DESIGN METHODOLOGY FOR DUCTILE FRACTURE CONTROL ON THE ALASKA HIGHWAY PIPELINE PROJECT

Foothills Pipe Lines (Yukon) Ltd.
February 1, 1978

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1.0 INTRODUCTION

The function of this report is to provide an overview of the design methodology for ductile fracture propagation control, as adopted for the Alaska Highway Pipeline Project. In the following sections the background for this design consideration is outlined to place it in perspective. This is followed by a description of the design objectives and basic work completed to date. The next section details the plans for confirmatory testing of the design components which will be used to finalize the design. The final sections describe the development of design acceptance criteria and their application to final design and construction.

2.0 BACKGROUND TO THE PROBLEM

At the outset, it should be pointed out that the primary fracture control design is related to prevention of fraction initiation through specification of high minimum fracture toughness in the pipe. This ensures that the largest possible defects can be sustained without allowing fractures to initiate. This aspect has been described in detail in the applications, related submissions and evidence, as well as in the technical literature.[1] As a result, the adoption of a design to control ductile fracture propagation length is considered a supplementary or backup design measure.

Where minimum notch toughness has been specified for conventional large diameter gas pipelines, it has been done so primarily for the control of fracture initiation. This has provided a low incidence of fracture initiation and has contributed to the short length of fractures where they occur. The rapid arrest of the large majority of such fractures results mainly from self-arrest due to pipe toughness and from circumferential fracture of normal field girth welds. The former factor comes into play due to the distribution of higher toughness pipe above the minimum specified level, which is normally obtained in achieving the minimum. The latter factor, like other natural crack arrestors (heavy wall pipe, weights or components), is built into any pipeline. This general experience suggests that a very low probability of experiencing a long ductile fracture exists for a pipeline rigorously designed for fracture initiation.

While the proposed pipeline system is rigourously designed for fracture initiation and the above conclusions remain valid, the adoption of supplementary requirements for ductile fracture length control is felt necessary in this case. This necessity arises from the need to more accurately predict the probable fracture lengths within the overall low probability associated with fracture initiation. The probable fracture lengths, in turn, relate to the assurance of high pipeline reliability, through the ability to make repairs without extended outages.

3.0 BASIC FRACTURE PROPAGATION CONTROL DESIGN METHODOLOGY

3.1 Design Objectives and Components

As introduced in the previous section, the basic objective of the design is ensuring that in the unlikely event of initiation, the fracture lengths are tolerable and that these lengths can be reliably predicted. The first step in achieving this objective is the selection of mechanism(s) for fracture arrest in terms of parameters which are known at each point along the pipeline. Where arrest due to pipe toughness is selected, the fracture propagation phenomenon must be characterized in terms of three fundamental components. These are a fracture arrest hypothesis, gas decompression behavior and pipe toughness distribution. A knowledge of these components then allows the statistical analysis of the fracture event for the unique operating conditions associated with each point along the pipeline. The final result can then be given in terms of fracture length and the overall probability of experiencing such a length.

In the following, each of the three components are described in terms of the knowledge available to date. The preliminary fracture length prediction study is then outlined.

3.2 Fracture Arrest Mechanism

To accurately predict fracture lengths, a reliable mechanism or mechanisms for arresting a fracture must be available. The present design is based primarily on having pipe with toughness levels capable of arrest, distributed along the pipeline. The primary design mechanism selected is called self-arrest. The rationale for selecting this method relates to its being consistent with the use of high toughness for the primary design (fracture initiation) and its proven effectiveness in full-scale tests.

A design utilizing the self-arrest by pipe toughness mechanism is based on the observed fact that fracture velocity is a function of the toughness of the pipe in which the crack is propagating at a particular time. When toughness is high enough, zero velocity or arrest will result. While a number of relationships have been put forward for the prediction of arrest toughness, the proposed design adopts the Battelle Hypothesis.(1) (2) It has been selected because comparison with the available full-scale test data in the literature, as a whole, shows that reasonably accurate but conservative predictions result in the range of pipe size and operating pressure of interest. In addition, it provides a detailed pressure, velocity and toughness relation for comparison with gas decompression curves and, in this way, can accommodate complex (two-phase) gas decompression behavior.

The specific relationships provided by the Battelle Hypothesis are available in the literature (1) (2) and their application to this specific project has been described in the applications and supporting evidence. These relationships provide the required toughness for arrest, or alternatively, the fracture velocity for a given toughness, as applied to the range of operating conditions that exist along the pipeline.

A secondary arrest mechanism is provided by action of natural crack arrestors. More specifically, weights and heavy wall pipe sections appear to provide arrest capability as well as being located at predictable locations along the pipeline. Therefore such components can and should be included in the statistical calculation of fracture length.

3.3 Gas Decompression Behavior

The driving force for ductile crack propagation is provided by the local gas pressure that exists at or immediately behind the propagating crack. The magnitude of this pressure, and therefore the force driving the crack, is controlled by the rate at which the gas decompresses upon rupture. This is normally characterized as a decompression wave travelling along the pipeline away from the fracture initiation site, in the same manner as the crack propagates down the pipe.

This wave is described by a pressure versus velocity relationship similar to the pressure versus velocity relationship that the Battelle Hypothesis predicts for each pipe toughness. Arrest in a particular pipe length having a given toughness is predicted when these curves do not intersect (i.e., the decompression wave is ahead of the propagating crack, thus insufficient driving force exists for propagation). Alternatively, propagation continues in a particular pipe having the toughness considered when the curves intersect (i.e., the propagating crack is ahead of the decompression wave and the driving force at the crack tip is maintained).

Given the critical relationship between crack propagation or arrest and decompression behavior, a necessary component of the fracture control design is an accurate characterization of gas decompression behavior. If the gas approaches pure methane (i.e., lean gas), this behavior is well established and defined by a simple continuous relationship.[(1) (2)] However, the gas involved in this pipeline is relatively rich in that it contains other components that become liquids upon decompression. This can cause a discontinuity or plateau in the decompression curve, which effectively delays the rate of decompression. The effect of this two-phase decompression behavior is to make crack arrest more difficult, and therefore, requires higher arrest toughness.

For the present design, the decompression behavior has been predicted by an analytical method that uses the actual gas composition and can account for the two-phase decompression behavior.[(3)] Its accuracy has been checked experimentally by shock tube tests.[(4)] This prediction can then be used in conjunction with the Battelle Hypothesis to predict the required arrest toughness and, subsequently, the fracture lengths. The shock tube tests indicated that secondary effects occur at some distances from the origin. These have been investigated[(5)] and found to be due to pipe friction and heat transfer. However, these investigations have also shown that the effects are manifest only at long distance from the origin in large diameter piplines.

3.4 Pipe Toughness

In order to apply the Battelle Hypothesis, it is necessary to know what pipe toughness a propagating fracture will encounter as it moves from pipe length to pipe length away from the point of initiation. This is obtained from the distribution of toughness obtained on pipe produced to the specification used. For the present design analysis, a distribution is provided by that which was actually obtained from 10 miles of 42" pipe in the proposed wall thickness.[(6) (7)] This pipe was made to a specified requirement of 50 ft. lbs. minimum and 80 ft. lbs. mean by the two prospective Canadian manufacturers.

It should be noted that the selection of the 50 ft. lb. minimum/80 ft. lb. mean specification for toughness was not arrived at analytically as part of the fracture control design. It simply represents the best toughness that was available on a production basis at that time in North America. In effect, it provides a baseline for statistical analysis. The resulting distribution is considered conservative for design purposes. A better toughness distribution is anticipated from the currently proven manufacturers once in full production.

