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Methods for the Fracturing of Icebergs

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Executive Summary

This study addresses an Environmental Studies Revolving Funds priority subject as identified in the *ESRF Update*, Vol. II (3), July 3, 1984.

The engineering feasibility of several potential methods for inducing the large scale fracturing of icebergs has been investigated. These methods included conventional explosives and incendiaries, thermal fracture of ice, various sorts of directed beams (radiation, fluid or particles), injected pressurized fluid (both confined and unconfined) and an ice cutting method using an electrically heated wire. All methods had in common the requirement for large quantities of materials and/or energy. Some methods, while technically and perhaps economically feasible, were unacceptable from an environmental viewpoint.

None of the beam methods appears technically feasible within the present limits of science and engineering. The thermal fracture method is impractical and uneconomic because of the enormous quantities of materials required. Explosives are almost certainly practical for iceberg fracturing if environmental concerns, particularly shock transmitted to the ocean, are neglected. The preferred mode of deployment would be to aerially bomb an iceberg with a single multiton "earthquake" bomb. The bomb would penetrate deeply into the iceberg before exploding. Suitable bombs (e.g. the 10 tonne "Grand Slam") were developed during the Second World War.

Fluid injection appears to hold promise as an iceberg fracturing technique, particularly in the confined configuration where a steel envelope (flat jack) is used to contain the fluid within the iceberg. Injection of unconfined fluids which plasticize or solidify as they flow may also prove feasible in iceberg fracturing. However, major engineering and design problems have yet to be addressed before any fluid injection method could be rendered useable in the marine operational sense.

It has been determined that the cutting of an iceberg with an electrically heated small diameter tube stands out as the most practical approach to iceberg fracturing. The tube is heated with a multi-hundred ampere DC current and simultaneously cooled with circulating fluid to prevent burnout. Electric power requirements are manageable in the marine context (a few hundreds of kilowatts) and equipment tends to be conventional and not overly difficult to obtain and configure.

A field program carried out within the context of the present study has demonstrated the functionality of the hot wire cutting method. Based on the results of this program, the design for a fully operational scaled up version of an iceberg cutting system has been outlined. This hot wire fracturing method is judged appropriate for serious consideration in developing iceberg management strategies for Canada's East coast oilfields.

Résumé

Cette étude concerne un sujet prioritaire des FRÉE identifié dans le Vol. II (3) du 3 juillet 1984 de la revue *Mise à jour FRÉE.*

On a évalué les possibilités techniques des différentes méthodes pouvant possiblement provoquer la fragmentation des icebergs sur une grande échelle. Parmi celles-ci figurent les explosifs et engins incendiaires conventionnels, la fragmentation thermique de la glace, toutes sortes de jets (de radiation, de liquides ou de particules), l'injection de fluides (confinés ou non) et une méthode de découpage à l'aide d'un élément électrique. Tous les moyens envisagés requièrent de vastes quantités de matière ou d'énergie. Certaines méthodes techniquement réalisables et même économiquement possibles ne sont pourtant pas acceptables au point de vue environnemental.

Dans les limites actuelles de la science et de l'ingénierie, aucune des méthodes utilisant les jets ne sont réalisables. La fragmentation thermique n'est ni pratique ni économique à cause des quantités énormes de matière nécessaire. Si l'on ne tient pas compte des questions environnementales, et plus particulièrement de la propagation de l'onde de choc dans l'océan, il est certain que l'emploi des explosifs est une méthodes pratique. Le moyen préféré consisterait à larguer du haut des airs sur l'iceberg une seule bombe conventionnelle de très forte puissance du type "earthquake". Elle pénétrerait profondément dans la glace avant d'exploser. De telles bombes ont déja été utilisées pendant la Seconde Guerre mondiale, notamment la bombe de dix tonnes "Grand Slam".

L'injection de fluide serait une méthode possible de fragmentation des icebergs, surtout si une enveloppe d'acier pouvait être posée pour retenir ce fluide dans la glace. L'injection de fluides qui se plastifient ou se solidifient en s'écoulant pourrait être possible également, mais des problèmes majeurs d'ingénierie et de conception devront être résolus avant que ce moyen ne soit utilisable sur le terrain.

On a démontré que le moyen le plus pratique de découper un iceberg consiste à chauffer un tube de faible diamètre rempli d'un liquide caloporteur à l'aide d'un courant direct de plusieurs centaines d'ampères. Ce fluide empêche le tube de surchauffer. Les quelques centaines de kilowatts d'électricité nécessaires peuvent être produits en mer avec un équipment facile à obtenir ou à fabriquer.

