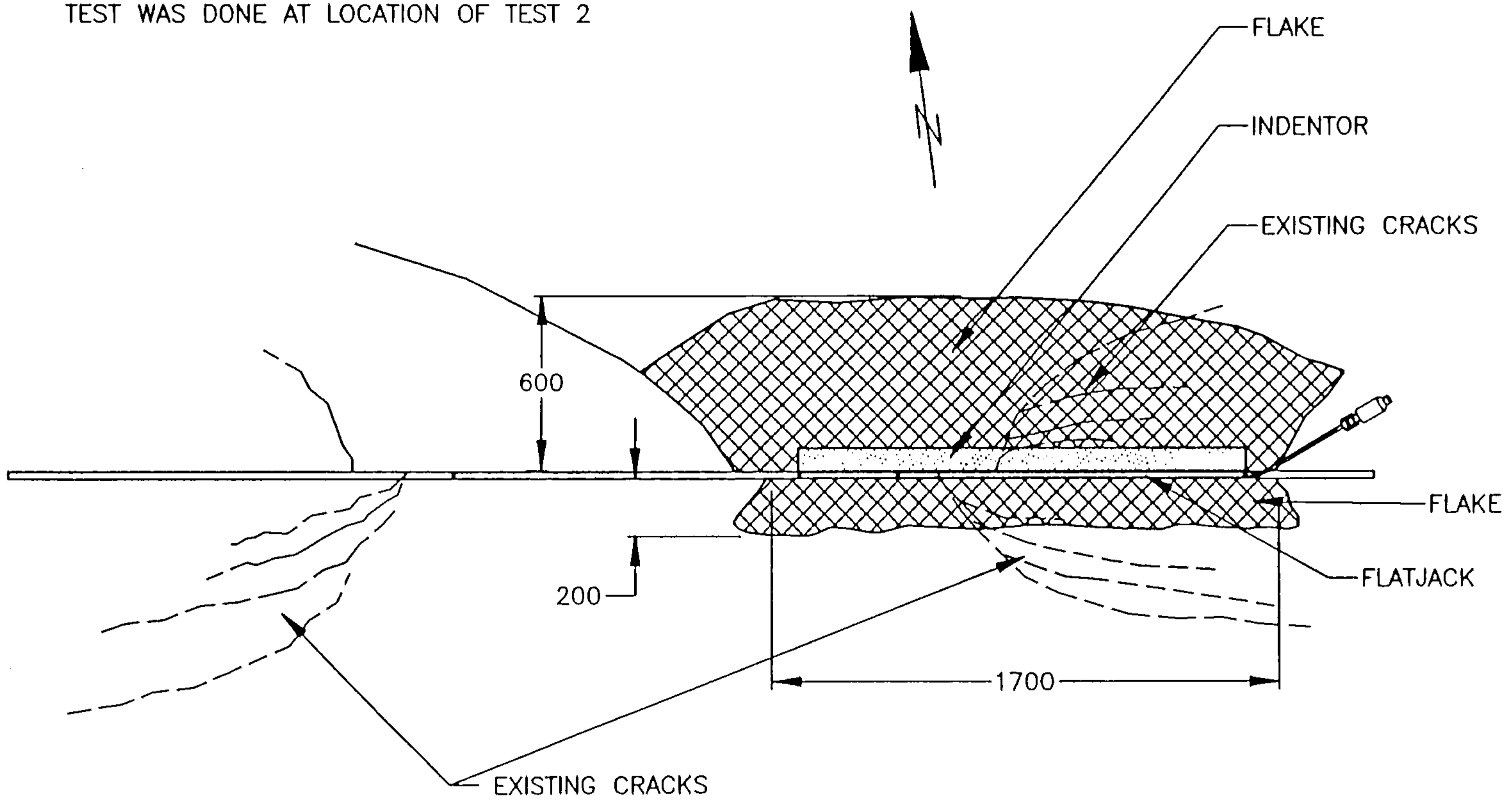


CRACK PATTERN FOR TEST 13

Sandwell

ACAD 3281C013.DWG

10:30 18 FEB 94
AIR TEMP −18°
200MM DOWN −11.6°
TEST WAS DONE AT LOCATION OF TEST 2

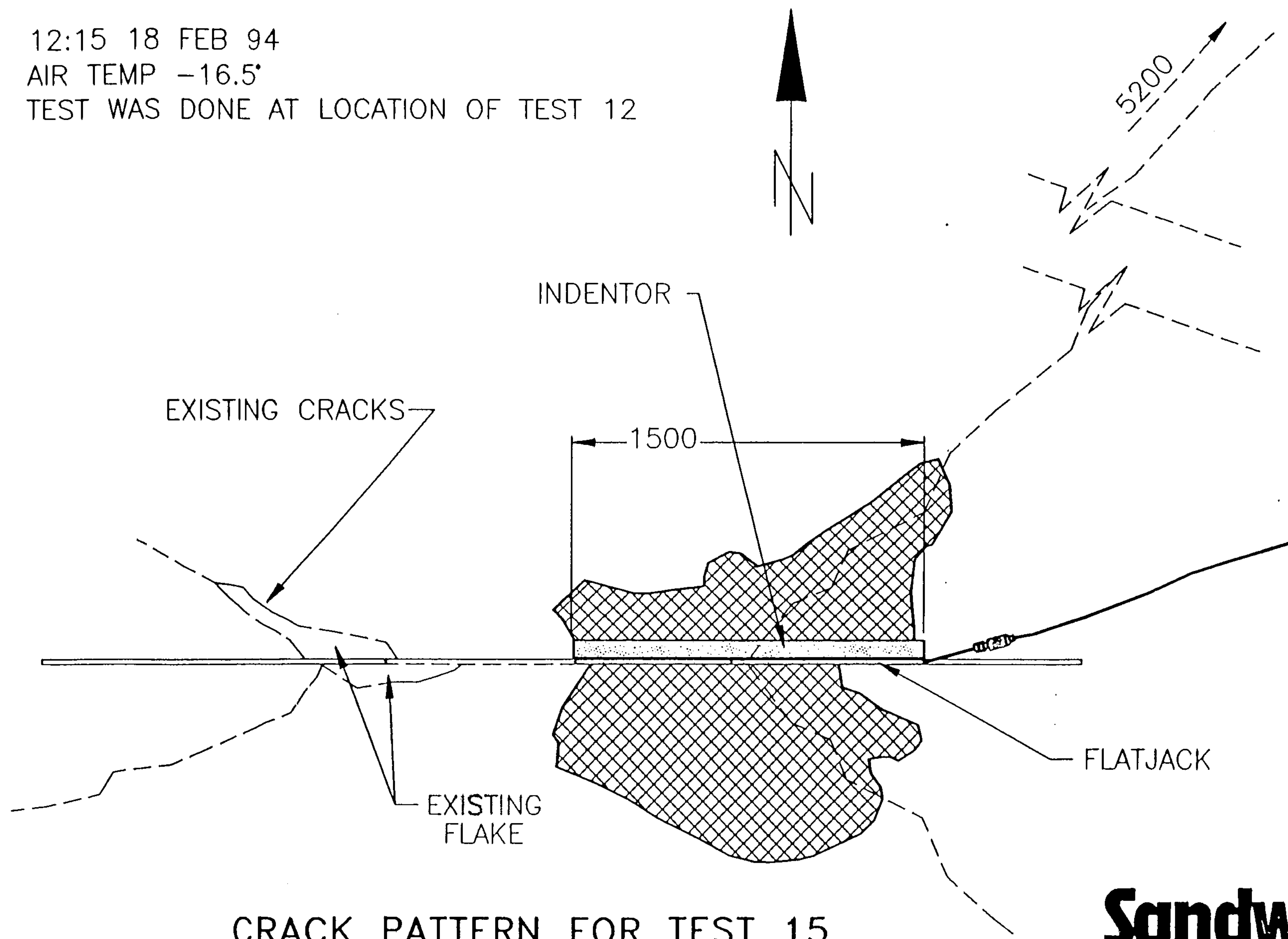


CRACK PATTERN FOR TEST 14

Sandwell

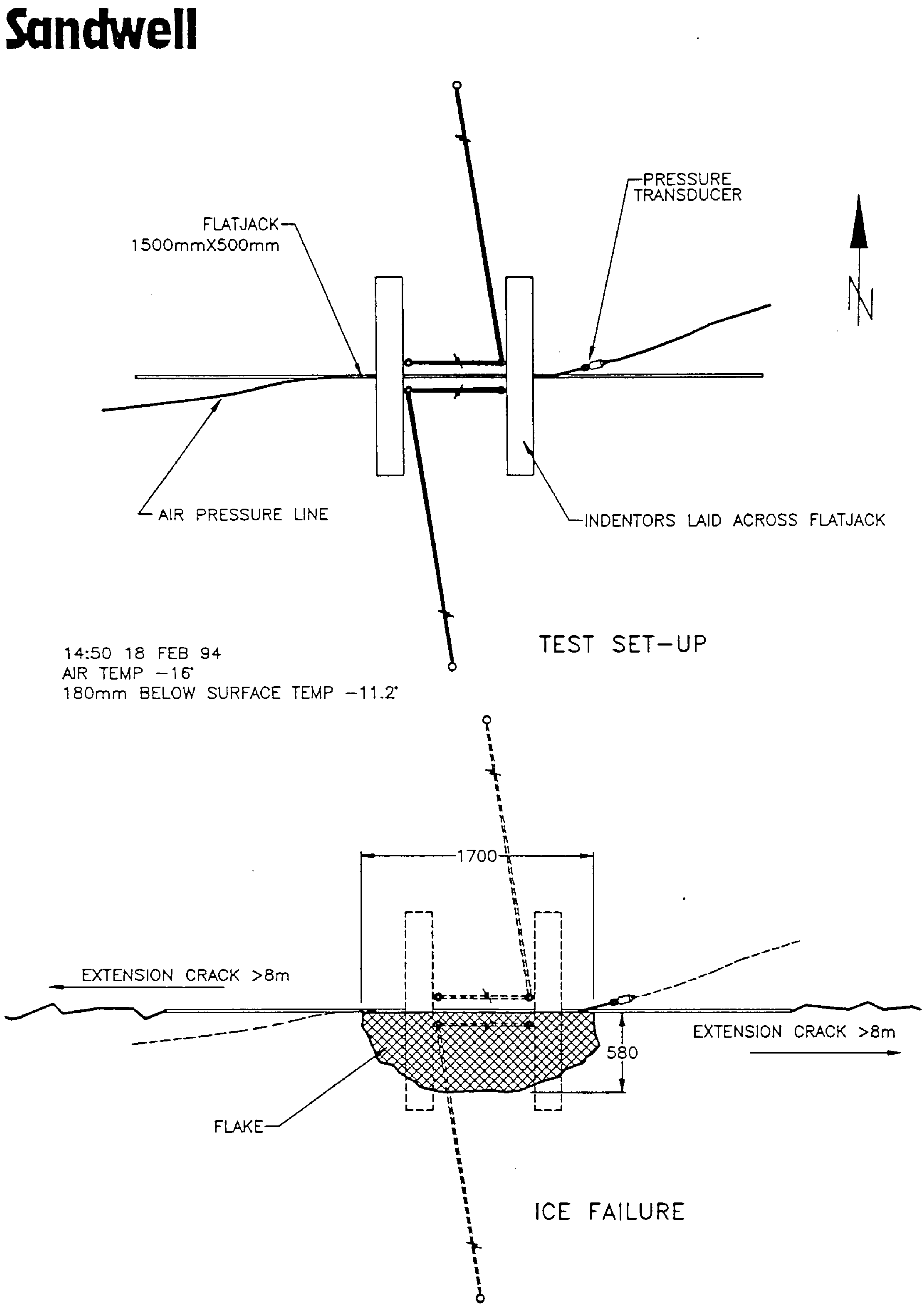
ACAD 3281C014.DWG

12:15 18 FEB 94
AIR TEMP −16.5°
TEST WAS DONE AT LOCATION OF TEST 12



CRACK PATTERN FOR TEST 15

Sandwell



TEST SET-UP FOR TEST 16

ACAD\3128C015.DWG

Helsinki University of Technology
Arctic Offshore Research Centre

Otaniemi 11.10.1994

REVIEW OF THE REPORT

Sandwell Inc: Ice Flaking Tests Conducted with a Gas Actuator System
June 1994

Submitted to INSROP Project I.1.7. Large Scale Hull Loading of First Year Ice. Review performed by Dr. K. Riska, Helsinki University of Technology.

Scope

The work carried out is associated with an active research topic, structure-ice interaction. Recent research has pointed out that the brittleness of ice may control the failure type of ice. The failure may occur through some micro cracking mechanism when the ice is less brittle i.e. in slow loading rate or warm ice. A flaking or spalling