3.5 Fracture Length Prediction

As stated above, the ultimate objective of the fracture propagation design is to limit the potential fracture to an acceptable length. Because each point along the pipeline is effectively unique in terms of the pressure and temperature, the prediction of fracture length is essentially a statistical problem. The analysis used to address the problem and the results for the northern portion of the project have been presented elsewhere. [8] In effect, this work takes the pressure/temperature gradients that will exist during normal operation along the pipeline, superimposes a toughness and natural crack arrestor distribution for the pipeline, and then calculates the probability of various fracture lengths, using the selected arrest hypothesis and pre-established decompression behavior, applied incrementally along the pipeline.

4.0 CONFIRMATORY TESTING OF THE BASIC DESIGN

4.1 Confirmatory Testing Requirements

The methodology described and the results referenced above provide a basic measure of the design development to date. However, this is based, in part, on the assumption that the characterization of the phenomenon is as valid or conservative for the proposed pipe sizes and operating conditions as has been shown for the sizes and operating conditions on which the characterization is based. Therefore, it is felt that it is necessary to confirm these relationships for the project conditions.

The specific areas requiring confirmitory testing have been identified as the effectiveness of natural crack arrestors, the influence of backfill properties on fracture propagation and arrest, the relationship of other fracture toughness tests to arrest toughness and the full-scale propagation and arrest behavior of project pipe under operating conditions. In the following, the planned evaluation of these aspects is outlined with particular emphasis on the full-scale burst test program, which is intended to directly confirm the primary self-arrest mechanism.

4.2 Natural Crack Arrestor Evaluation

In order to support the inclusion of natural crack arrestors in the fracture length prediction analysis, some demonstration of their effectiveness is planned. Preliminary plans call for a full-scale burst test to be conducted at an existing contract test site. This will employ natural gas exhibiting two-phase decompression and pipe capable of propagating a ductile fracture. On one end of the test section, commercial full encirclement, bolt-on weights will be placed and on the other a section of heavy wall pipe will be installed. In both cases the arresting component will be as close as possible to the normal pipeline installation.

4.3 Model Test Evaluation of Backfill Behavior

A model test program at an existing facility is planned to determine, initially, whether frozen backfill acts in a different fashion relative to unfrozen backfill. Should frozen backfill prove to be a significant variable, further model tests will be conducted to evaluate variation in this type of backfill. These tests are simply comparative with each other and designed to identify the relevance of this variable in the chilled sections of the pipeline.

Concurrent with this work, a review of the mechanical properties exhibited by frozen soil will be undertaken, with particular emphasis on dynamic properties. This work is intended as a basis for quantifying any effect, should it exist.

4.4 Evaluation of Pipe Fracture Toughness

Ontario Research Foundation (ORF) has a program underway on behalf of the project to investigate various toughness tests using pipe at various toughness levels. This is aimed at establishing the best method of specifying toughness from a propagation viewpoint. Burst tests have, in general, been assessed on the basis of Charpy energy. Battelle and others have worked on relating the behaviour to DWTT energy. Various groups have looked at propagation behaviour on the basis of other tests. The ORF program will select the most appropriate test(s) on the basis of suitability for use in a pipe mill and the accuracy of prediction of propagation behaviour. This selection will then be used as part of the burst test program, both in the selection of pipe for the test and for evaluating the results.

4.5 Full-Scale Burst Test Program

4.5.1 Test Program

The total number of tests required will depend on the final decision on pipeline size. The sponsors believe that duplicate test data must be obtained for each design variable to be tested and, therefore, that a minimum of two tests must be planned, based on the past experience that up to half the data from the tests is lost or unuseable. Each test yields two sets of data (fracture propagates in two directions); therefore, two tests yield four sets of data, and even if half is lost, duplicate results will be available. Although two tests are planned for each variable, in some cases one test will be sufficient if duplicate data is obtained.

The remainder of this document is based on the assumption that a decision in favour of the 48"/54" low pressure system will be reached; any other decision or no decision would result in major changes in the remaining discussion.

The first test is currently proposed to be run at a reduced pressure and natural ground temperature. The test would be designed to obtain as much information as possible and to check out the new facility. Since more information is obtained in a test in which arrest occurs, and the conditions resulting in arrest are of the greatest importance, it is considered prudent to start at a reduced pressure for the first test. It is also imperative that a warm (not in the winter and without major artificial cooling) test be conducted before refrigerated tests are undertaken. There are two prime reasons for this: start-up problems with the equipment and possible instrumentation problems. The equipment can only be fully tested by conducting a test. Small equipment problems can be sorted out in a warm test by introducing a delay, but in a cold test the same problems may force venting of the test gas due to a pressure rise. The equipment may also have additional cold temperature problems which, when combined with the normal start-up problems, result in a much greater risk of a negated test. With a warm test, any instrumentation problem (on the pipe or buried cables) can be corrected by excavation without damage to the instrumentation; in the case of a cold test (frozen soil), this is almost impossible.

The test program for the whole project would, therefore, consist of a minimum of three successful tests: one 48" cold, one 48" warm and one 54" warm. To achieve these successful tests, it is necessary to plan for two tests in each case. Additional tests may be conducted if any of the participating companies decide that mechanical crack arrestors are required for a specific area or if additional data is required for the 48" warm case at full pressure (about 1100 psig is planned for the first test). Additional tests may also be required to accommodate specifically imposed regulatory requirements or specific design features.

All six planned tests would consist of a center section with special welds for the actual test of propagation resistance, bounded by conventional pipeline welds which may arrest the fracture if the pipe did not. Bolt-on weights, or other types of crack arrestor configuations under consideration, would be installed beyond these welds to act as crack arrestors if both the pipe and welds failed to arrest the crack. Beyond these would be the reservoirs (additional lengths of pipe) with the associated anchor forgings and inlet connections. These reservoirs supply gas to the failure so that the decompression in the test section simulates an infinite length pipeline. The pipe lengths are arranged so that toughness is increasing as the fracture moves away from the origin.

Fracture speeds are measured by means of wires around the pipe at two-foot intervals. Failure of these wires indicates passage of the fracture. The time of the wire failure is recorded and, from this, the fracture speed can be calculated. The gas decompression behaviour is determined by means of pressure transducers at a number of locations along the pipe. The pressure is recorded as a function of time at each location. Both the timing wires and the pressure transducers would be installed on the pipe prior to laying it in the ditch. After welding the pipe into the test section, the instrumentation is connected by cables to the recorders and the circuits checked.

The test section is then backfilled and pressure tested. After dewatering, the line is pressured with gas of a similar composition to that proposed for the pipeline. If required, the temperature would be adjusted at this time. Valves isolating the test section from the remainder of the equipment are then closed and the equipment blown down. A rupture is then initiated in the center of the test section. This results in a linear longitudinal defect significantly larger than the critical crack size, resulting in propagation in both directions.

Arrest is not expected within about 60' in each direction from the origin because time is required to allow sufficient gas to escape, thereby reducing the pressure at the fracture tip, and lower toughness pipe is used near the origin. After the fracture passes this initial length, it encounters higher and higher toughness pipe and, at some point, arrests. This provides a measure of the toughness required for arrest. The fracture speeds and their variation with distance from the origin also provide information on the arrest toughness.

In practice, the pipe lengths will be picked to differ from the adjacent pipe lengths by about 10 ft. lbs. and, therefore, the actual arrest will only bracket the arrest toughness (e.g., propagates through X ft. lbs., arrests in X + Y ft. lbs., therefore the arrest toughness is greater than X ft. lbs. and less than X + Y ft. lbs.). The fracture speed behaviour in the joints which permit propagation would give an indication as to where in the range the arrest toughness is, as would the length of propagation in the arrest joint.

Present plans call for warm tests in the summer of 1979, followed by the cold tests in the winter of 1979/1980.

4.5.2 Test Site

The primary factors to be considered in locating a test site are:

1. Source of natural gas which does not require extensive modification.
2. Away from populated areas.
3. Soil conditions permitting year-round access and construction and simulating the right-of-way soil conditions. This could also be accommodated by soil replacement.
4. Low winter ambient temperature to ensure good frost penetration for the chilled tests.
5. An area which will not cause problems obtaining a government permit (environmental, etc.).