L'essai en mer d'un prototype a démontré que cette méthode fonctionne; les résultats ont servi à concevoir un appareillage de pleine puissance. Nous jugeons que le découpage d'icebergs par élément électrique mérite d'être considéré lors de l'élaboration des stratégies de protection contre les icebergs dans les zones pétrolifères de la côte Est du Canada.

CHAPTER 1.

INTRODUCTION

This study investigates one aspect of the general problem of iceberg management in support of the development of offshore petroleum resources. Specifically, the problem of iceberg size reduction through iceberg fracturing is addressed.

A detailed discussion of the problems posed by icebergs is given in the Hibernia Development Project Environmental Impact Statement (Mobil 1985). The oilfields and areas of petroleum exploration on the Grand Banks pose no problems for development which have not already been dealt with successfully in the North Sea, other than icebergs and sea ice. The water is in fact shallower than some of the North Sea fields currently in production, and the weather and wave climate are only marginally more severe (op. cit., vol. 2, p. 27). However, the presence of large ice masses is a severe complication. A floating production system may expect substantial downtime per year owing to ice problems. Even a fixed system could experience some downtime from the same cause, mainly by inhibition of the transportation to remove petroleum stored in tanks on the platform. Furthermore, while fixed production platforms, if implemented, will be designed to withstand iceberg impact, for both fixed and floating production scenarios, "icebergs may damage subsea equipment by scouring" (op. cit., p.7, vol. 2), though the gathering system will be expensively designed to minimize the effects of such incursions.

Present iceberg management has two parts: detection and towing. Improvements in the current procedures for both of these have been considered, and are likely feasible. In fact, as will be seen, part of our field test in this program is relevant to enhanced towing. However, other approaches to iceberg management have been considered. One of these, historically the first to be attempted, is the demolition, fracture, or most generally the "enhanced ablation" of icebergs. This report will show that iceberg fracture is not only feasible, but can almost certainly be developed into an effective operational tool for iceberg management.

Why indeed should it be thought desirable to fracture icebergs, assuming that it proved practicable to do so on a routine operational basis, or even as part of an emergency procedure? Inappropriately applied, the fracture of an iceberg would leave two or more large ice masses to be managed rather than one, and, furthermore, large ice masses which might conceivably pose greater hazards, individually, than the original berg.

To provide an answer to the above question, it is useful to distinguish between two aspects of iceberg management: tactical and strategic. We distinguish between iceberg hazards on that basis, and, rather arbitrarily, distinguish on the basis of time: tactical methods are those relevant when the iceberg is within approximately twenty-four hours, or within radar range, of the drillrig or oilfield; strategic methods are those applicable to icebergs further away.

For tactical purposes, iceberg fracture has three potential benefits, benefits realizable if fracturing is appropriately applied:

1). fracturing will reduce the mass, and hence the impact force, of iceberg fragments coming in contact with fixed production facilities;
2). fracturing **may**, if carefully applied, reduce the draft of the iceberg fragments, and hence the probability of scouring and consequent damage to seafloor portions of a completion system;
3). the fragments will individually have less **drag** than the original iceberg, and hence will be more amenable to towing, whether conventional or enhanced.

In regard to benefit 2 above, it must be noted that icebergs can easily **increase** their drafts as they ablate (Lewis and Bennett 1984), though the overall trend must of course be towards shallower drafts. Hence care must be taken if draft reduction is sought, and the iceberg should be carefully surveyed first.

All of these benefits obtain if iceberg fracture is applied strategically, i.e. well upstream of the facility or facilities to be protected. In addition, a fourth and fifth benefit will accrue:

4). the iceberg fragments will tend to disperse, so that the total ice mass requiring tactical management will be very substantially reduced;
5). the iceberg fragments will be reduced by **natural ablation**, perhaps even to the point of melting completely.

While we see some role for iceberg fracture in tactical iceberg management, we view its great potential importance as lying in the strategic arena. As an example, or perhaps rather a paradigm, consider the case of an extremely large iceberg encroaching on a fixed structure on the Grand Banks: owing to the relatively shallow depths (80 to 100 m) typical of the region, this would be a 12,000,000 - 15,000,000 tonne tabular iceberg, very flat, with height and draft very small compared to its horizontal dimensions. The berg tracked north of the Grand Banks by Robe, Maier, and Kollmeyer in 1976 (Robe et al. 1977) is an example. The probable origin of this iceberg was the Petermann glacier in northern Greenland. The example berg would, with the surveillance system currently in place, be detected at least two **months** before it reached the Grand Banks, and in fact should be picked up the year before. It would be an ideal candidate for iceberg fracture. If the berg were fractured near St. Anthony[1], the shallow-draft fragments would probably ablate completely before reaching the vicinity of the Grand Banks. Indeed, if iceberg fracture is feasible, as we in fact maintain, there is no excuse for allowing the current "design berg", or any ice mass even approximating to it in size, to come anywhere near production facilities to be completed on the Grand Banks.