mechanism is thought to take place when ice is more brittle. The subject area of the report is to investigate the flaking failure. The research topic as such is a valid one.

The present test series may shed some light on the flaking problem. More physical insight would have been obtained, however, if the test series would have been preceded by some theoretical calculations. These would have shown that the cracks in similar geometry like in the tests should run towards the lower edge of ice complicating the interpretation of test results, see (Ingraffea 1987). Boundary element calculations of J. Tuhkuri confirm this, see the attached figure.

Performance of tests

The tests were performed in a professional manner. The reporting was comprehensive. Only the data about ice type together with ice thickness and other geometric data was missing. Also vertical sections perpendicular to the slot would have illuminated much the ice failure patterns. Finally it was stated that thin sections were made by IMD. Inclusion of these results would have improved the present report.

Test results

The test results include a measure of the expansion of the flat jack, pressure inside the flat jack and description of the ice failure patterns observed on top of the ice field. These results are as such difficult to apply in investigating the structure-ice contact as only some clues to cracking pattern in ice floe splitting or through body cracking may be obtained. The test series provided much insight for this kind of testing, the advantage of which is that it is easy to perform. Modifications to the present test system could

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achieve the goal to produce flakes in a controlled manner and register the forces required.

Conclusion

The present test series together with the previous one carried out in Resolute Bay in winter 1993 should be seen as a pilot test series. The final aim should be to gain understanding which parametres control the force when ice is failing in the flaking manner and what are the parametres determining the type of ice failure. In the conclusions of the report the two aims of the project were stated. These were to investigate the rigid flatjack configuration and air as the pressurizing medium. These aims were fullfilled per se.