6. Hill preferred on the boundary of the site for an observation point.
7. Airstrip and road within reasonable distance of the site.
8. Minimization of the length of road and supply pipeline construction.

The test site would consist of a one square mile fenced area. In addition, we would require permission to limit access within a half mile of the site boundary during a test.

It is estimated that clearing would be required on about seventy-five acres within the site, but this will depend on the site's specific topographical details. The areas to be cleared would include a strip along the test section to act as a fire guard, a strip from the pipe to the chiller and the gas mixing equipment, and a strip for the installation of the fence and road. Further clearing may be required to provide visual observation of the pipe from the instrument building and the observation site. Depending on location, and in particular the presence of roads or seismic trails, clearing may also be necessary for access and/or construction of the gas supply pipeline.

At present, we are looking at a site in Alberta (S10, T111, R5 W5) and another in the vicinity of Station N4 on the WTCL system (122^{o} 15'+ W, 56^{o} 50' N). Both sites meet the selection criteria and will be evaluated on the basis of costs and benefits. The sites are located on the drawing which follows, with further details provided on two additional drawings in the envelope in the back of this report.

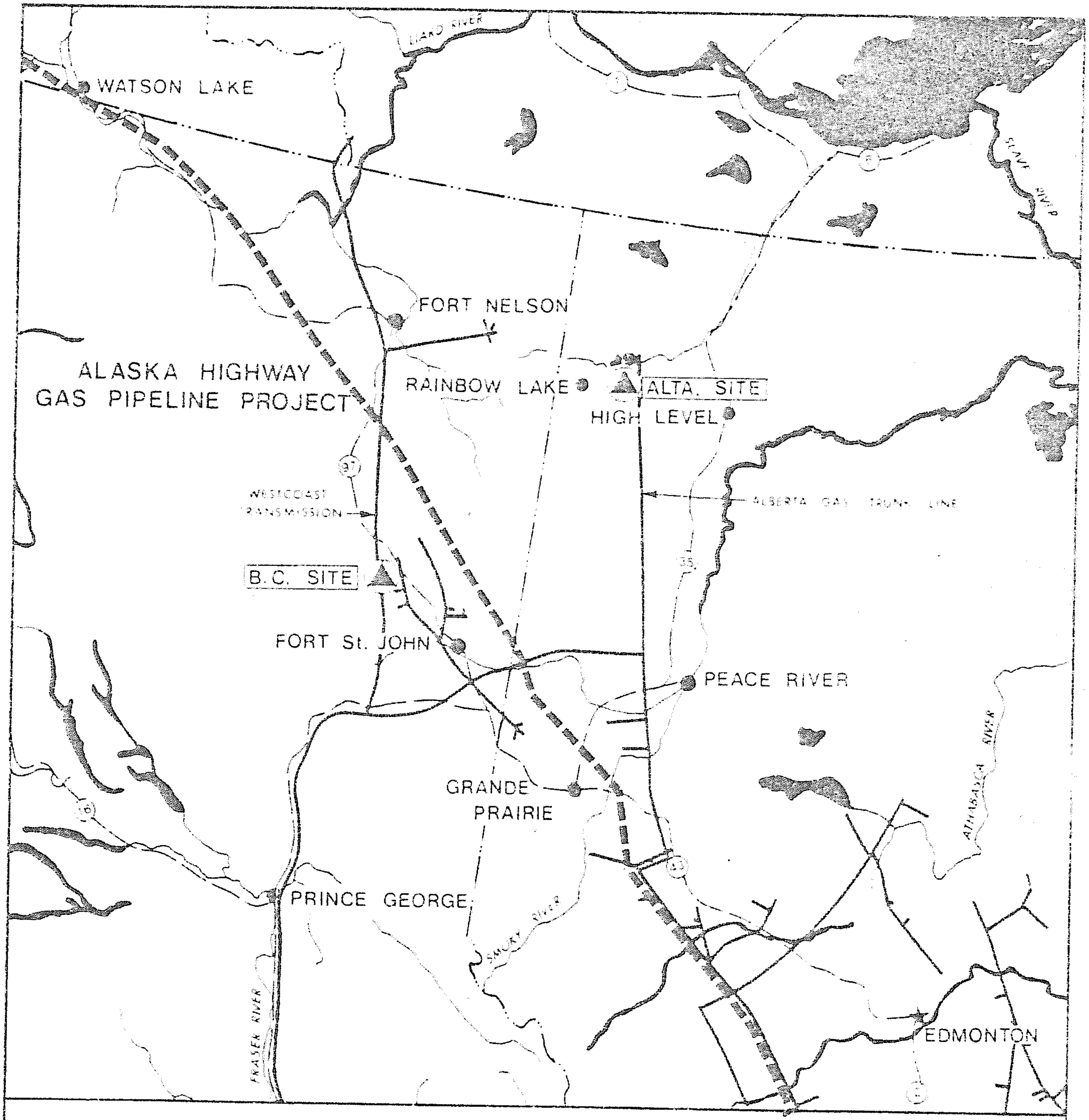
4.5.3 Facilities

The primary facilities necessary at the test site are: the pipe test sections with reservoirs, equipment to vary the temperature of the gas within the test section, equipment to supply the natural gas at the correct pressure and composition, and the instrumentation necessary to obtain the test results.

A general arrangement drawing showing the location of the groups of equipment at the Alberta site, a general piping diagram and the associated major materials list are in the envelope in the back of this report.

Line Pipe

In addition to the heavy wall pipe for the reservoirs, the test will require test pipe with specific toughness. To obtain this range of toughness, it will be necessary to melt



BURST TEST SITE LOCATIONS

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a number of heats of steel. These heats would yield far more pipe than would be required for the tests, and the excess pipe will be stockpiled for the project and other testing. This will allow the steel company to melt sufficient steel to obtain a range of properties and pick and choose plates to be made into the test pipe. The test pipe for the warm tests would probably not be manufactured until after completion of the installation of the cold expansion equipment at Welland and/or the installation of desulphurization facilities at Regina. The need to use offshore melted steel for producing the pipe for the first warm test is presently being investigated. The test pipe for the cold tests would probably be a long seam product.

Chilling Package

This package unit would fill two primary purposes: heavy hydrocarbon removal and circulating gas temperature control. The package would consist of three primary units: two tubular heat exchangers and a package propane refrigerator. A number of smaller items would also be included such as separators, dehydrators and glycol injectors. One of the exchangers, using propane, would chill incoming pipeline gas in order to remove heavy hydrocarbons. The other exchanger, again using propane, would form part of the circulating loop and be used to chill the gas in that loop.

Line Pack Compressor

This unit would take the gas from the supply pipeline, after passing through the hydrocarbon removal unit, and compress it to the desired test pressure. An aerial cooler would be included to reduce the exit temperature of the gas.

Gas Component Additions

Facilities would be provided to add additional quantities of the individual gas components to modify the pipeline gas composition to approximate that proposed for the project. Because the storage of gaseous components is expensive, a gas pipeline source has been selected which does not require major changes in these components. Because there is no economical method of removing either nitrogen or carbon dioxide, the test gas may contain significantly higher quantities of one of these than that proposed for the project. Both components have only minor effects on the gas decompression behaviour because their percentages would not be significantly different in the gas and liquid phases than they were in the all-gas phase.

Circulating Compressor

This unit would circulate the test gas around a loop consisting of the test section, small diameter feeder lines to and from the test section, the gas temperature control heat exchanger, and the addition point for gas components. The required differential pressure is small, but the need for a casing which will withstand the operating pressure results in a non-standard design item.

Electric Generator

If power is not conveniently available from another source, a diesel electric generator will be installed to provide power for the chiller unit and the instrumentation, lighting, etc.