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[1] The fishing village of St. Anthony is located on the NE of the Northern Peninsula of Newfoundland, of which it is the leading community. It has a good harbour, and is accessible by road and by air. For these reasons, and because it is located just off the iceberg stream that comes down the coast of Labrador, it is a common port of call for vessels engaged in iceberg work, and would be the natural base for strategic iceberg management for the Grand Banks, should such be undertaken. St. Anthony experiences significantly less fog, and significantly more sea ice, than more southerly parts of Newfoundland.

This brings us, then, to one of the important motivations for this study. The knowledge that iceberg fracturing is feasible could be significant for planning decisions on ice management strategy.

It could also be significant for the design of petroleum production facilities on the Grand Banks. The availability of iceberg fracture as a management tool implies that the collisional energy and momentum which a fixed production facility must be built to withstand is less than with the above-described "design berg". This may mean cheaper and more rapid completion of the facility. Even if the production facility is built to withstand or endure contact with the "design berg", it is desirable that it be put to the test as infrequently as possible, both for environmental safety and for the security of the revenue stream flowing from it. Hence even for facilities built to withstand impacts with such massive objects, and gathering systems built to withstand scour intrusion, safety and security might be enhanced by the availability of successful iceberg fracturing methods.

In summary:

1). This study may affect decisions on methodology of iceberg management and on drilling/production in iceberg infested waters. Reduction of iceberg mass can improve tow success and reduce impact hazard to structures.

2). This study will facilitate an informed assessment of the general feasibility of introducing iceberg fracture as a useful technique to be included in the growing list of iceberg avoidance/management methods.

Furthermore,

3). The results may bear on other ice control problems, for instance the demolition of ice jams, removal of ice from inland waterways or the destruction of pressure ridges in the Arctic.

4). The study has the potential to generate a new Canadian technology and area of expertise.

We would like to conclude this introduction with a few brief comments on some of the earlier attempts at iceberg fracturing. The two approaches which have received serious attention are blasting using conventional civil explosives and military ordnance, and the use of thermite. Both of these are discussed in more detail below. In regard to explosives, it can be said that the armed services of various countries have from time to time used icebergs for target practice, with little result. However, systematic blasting by means of charges carefully emplaced in shotholes has been "successfully" demonstrated by Mellor and Kovacs (1972); "successfully" in quotation marks, because the explosive charge required even for a medium-sized iceberg is large, with large environmental impact expected, a party must board the berg and work on it for an extended period of time, and the consequences of a misfire are unpleasant indeed.

The other method which has received much attention is the use of thermite, an incendiary mixture of a strongly reducing metal with a metal oxide, both being in powder form. Thermites have been extensively used for spot welding in civilian practice, and are the basis of many incendiary weapons. The sole reason for the attention given to thermite is a series of papers by H.T. Barnes published in the late 1920's which strongly and colorfully purport to describe **successful** tests with this material. Barnes's tests were not substantiated by U.S. Coast Guard trials; with good reason: there is no physical basis whatsoever for the fracture of icebergs with the relatively small charges which he used.

Barnes's publications describe experiments, carried out off Twillingate, Newfoundland, in 1926, in which relatively small (approximately 100 kg) charges of thermite, shallowly embedded in three different icebergs, were ignited. A wave mechanism of some sort supposedly propagated a thermal effect rapidly through the bulk of the iceberg. Over a period of a few hours or a few days the thermal effect, hypothesized to act mechanically through the mechanism of thermal expansion, was claimed to have led to the cracking and then the complete disintegration of the bergs.

Because of the attention which thermite has received, we review the method at length in Chapter 3.