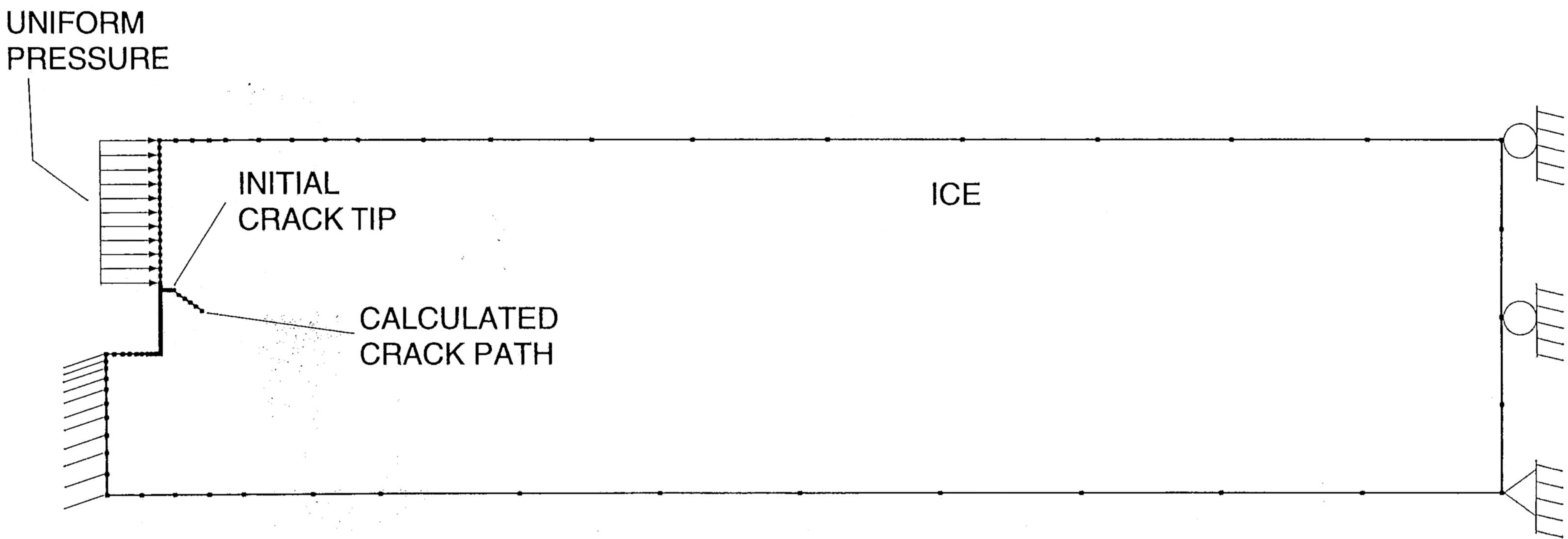
The application of this kind of empirical research to ship hull loading is, however, a task which requires much work. The first open question is what type of ice edge failure determines the design ship hull loads. If it is identified that flaking is that mechanism then tests concentrating on flaking should be carried out. This comment points out the possible direction of continuation of this project.

Reference

Ingraffea, A. 1987: Theory of Crack Initiation and Propagation in Rock. In Fracture Mechanics of Rock, ed. B. Atkinson, Academic Press, London 1987, pp. 71-

Kaj Riska, Dr. Tech.

In response to these reviewer's comments we attach Appendix A which gives the thin section analysis of the pond ice referred to in the text.


UNIFORM
PRESSURE
INITIAL
CRACK TIP
ICE
CALCULATED
CRACK PATH

APPENDIX A: THIN SECTION ANALYSIS OF ICE FROM THE SITE OF THE FIELD TESTS

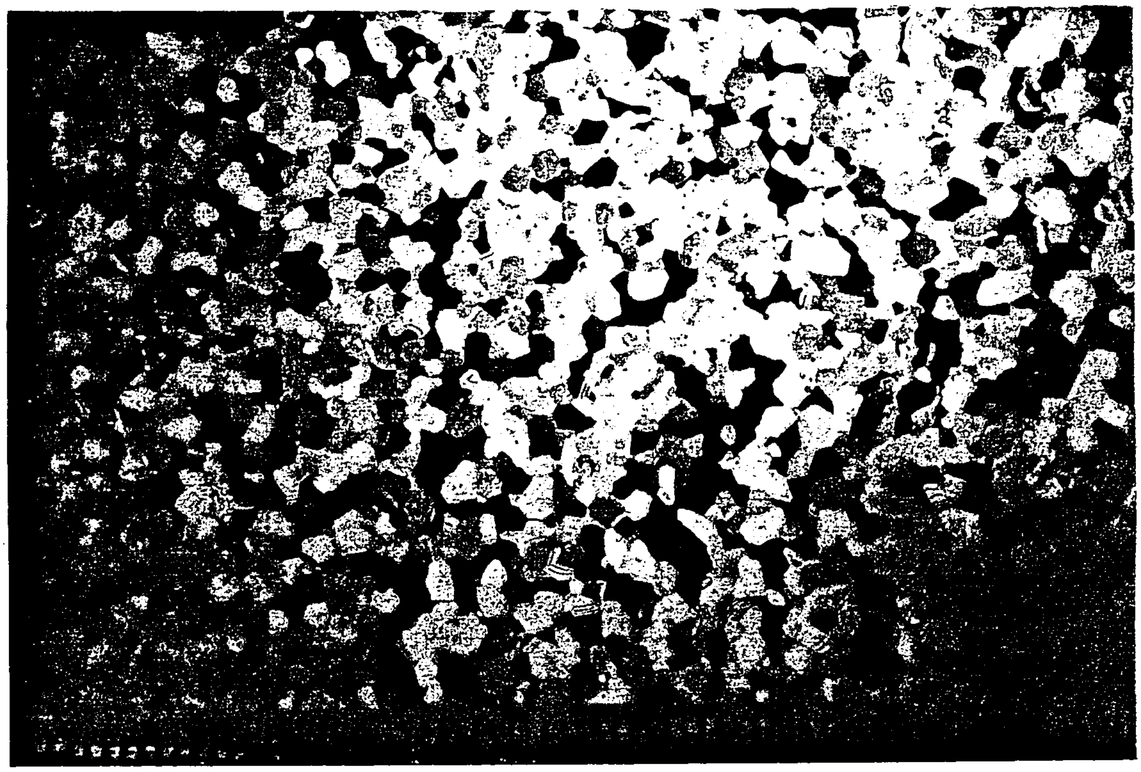
The thin section analysis was performed on two pieces of ice taken from locations on the pond within 0.5 m of each other, near one of the test sites. The pieces extended through the full thickness of the ice cover. One piece was a vertically-oriented rectangular column from which horizontal thin sections were taken at 10 cm intervals, starting near the top surface. These were prepared using a microtome. The second piece was a vertically-oriented plate from which a single large thin section was made by melting the plate, to a thickness of 2-3 mm, using a slightly warmed flat metal surface. This section showed the crystallographic structure throughout the full thickness of the pond ice.