Buildings

A trailer provided with a blast shelter will be included to contain the instrumentation. A shop building will be provided for instrumentation of the pipe joints and other miscellaneous work.

Instrumentation

Instrumentation will consist of timing wires installed at about two-foot intervals along the test section and six or more pressure transducers. Alternate timing wires and pressure transducers would be connected by a multi conductor cable to a recording system located in the trailer. The remaining wires and transducers would be connected by a parallel cable to a separate recording system. This system will provide redundancy, as even with failure of either system, sufficient data will be obtained to analyze the test.

4.5.4 Schedule

A preliminary schedule up to the first test is included in the envelope in the back of this report. Because it is not considered prudent to conduct a cold test at a facility which has not yet done a warm test, the attached schedule is based on doing a warm test as early in 1979 as possible. An evaluation is being conducted to determine whether the program can be accelerated to allow a first test in the fall of 1978. It is not considered wise to have instrumented pipe in the ground during spring breakup or to attempt to install it during spring breakup and, therefore, the earliest test would be in early July. This date can be met if the reservoirs and preliminary site work are done the previous fall. The critical items, therefore, are: to obtain approval for the use of the site, to do site preparation work, including construction of roads and a pad for the shop, and delivery of the pipe and associated fittings for the reservoirs. These are critical items in terms of completing the reservoirs in the fall. It is possible to install these reservoirs during the winter, but it is preferable that the concrete is poured before freeze-up.

On the basis of the above, a likely schedule for the burst tests is as follows:

Test #	Diameter	Warm/Cold	Date
1	48"	Warm	July 2, 1979
2	54"	Warm	Aug. 6, 1979
3	48"	Warm	Sept. 10, 1979
4	54"	Warm	Oct. 15, 1979
5	48"	Cold	January 1980
6	48"	Cold	March 1980

4.5.5 Costs

The total cost will depend on the final site selection and the total number of tests required, but the following figures would be applicable for the planned six tests at a site in Alberta in escalated dollars.

Site Development Costs (suitable for 6 to 10 tests)	$3,125,000
48" 1260 psig Warm Tests ($405,000 x 2)	810,000
48" 1260 psig Cold Tests ($485,000 x 2)	970,000
54" 1120 psig Warm Tests ($415,000 x 2)	830,000
In House Costs	450,000
Assume Total for 6 Tests (two tests each)	$6,200,000

In order to obtain the distribution of toughnesses desired, it will be necessary to buy substantially more pipe than is required for the burst tests, but it will be used for the project. It is estimated that this additional pipe will cost approximately $2,500,000.

4.5.6 Consultants

It is proposed that consultants be used in at least the following three areas: detailed design of the facilities, in an advisory capacity with regard to conceptual design and instrumentation, and in site environmental statement.

Pryde Flavin Consultants Limited have been used to do the detailed facilities design. These responsibilities might be expanded to include on-site construction supervision. Included would be the supply pipeline on a turnkey basis. Another possibility would be for the construction to be done by the operating pipeline company maintenance crew in the area (WTCL or AGTL).

Two consultants are being considered for the advisory work: Battelle and British Gas. Both consultants have expressed a willingness to work with the project sponsors and are currently involved in the review of the design to ensure that it is suitable and practical. One or both would, in the future, be involved with the instrumentation and, in particular, the measuring, timing wire installation and recording equipment, and perhaps to do an independent assessment of the data.

4.5.7 Test Details and Justification

Test 1

1. Planning

   A. Test Section Layout - See Section 4.5.3.

   B. Main Purpose - To test out the new facility and obtain as much data as possible, including a sure arrest due to pipe toughness. The test is presently planned using a "Prudhoe Bay" gas at approximately 1100 psig and natural ground temperature (approximately 60°F).

   C. Pipe - Pipe would be made to the project specification in as similar a manner as possible to that to be used for the project. Pipe toughness will vary from about 60 to 110 ft. lbs. for this test.

   D. Target Gas Composition

Component	Mole Per Cent
N_2	0.6
CO_2	1.0

Component	Mole Per Cent
C_1	85.3
C_2	8.1
C_3	4.4
$i\text{-}C_4$	0.2
$n\text{-}C_4$	0.3
$i\text{-}C_5$	0.03
$n\text{-}C_5$	0.03
C_6	0.008
C_{7+}	0.002

E. Gas Decompression - A two-phase gas decompression curve is available for this gas with an initial condition of 1100 psig and 60°F. The two-phase region has the following end points:

P = 620.9 psig

T = -10°F

V = 561 - 631 fps

The pressure level that moves with zero velocity is 350 psig at -60°F. Calculation, using this curve, of the toughness necessary for arrest yields 76 ft. lbs. for 48" x 0.540" Gr. 70 pipe.

F. Instrumentation - The following instrumentation will be used:

1. Timing wires on two-foot centers;
2. Six to ten pressure transducers;
3. Thermister or thermocouples to measure pipe and backfill temperature;
4. Strain gauges in the vicinity of the weights (to be used during hydrotest).

2. Test Procedure

1. Hydrostatically test all piping to a minimum of 1575 psig including a pressure volume plot. Other equipment will be pressure tested by the manufacturer to a minimum of 2160 psi.
2. Dewater.
3. Reconnect instrumentation and complete all final hook-ups.
4. Check out.
5. Dehumidify loop.
6. Pressure with gas to pipeline pressure.
7. Inject gas modification components.
8. Pressure to approximately 1100 psi.

9. Conduct gas analysis.
10. Adjust temperature if necessary.
11. Turn off all equipment.
12. Isolate test section and blow down circulating loop.
13. Initiate test.

As soon as the pressure is raised above 900 psi, all personnel would be restricted from approaching closer than 500' to the test section. All personnel not directly associated with the test must remain outside the fence from this time until the test is completed. Patrolling of the restricted area would start prior to reaching 900 psi, and that pressure would not be exceeded until the patrol had reported the area clear of all unauthorized personnel. Air Navigation would be informed of the hazard to aircraft at this point in time.

Other Tests

Specific details would be established later, but the following general statements can be made:

1. Tests would be conducted using project pipe under operating temperatures and pressures.

2. Test procedures would be similar except that the ditch for the cold tests would be opened at the beginning of the winter to allow frost penetration, and the actual details of the chilling and gas additions would have to be adjusted to ensure that no liquid drop-out occurred.
3. Preliminary chilling would be conducted prior to reaching full pressure.
4. Because of the effect of the chilling on pressure, gas would have to be added up to the time the equipment is turned off.
5. The equipment would be turned off at a temperature and pressure slightly below test conditions. Natural warming would then be used to reach the test conditions.

Justification of Test Details

The primary purpose of the burst tests is to demonstrate that the Battelle Hypothesis provides an accurate or conservative predictor of arrest toughness for use as input data in the fracture length predictions. The burst tests should, therefore, be done under one of the conditions that will be used for the fracture length predictions. Fracture length predictions are based on standard operating conditions, that is, compressor station discharge at design pressure and temperature and downstream pressures and temperatures calculated for those discharge conditions. This is the best available information on the actual conditions in operating pipelines which will occur over 99% of the time. If no other information were available, the best test conditions would be half way in between discharge and suction conditions. However, confirmatory test data already exist at lower pressures. Therefore, it is better to have the test at maximum operating pressure. This will enable arrest toughness to be determined for all other operating conditions by interpolation rather than extrapolation (by means of the Battelle Hypothesis). Because the project consists of a cold and a warm section using different pipe for each, a set of tests for both cold and warm conditions is proposed.

The first test is proposed at a lower pressure to ensure arrest, but the temperature is also lower than discharge conditions. This will have a side benefit, therefore, of testing a condition intermediate to the stations and providing confirmation of the interpolation.

There have been suggestions that the tests should be run under what could be called upset conditions. This could mean the loss of a station, the loss of a heater at a station or line-pack due to shutdown of the system. Due to the infrequency of these events, their inclusion would have an insignificant effect on the overall system reliability predictions.