Thermite, in Barnes's explanation, is one of several methods which can best be characterized as "magical". Two others are the reduction of icebergs by spreading them with black, radiation-absorbent powders, and attempting their destruction by acoustic signals resonant with one of their low-frequency vibrational modes (a frequently proposed method; presumably based on the analogy of "the opera singer and champagne glass"). These are magical in that the effect sought, the destruction of an iceberg, is totally disproportionate to the forces and energies available. Of course, it is true, and obviously true, that a ***sufficiently large*** quantity of thermite suitably placed will destroy an iceberg; one million kg would in all likelihood do very significant damage to a medium-sized berg; spreading soot on a berg would very likely cause it to melt rapidly away, if the Earth were as close to the Sun as Mercury, and if somehow the soot could be fixed to the ice so that it would not run off; and acoustic waves will indeed break up a berg, if they are provided by the detonation of many tons of high explosive. We suggest to those who advocate such methods, that they might profitably occupy themselves next winter by sticking pins into an icecube; or perhaps by singing to it to shatter it. While awaiting its disintegration, we recommend that they amuse themselves by computing the normal modes of vibration of a real iceberg.

In the following, we discuss several serious methods for the fracture of icebergs. Several of these do not survive detailed analysis. We will argue that in fact, for emergency use, if environmental consequences must be traded off against human survival or the integrity of the production system, explosive demolition using very high power bombs, such as the WWII "earthquake" bombs, is likely to be practicable. For ordinary, nonemergency use, three methods are identified as of potential usefulness, and one of these, called by us the "hot wire" method, can be taken to full operational status.

CHAPTER 2.

ENUMERATION AND CONCEPTUAL EVALUATION OF POTENTIAL METHODS FOR THE FRACTURE OF ICEBERGS.

2.1. Introduction

It is worthwhile to state carefully the problem which the reduction of icebergs poses. The essence of the problem is that an iceberg is a large mass of tough ice which is capable of moving into areas of human activity and disrupting them, and of doing so under atmospheric and sea conditions which are sufficiently adverse that human activity is severly curtailed if not impossible. A method which will fracture an icecube probably cannot be scaled up. A method, such as certain demolition scenarios, which would be quite feasible on a glacier, well may be completely impracticable at sea.

Furthermore, the fact that a given iceberg actually presents a hazard necessarily implies that it is sufficiently close to areas of human habitation or human economic activity that some technically feasible methods must be ruled out because of their potential for ancillary damage to the human environment.

On the other hand, it is important not to **overstate** the problem. Icebergs are indeed large, but the largest to reach the Grand Banks are of the order of a few millions of tonnes; they are not so large as a mountain[1]. Icebergs move, but they do so relatively slowly - typically at speeds of less than a knot. Iceberg ice is hard and tough, but it is by no means so hard and tough as rock or concrete. Finally, ice **melts** at a temperature sufficiently low to be readily accessible to a variety of technical processes.

In these properties must be found the solution to the problems which they pose.

A large number of methods can be envisioned for approaching the general objective of reducing iceberg mass. In the discussion below, only nine methods have been singled out for analysis. In selecting these nine methods, consideration has been given to several factors, including general feasibility, historical interest, current interest within the community, and work which may already have been carried out on them. All of the methods selected can be described as **active** methods, that is, they involve the deliberate **breaking** or **cutting** of iceberg ice.

One passive method which may eventually prove practical but which does not fall within the scope of this study, and which in consequence has not been analysed herein,

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[1] Antarctic bergs, and the the largest of the Arctic bergs, on the other hand, can readily contain several cubic km of ice.

would involve the anchoring of an iceberg to the ocean floor. Natural forces would then be relied upon to break up the iceberg while it was held distant from an area of offshore operations. This method also has not been considered within the present study owing to its dependence on anchoring technology which is not as yet completely developed. The development of such a capability would be a major undertaking which is probably more relevant to the ESRF study on enhanced iceberg towing technology (ESRF 1984).

Other active methods have not been considered because of clear technical, environmental or regulatory problems associated with their potential use. In this context it is worth noting that environmental and regulatory problems can often dominate technical problems in leading to the early elimination of a method from serious consideration. For example, a "peaceful nuclear explosion", while ideally suited for iceberg demolition in the technical sense, would create political and environmental problems unparalleled in Canadian history[1], and accordingly the method is not worthy of even cursory examination. Similar arguments could well apply to the crude use of conventional explosives. For example, if one were to discount the environmental, safety and regulatory problems, then the most convenient way to demolish an iceberg through blasting might be to simply float a bargeload of explosives, that is to say several hundreds of tonnes, alongside and set it off. Needless to say, this method would be problematic from a regulatory viewpoint.