Figure A1 shows the series of horizontal thin sections. The ice was fine grained at the surface (Figure A1, a). This indicates that it probably started to grow when snow crystals fell on the pond when the water was at the freezing temperature, and that the ice was therefore S2 type. The ice grains grew down from the surface as columns that gradually increased in diameter with depth (Figure A1 and Table A1). The grains were initially fairly equi-axed with no interlocking and no preferred c-axis orientation. These characteristics continued to a depth of about 30 cm, at which point a distinct transition occurred (Figure A2). Below this transition the columnar structure of the ice was much less defined and grains appeared tangled. The grain size increased dramatically. The reason for the transition is not clear, however, it may have been caused by the growth of dendritic ice fingers from the edge of the pond, underneath the ice that was growing down from the surface.

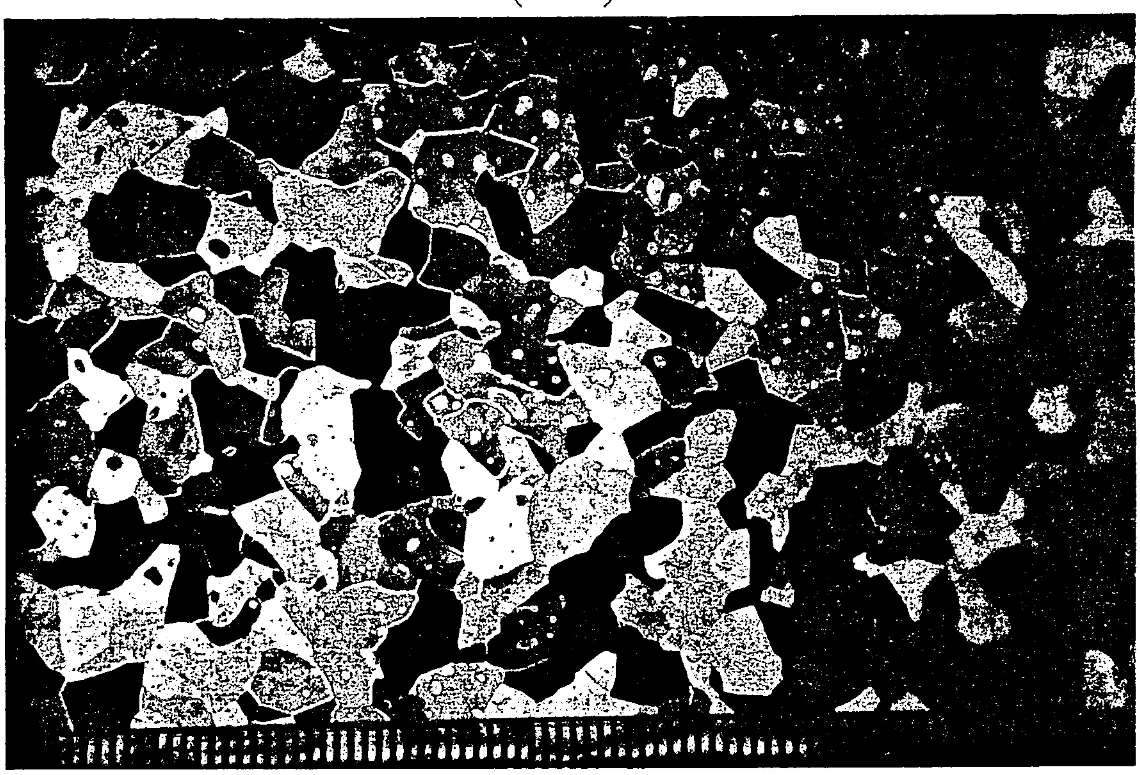
The ice was relatively free from air bubbles throughout its full thickness except for the bottom few centimeters.

Table A1: Approximate grain diameter (in section) at 10 cm intervals throughout the full thickness of the ice sheet.