In order to avoid possible questions about the validity of the tests, pipe manufactured as closely as possible to that to be used for the project will be used for the tests. The arrangement of the pipe so that the fracture is entering higher and higher toughness material as it progresses away from the origin is important in that it increases the amount of data obtained in any test.

It is very important that a gas composition similar to that proposed for the project be used in the tests, since the project gas would experience two-phase decompression in the event of a rupture.

For the cold tests, it is considered mandatory that sufficient frozen ground surrounds the pipe to simulate an infinite permafrost layer. The lateral extent of this frozen layer is considered far more important than the depth, as the primary effect is thought to be on the behaviour of the flaps during rupture. The frozen soil beside the pipe may hinder the opening of the crack or the frozen soil beside and above the pipe might move more easily than unfrozen soil (this seems very unlikely). It is felt that there exists no mechanism whereby the soil under the pipe would have a significant effect. It also is important that the thermal regime around the pipe be similar to that of the project.

The basis of this is that mechanical properties of soils depend very strongly on temperature below the freezing point.

4.5.8 Test Site Management

Project Management

It has been agreed by Foothills (Yukon) and Northwest Alaskan that the burst test site shall be in Northern Canada and further that Foothills (Yukon) will be the manager for this burst test project. In keeping with this policy, Foothills (Yukon) will appoint a project manager who will be responsible for site selection, facilities design and implementation of the burst tests. Northwest Alaskan, in turn, will appoint an assistant project manager who will be responsible for similar activities on behalf of Northwest Alaskan and work closely to assist the Foothills project manager. In this way, it is intended that input from both companies will be considered and further that test data will be shared. It is also in this manner that Canadian and U.S. regulatory agencies will be informed about the progress of the burst testing program and common reporting of results can be achieved.

The burst test project manager for Foothills will report to the Vice President of Engineering of Foothills. The progress of the burst tests will be reported to the Foothills

Engineering Committee and, in this manner, will be transmitted to the Foothills companies. The burst test assistant project manager will report to the Director of Engineering, Special Projects of Northwest Alaskan.

Data Exchange

The process described above of having a Foothills project manager and a Northwest Alaskan assistant project manager will ensure that both companies participate in the formulation of the tests and in the interpretation of the test data. In this way, information will be shared between the Canadian and U.S. companies and will be made available to the appropriate regulatory agencies through the normal established channels.

Long-Term Usefulness of Test Site Facilities

It is the expressed intention of Foothills (Yukon), as site manager, to explore the maintenance of the pipe burst test facility in Canada for future Canadian, U.S. and overseas projects. The management of the site after use by the Foothills and Northwest Alaskan companies may be continued by Foothills or may be transferred to a Canadian university or research institution. Discussions will also be held with the gas transmission industry and with established pipe burst test research facility operators to see whether their participation would be desirable in the maintenance of the facility.

It is the desire of Foothills (Yukon) that the research facility contribute to Canada's long-term technological expertise in the area of natural gas pipelines.

5.0 DEVELOPMENT OF FRACTURE LENGTH ACCEPTANCE CRITERIA

The acceptability of the ductile fracture propagation design discussed above must ultimately be judged on the outage times associated with specific fracture lengths and, in turn, on the outage times that can be sustained before gas deliveries are critically effected. Both the outage time/fracture length relationship and the sustainable outage time vary from point to point along the pipeline. In addition, neither can be precisely defined for any given point until the final route survey is complete and gas delivery schedules are set. However, the factors affecting the outage time/fracture length relationship can be defined and estimates based on previous experience and general terrain types can be developed for potential outage times. In the following, this preliminary analysis is described.

Should any rupture initiate in the pipe, the pipeline must be shut down for repair and an outage of some duration will occur regardless of length. This is simply because time is needed to isolate the section, secure the site, move in men, equipment and materials and effect repair. The base outage time will vary with the following parameters:

- (a) Location of failure relative to maintenance bases
- (b) Local terrain conditions
- (c) Right-of-way accessibility
- (d) Season
- (e) Weather

For a specific case or location, the length of failure only begins to increase this base outage time when the capacity of immediately available maintenance support is exceeded. In particular, the amount of pipe that can be moved to the site in a single operation is fixed by the number and capacity of haulage vehicles that can be mobilized. If the fracture length exceeds the footage of pipe that can be delivered initially to a particular site, the outage time may increase. At longer lengths, the number of welders and amount of support equipment available could also become a factor. In both these cases, the base outage time can be held constant for longer fractures simply by increased deployment of maintenance equipment and personnel.

While none of these times can be fixed at this time on a site specific basis, a preliminary estimate of times can be made on the basis of existing experience. A study for various parts of the AGTL system [9] provides an example of how the final design can be evaluated. This considers four terrain/season cases on the proposed pipeline route for which operating experience exists. These are:

(a) Muskeg - summer

(b) Muskeg - winter

(c) Prairie - summer

(d) Mountains - any season

This analysis assumes that current AGTL maintenance facilities and repair procedures are used, without the addition of further facilities that could be developed for the project.

This analysis shows that the maximum or conservative base outage time is primarily location and terrain dependent. A base outage time for any failure up to 250 feet varies from 39 hours, prairie terrain, to 56 hours under muskeg conditions, to 60 hours in mountainous terrain. This time increases linearly as the fracture length increases beyond 250 feet such that a 1000 foot failure involves a 79 hour outage on the prairies, a 101 hour outage in muskeg and a 120 hour outage in the mountains.

It should be noted that the service experience outline in this study for comparison shows shorter times are normally achieved for service ruptures and the base outage time may be associated with longer fractures than estimated in the study. For example, a 575 foot repair (for a brittle fracture) was completed in 21 hours under spring muskeg conditions. It is also of interest to note that the longest outages in practice are associated with leaks, rather than ruptures, due to the need to remove gas in the line and due to more extensive site preparation.

In summary, this preliminary analysis indicates that base outage times are fixed primarily by terrain and location and are independent of fracture propagation control design (i.e., fracture length). Above some fracture length a modest increase in outage time will result with increased fracture length. However, it appears that the most serious or longest outages in practice will result from leaks and not ruptures.

A further consideration related to the acceptability of the fracture length control design has to do with safety. This is largely a site-specific consideration that is inherently accommodated by the built-in use of design class locations and therefore lower operating stress levels. This offers a reduced initiation potential as well as reducing fracture length. However, consideration will be given to this aspect on the site-specific basis during the final design evaluation described in the next section.

6.0 APPLICATION TO FINAL DESIGN AND CONSTRUCTION

In the above sections, the development of the ductile fracture propagation control design to date is outlined as is the planned confirmatory testing of the components used in it. Upon completion of confirmatory testing and as the final overall design and routing of the project evolve, the ductile fracture propagation control design will be refined and applied to site specific cases where required. The attached drawing summarizes and relates all of these past, planned and future activities to illustrate how the design will ultimately be applied and evaluated.

Of particular note is the judgment of design acceptance toward the end of the final design stage. At this point, definitive fracture length predictions will be available for each section of the pipeline as will the relationship between outage time and fracture length, and the maximum allowable outage time associated with each section. Should the design show site specific deficiencies at this point, additional measures can then be input into the construction plan on a case by case basis. This most probably would involve the placement of additional natural crack arrestors.

This acceptance evaluation can also be used as input into the development of operation and maintenance plans at this point. In particular, the equipment and stockpile capability and/or location will be optimized for minimizing the base outage times.

After completion of construction and implementation of the operations and maintenance plan, the final reliability study will be undertaken using the as-built conditions and actual pipe installed.

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(1) Maxey, W.A., Fracture Initiation, Propagation and Arrest, 5th Symposium on Line Pipe Research, American Gas Association, Catalogue No. L 30174 (1974) J1.