Depth (cm)	Grain Diameter (mm)
0	1-3
10	4-10
20	5-16
30	7-23
40	11->30
50	>46

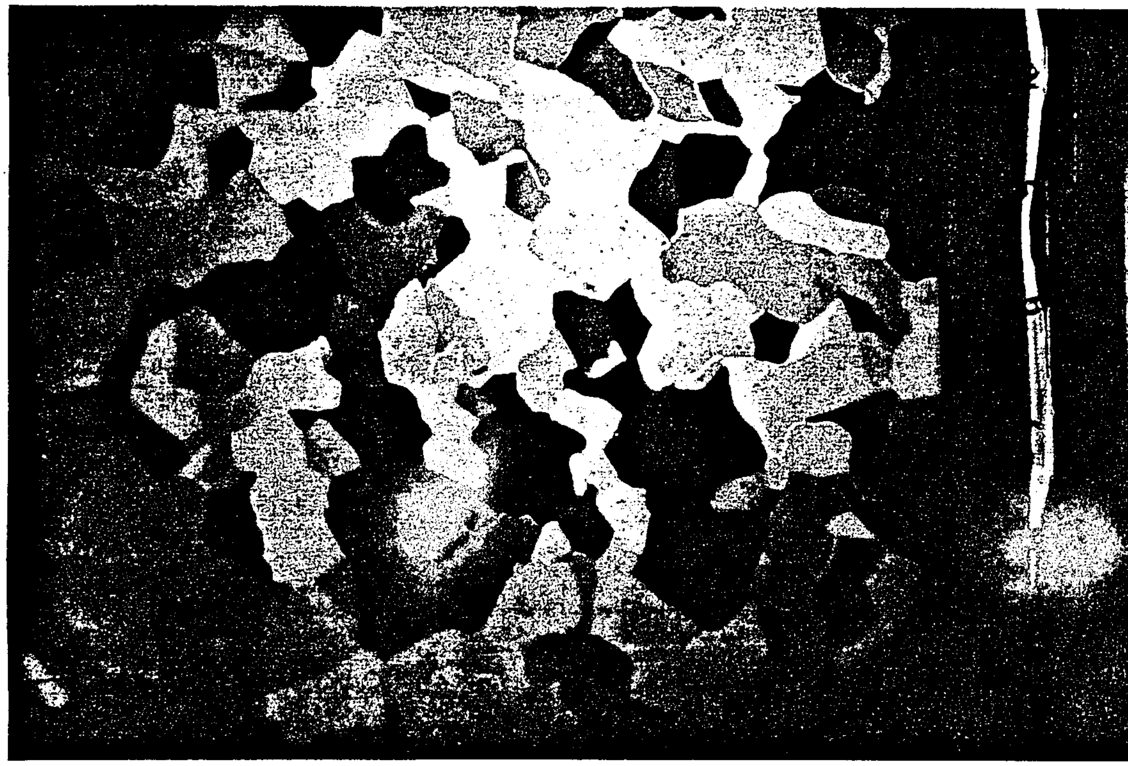


a (0 cm)

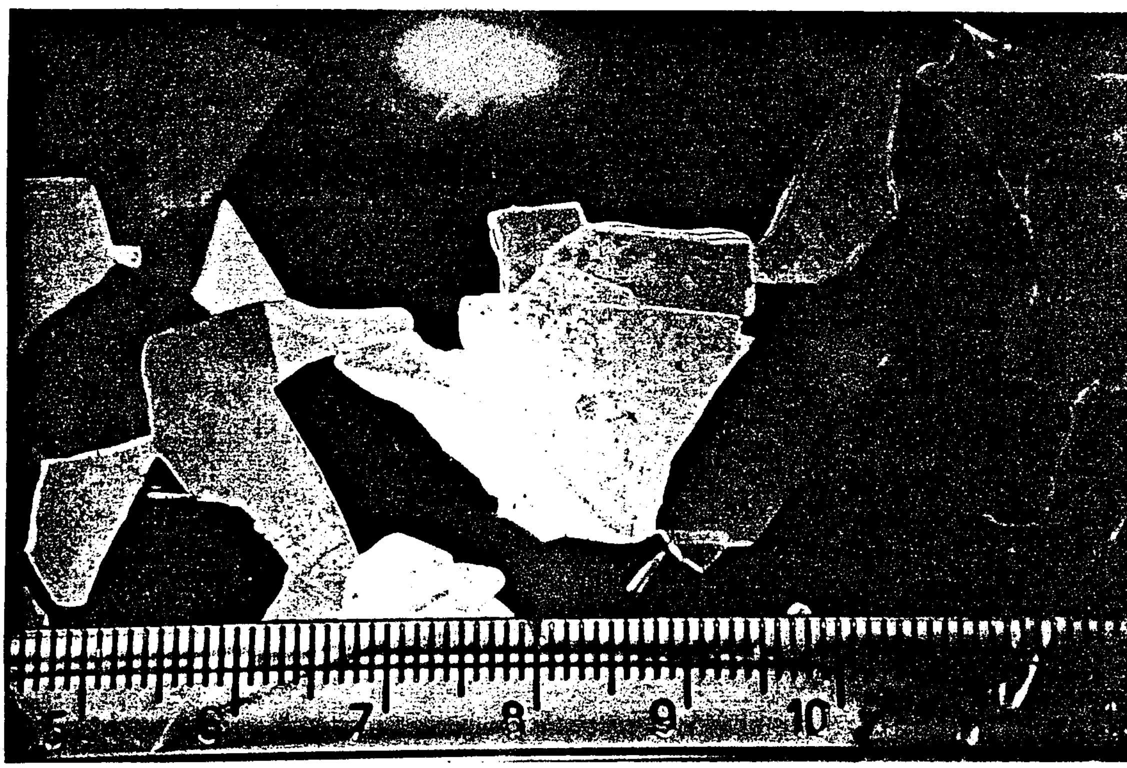


b (10 cm)

Figure A1. Series of horizontal thin sections at 10 cm depth intervals, starting from the top surface, through the full thickness of the ice cover. The small unit on the scale is millimetre.