(2) Maxey, W.A., Kiefner, J.F., and Eiber, R.J., Ductile Fracture Arrest in Gas Pipelines, American Gas Association, Catalogue No. L 32176, May 1976.

(3) Bishnoi, P.R., and Groves, T.K., Calculated Velocity of Decompression Waves in Natural Gases in Pipe Lines, Foothills Pipe Lines Ltd. Report, 1976.

(4) Groves, T.K., Measured Velocity of Decompression Waves in Natural Gases in Pipe Lines, Foothills Pipe Lines Ltd. Report, 1976.

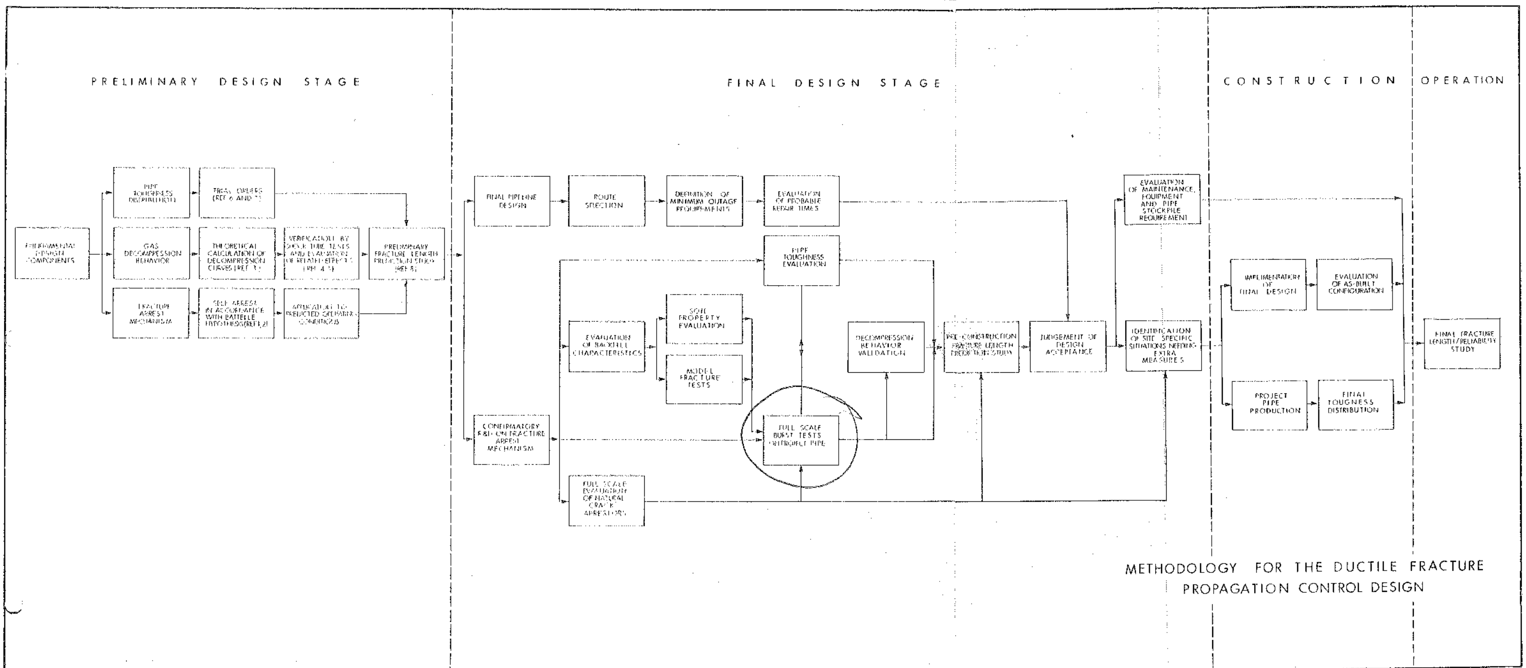
(5) Report to Foothills Pipe Lines, in preparation.

(6) Miller, D.W.J., Pipe Mill Completion Report, 42" O.D. x 0.540" Gr. 70, Foothills Specification P-100, Produced by Stelco (Stelform), AGTL Materials Engineering Report, February 1976.

(7) Miller, D.W.J., Pipe Mill Completion Report, 42" O.D. x 0.540" Gr. 70, Foothills Specification P-100, Produced by IPSCO, AGTL Materials Engineering Report, September 1976.

(8) Wallbridge, J.M.E., Alex, E.T., and Kwok, D.N., Fracture Length Predictions for the Foothills (Yukon) and Maple Leaf Projects, Foothills Pipe Lines Ltd. Report, 1977.

(9) Alaska Highway Pipeline (Alberta Section) - Relationship of Out of Service Time to Length of Fracture, Alberta Gas Trunk Line Report, January 1978.



METHODOLOGY FOR THE DUCTILE FRACTURE PROPAGATION CONTROL DESIGN

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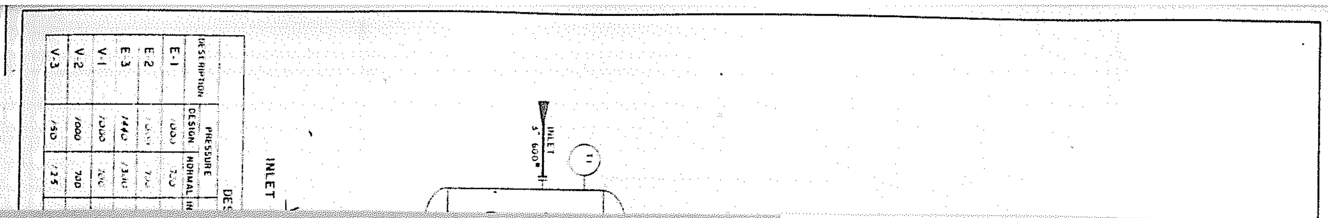


DRAWINGS, ETC.