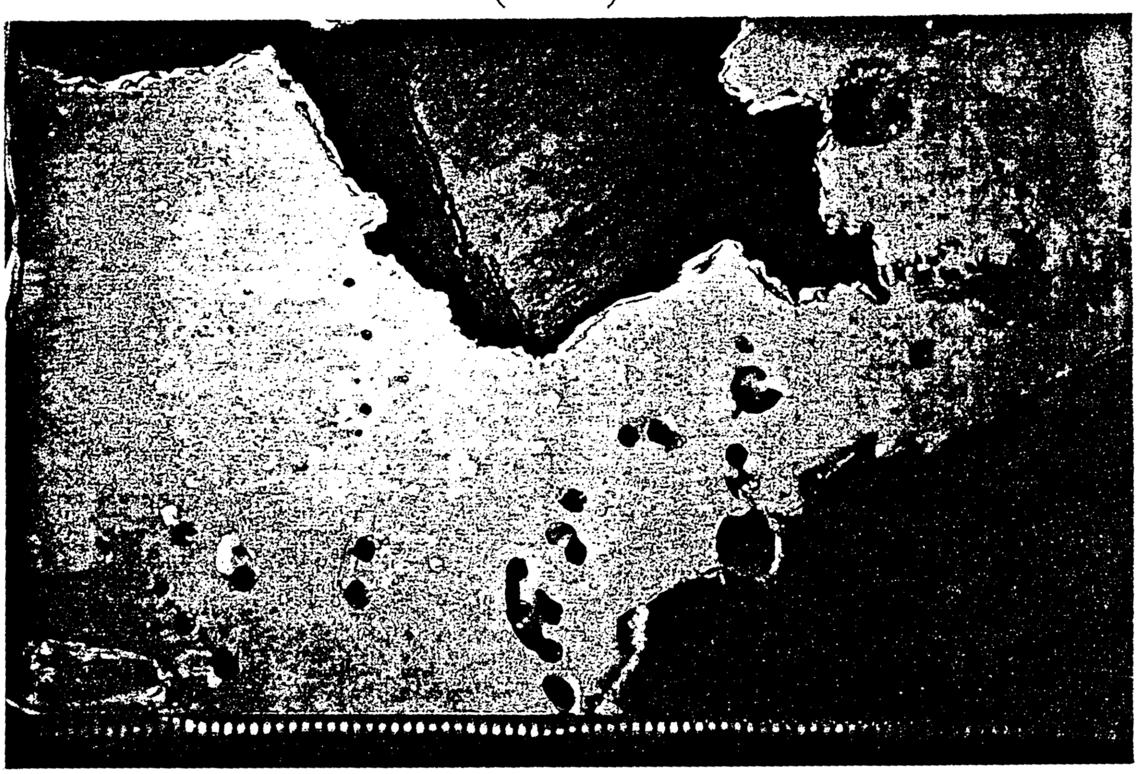
c (20 cm)



d (30 cm)

Figure A1. Continued.

e (40 cm)



f (50 cm)

Figure A1. Continued.