Location Map - Burst Test Facilities
YK-04-0300-06-D

B.C. Burst Test Site Location
YK-04-0300-110-D

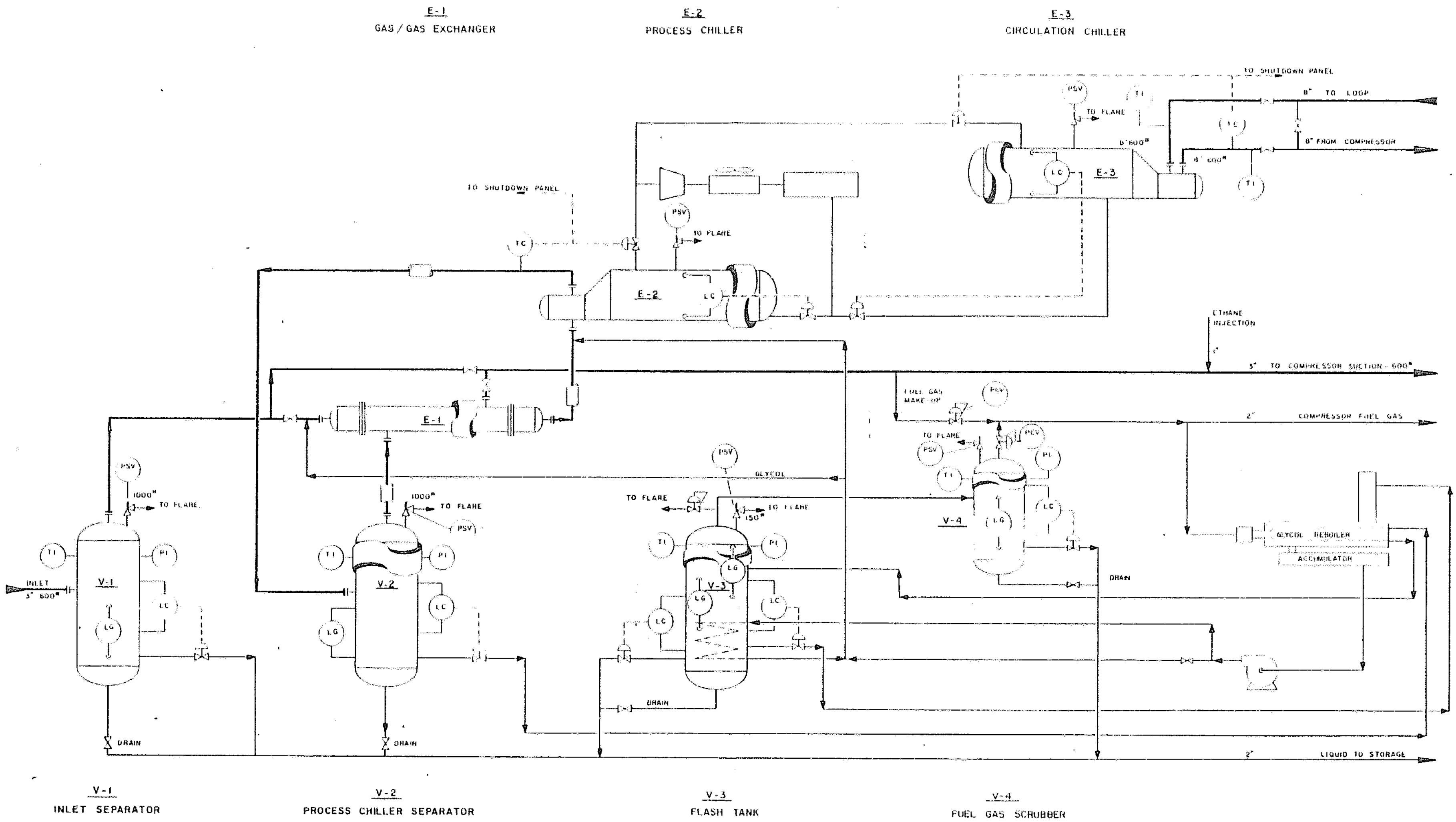
Process Diagram - Refrigeration Skids
YK-04-0300-07-D

Process Diagram - Test Section and
Circulating Loop
YK-04-0300-08-D

Burst Test Equipment List

Critical Path - Burst Test
YK-04-0300-02-D

Explanation of Asterisks on Drawing
No. YK-04-0300-02-D



DESIGN CONDITIONS									
DESCRIPTION	PRESSURE		TEMPERATURE				FLOW	ΔP
	DESIGN	NORMAL	IN MAX	IN MIN	OUT MAX	OUT MIN		
E-1	1000	700	55	-30		0	2MM	10
E-2	[illegible]	700				-30	2MM	10
E-3	1440	1300	30	-5		-30	30MM	15
V-1	1000	700	55	25			2MM	5
V-2	1000	700		-30			2MM	5
V-3	150	125		-30				

SHEET 1 OF 2

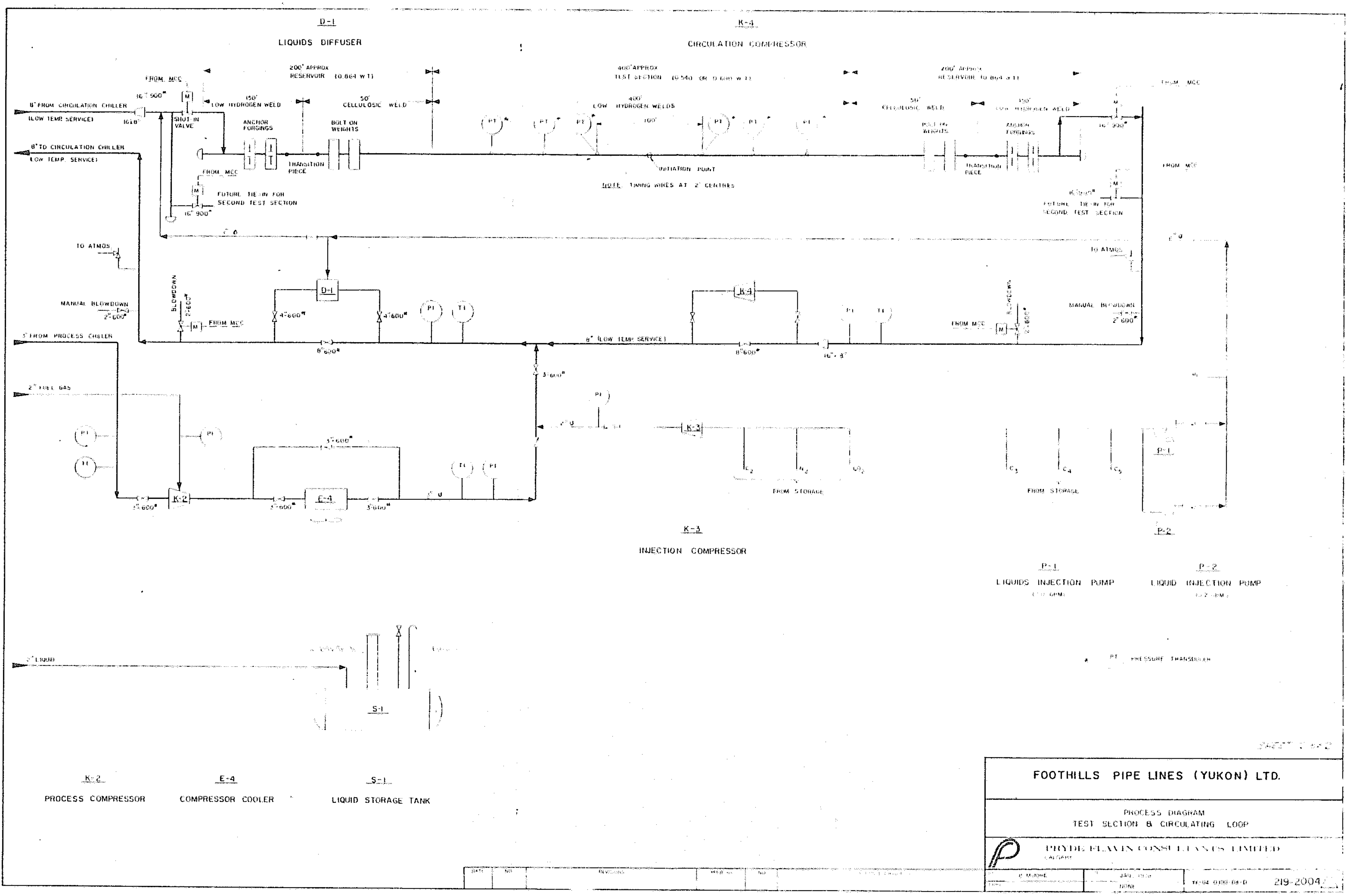
FOOTHILLS PIPE LINES (YUKON) LTD.