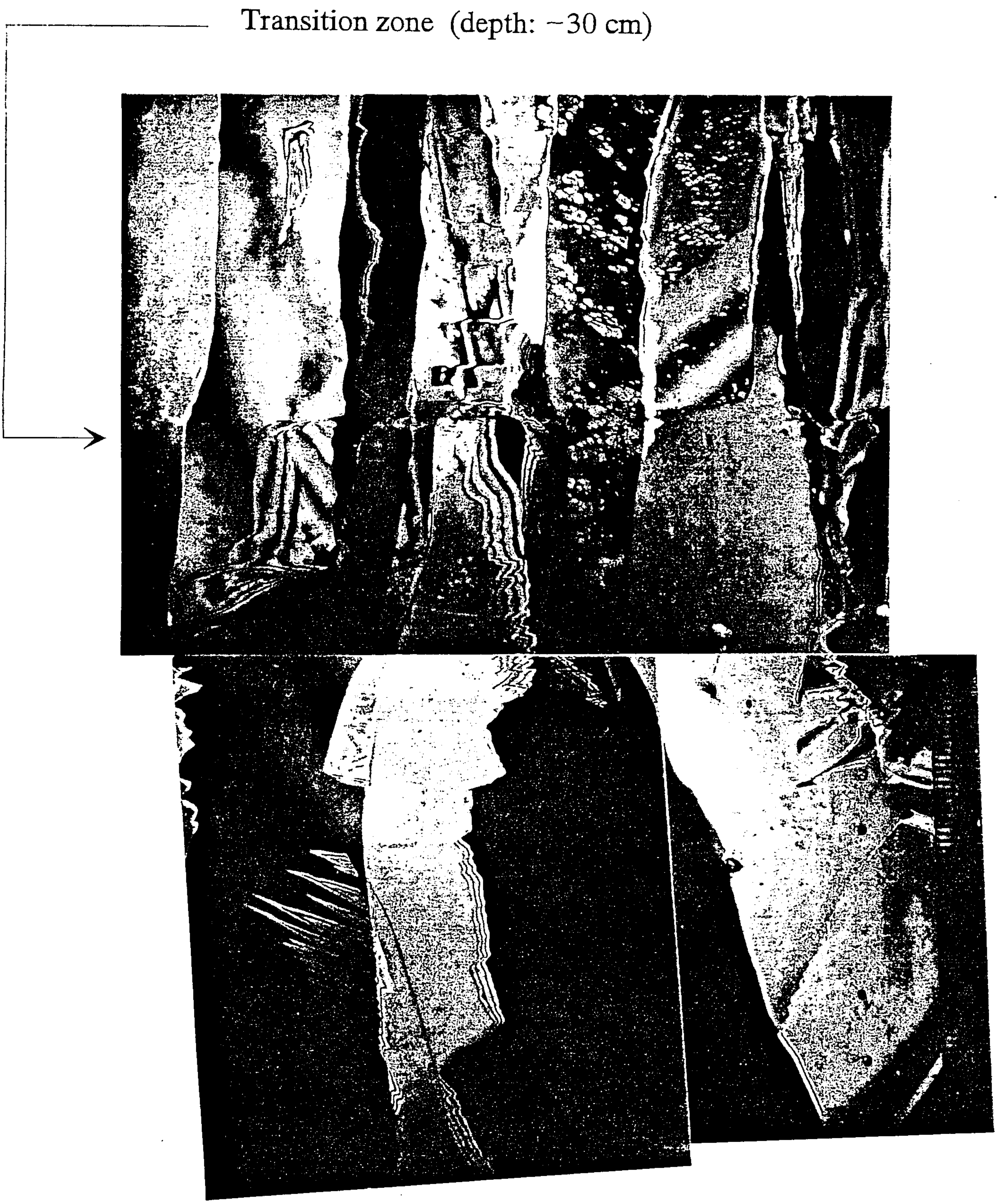
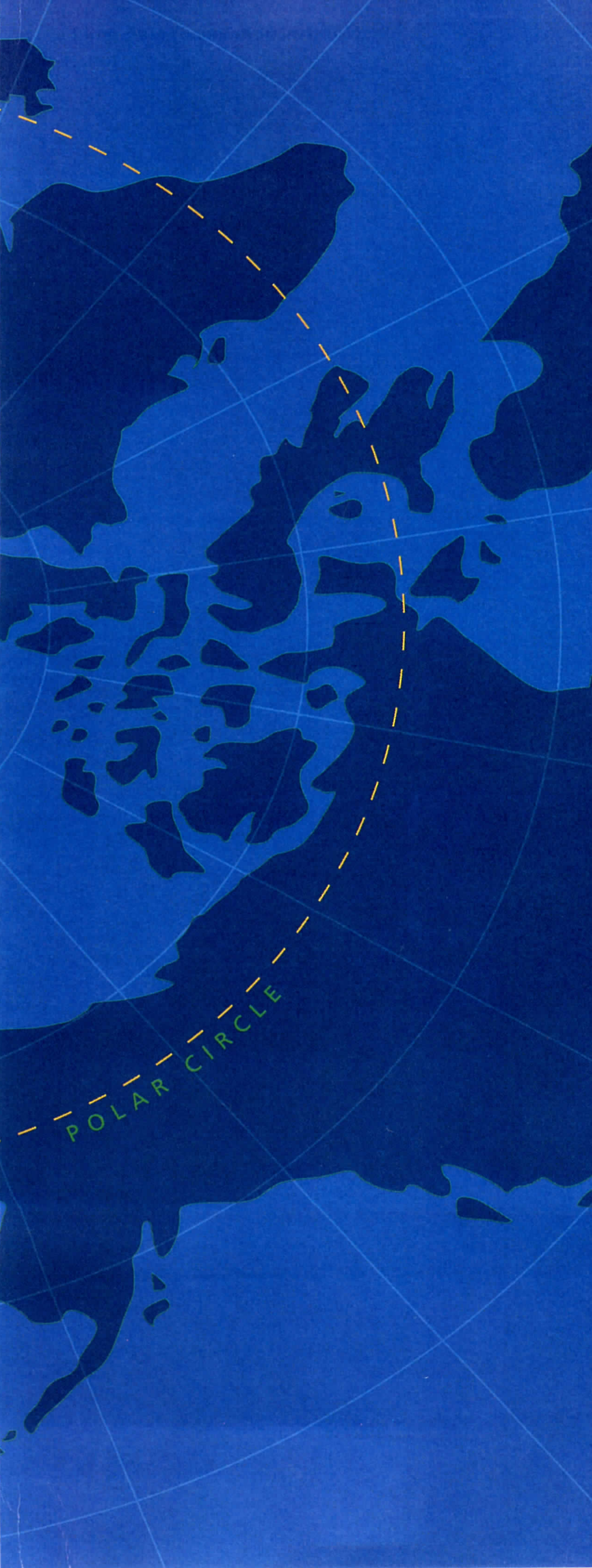


Figure A2. Mosaic showing the segment of the large vertically-oriented thin section where the transition from columnar ice (top) to the structurally disrupted region (bottom) occurs. The markings on the scale at the right correspond to millimeters.



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.