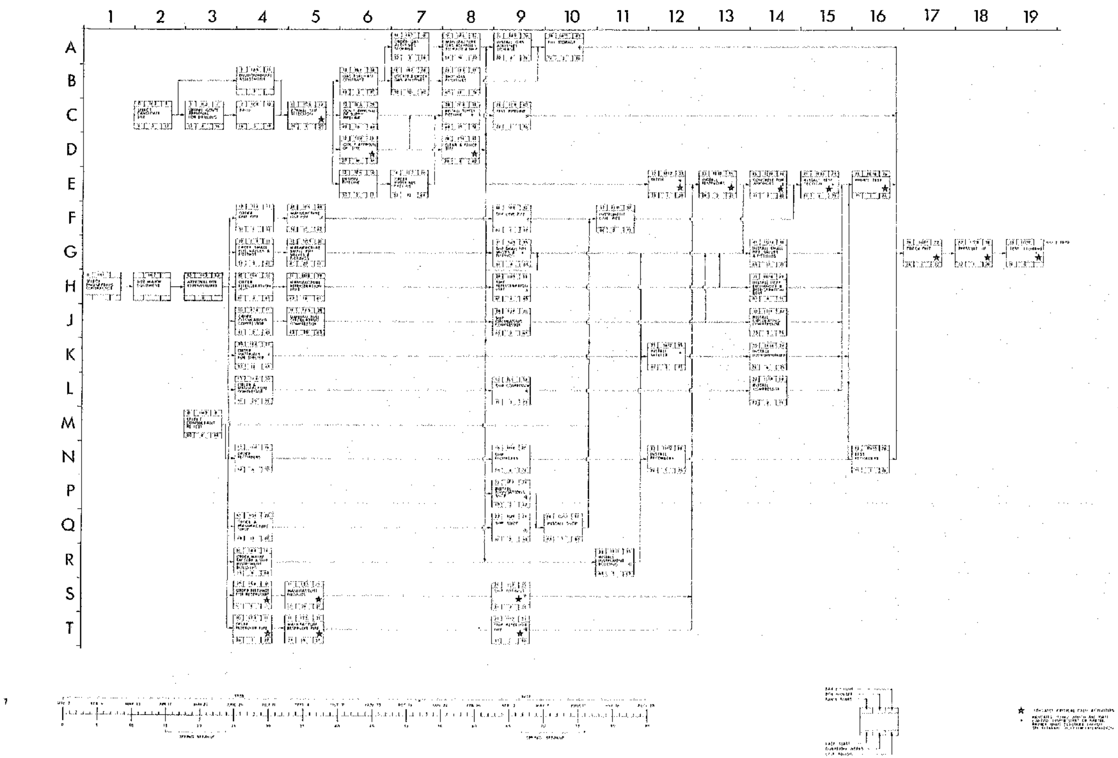
PROCESS DIAGRAM
REFRIGERATION SKIDS

PRYDE FLAVIN CONSULTANTS LIMITED
CALGARY ALBERTA

DATE	NO.	REVISIONS	APPR. BY	NO.	REFERENCE DRAWINGS

BY	DATE OCT 1977	DWG. No. YK-04 0300-07-D	219-2003
CHKD	SCALE NONE		


D-1
LIQUIDS DIFFUSER
K-4
CIRCULATION COMPRESSOR
FROM MCC
200' APPROX
RESERVOIR (0.864 W.T.)
400' APPROX
TEST SECTION (0.540 OR 0.600 W.T.)
200' APPROX
RESERVOIR (0.864 W.T.)
16" 900"
8" FROM CIRCULATION CHILLER
(LOW TEMP. SERVICE)
16 18"
SHUT-IN VALVE
150'
LOW HYDROGEN WELD
50'
CELLULOSIC WELD
400'
LOW HYDROGEN WELDS
50'
CELLULOSIC WELD
150'
LOW HYDROGEN WELD
ANCHOR FORGINGS
BOLT ON WEIGHTS
TRANSITION PIECE
100'
INITIATION POINT
NOTE: TIMING WIRES AT 2' CENTRES
8" TO CIRCULATION CHILLER
(LOW TEMP. SERVICE)
FUTURE TIE-IN FOR SECOND TEST SECTION
16" 900"
TO ATMOS.
MANUAL BLOWDOWN
2" 600"
BLOWDOWN
2" 600"
4" 600"
8" 600"
8" (LOW TEMP. SERVICE)
16" x 8"
3" FROM PROCESS CHILLER
2" FUEL GAS
3" 600"
PT
TT
K-2
E-4
K-3
FROM STORAGE
C_2
N_2
CO_2
C_3
C_4
C_5
P-1
P-2
K-3
INJECTION COMPRESSOR
P-1
LIQUIDS INJECTION PUMP
P-2
LIQUID INJECTION PUMP
2" LIQUID
S-1
* PT PRESSURE TRANSDUCER
K-2
PROCESS COMPRESSOR
E-4
COMPRESSOR COOLER
S-1
LIQUID STORAGE TANK
FOOTHILLS PIPE LINES (YUKON) LTD.
PROCESS DIAGRAM
TEST SECTION & CIRCULATING LOOP
PRYDE FLAVIN CONSULTANTS LIMITED
CALGARY
DATE
NO.
REVISIONS
219-2004



TITLE: CRITICAL PATH BURST TEST

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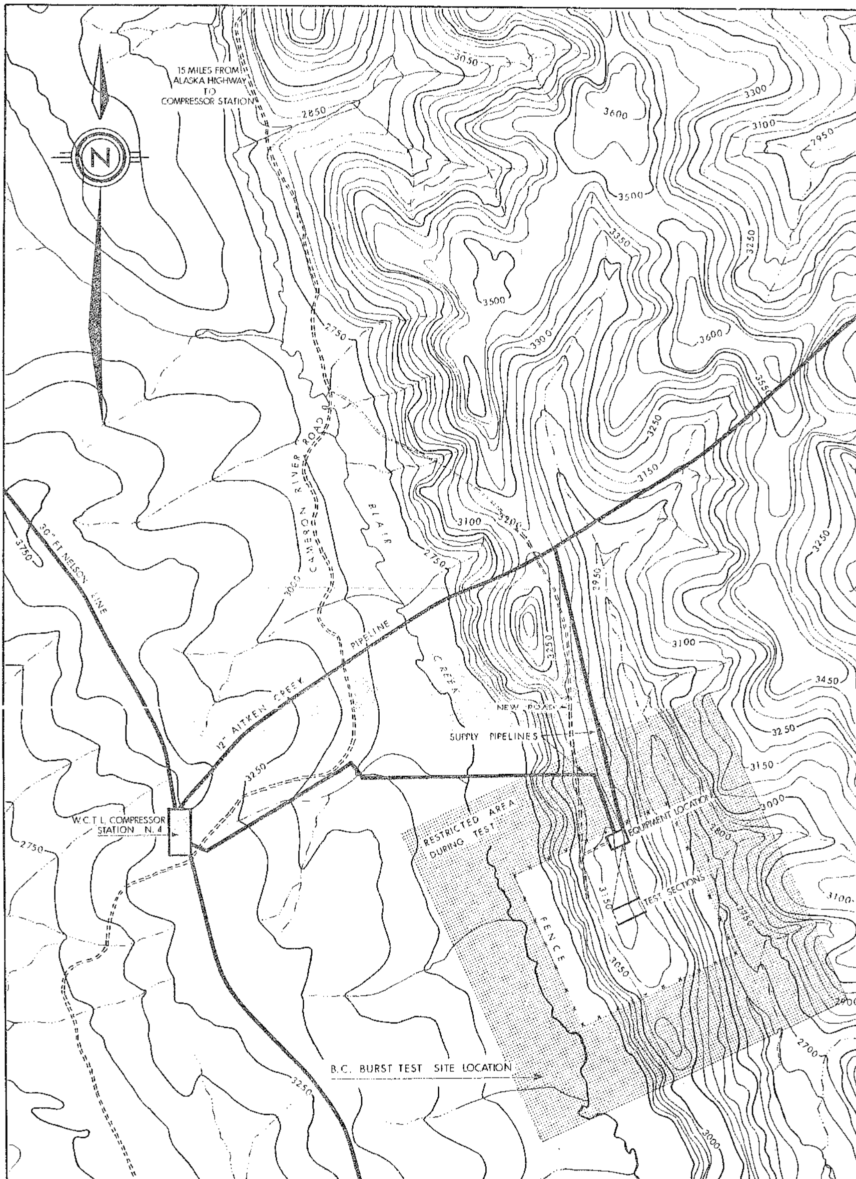

Title: B.C. BURST TEST SITE LOCATION

Date: JANUARY 30, 1978
Scale: [illegible] to 1mile (APPROXIMATELY)
Drawn by: A. GAGNE
Checked by:
Approved by:
Supv. engineer:
Drawing/Plan No. YK-04-0300-110-D

FOOTHILLS PIPE LINES (YUKON) LTD.