Other potential iceberg fracture methods do not bear consideration owing to the uncertainty of their functioning. For instance, dusting an iceberg with black powder so as to absorb sunlight and greatly accelerate melting would never prove reliable enough to be useful: inherent problems such as cloud, fog, iceberg roll and meltwater runoff do not lend themselves to engineering solutions.

Additionally, there is the class of "magical" iceberg fracture methods mentioned in the general introduction. These methods are characterized by the application of a small stimulus of some sort, followed by the large effect of the iceberg just falling apart. Such methods, which tend to contradict physical laws, can be proved nonfunctional only by actually going out and failing to break up several icebergs. Methods which do not function on straightforward physical and chemical principles have not in general been included within the context of this study, the sole exception being thermite demolition.

The nine methods to be enumerated in section 2.4 below have been evaluated according to a set of general criteria. These criteria, outlined in the list in section 2.3, provide a basis for determining whether a particular method is likely, within the foreseeable future, to prove useful operationally within Canada's East Coast offshore.

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[1] The same can be said of a method suggested in R.A. Heinlein's "The Moon is a Harsh Mistress": chunks of rocks, or other cheap, dense material are placed in orbit about the Earth, fitted with retrorockets and a terminal guidance system. Upon telemetered command, the retrorockets would fire, injecting the rock into a trajectory leading to impact with the berg.

2.2. Epistemological Considerations.

Barnes's claims for thermite do raise an important issue in regard to the evaluation of iceberg fracturing methods. Icebergs eventually ablate to meltwater entirely without human assistance. Furthermore, the final disintegration can be rapid indeed. One of us (JCL) in June of 1981 saw an iceberg, grounded near Belle Isle in the Strait of Belle Isle, break up and disintegrate over a five-hour period. The rapidity of the breakup was likely due to large stress fields induced in the grounded berg by more gradual ablation over the at least three-day period that it was, to our knowledge, grounded. A mate of one of the CN ferries out of Port aux Basques told a colleague of ours in all seriousness that many bergs came down the Strait, but that they usually "rolled over and sank". Indeed, the belief that icebergs can sink is commonplace among Newfoundland mariners, probably as a reflection of the rapidity of their disappearance.

Not that they need to break up to disappear. Many "grounded" icebergs off the Newfoundland coast are not grounded at all, but are held by wind and current against subsea ridges. The subsea topography off the coast of much of northeastern Newfoundland is as rugged as the land itself. If the current shifts, the iceberg can be gone in a few hours. This happened to a large iceberg which was, we thought, inextricably trapped in Flat Rock Cove, Newfoundland, in April of 1984.

Furthermore, identifying an iceberg which has changed its position and has not been kept under continuous observation is not trivial. If it has rolled and/or calved, identification can be impossible. Even if it has not, the appearances which a deteriorated iceberg presents when seen from different angles are so varied that positive identification must rely on point-by-point comparison with photographs.

The consequence of this for testing fracturing methods is that the effects of the fracturing method must be immediate and clearly visible for success to be claimed; the alternative, to attempt to infer that it works by performing a large number of tests, is not acceptable, because the number of tests to achieve any accuracy at all would be completely impracticable, even if, as is dubious, a measure for success meaningful for statistical analysis could be defined.

2.3. Criteria used in Judging Feasibility of Fracturing Methods.

a): Functionality. The method should stand up to careful scientific scrutiny and have a reasonable likelihood of success from the viewpoint of physics, chemistry, and mechanics.

b): Engineering feasibility. It is important for cost, time and regulatory acceptability that the selected method should utilize apparatus and materials which are presently available, and readily so, to the greatest extent possible.

c): Marine (operational) feasibility. The equipment should be deployable within a reasonable weather window from either an offshore supply vessel or a helicopter. Ease of deployment at sea is naturally a prime consideration in determining the usefulness and feasibility of any method.

d): Safety. There must be no perceived or actual hazard to the personnel operating the system. Use of hazardous substances offshore should be minimized.

e): Cost. A field demonstration of the method should be realizable within the parameters of the present ESRF-funded study and, for the operational version of the system, the cheaper the better.

f): Environmental considerations. No method deemed detrimental to the environment can be selected. Shock or vibrations transmitted to the water, along with the release of noxious substances into the ocean are two prime areas of environmental concern to be considered.

2.4. Enumeration of Methods for Iceberg Fracturing.

1): Explosives and Pyrotechnics.

Explosives, incendiaries, or other pyrotechnical chemicals can be used to effect iceberg fracture. The action is generally through a rapidly accumulating but short-duration stress field which breaks ice in tension. There are two basic principles on which this could operate: first, a rapid, detonating explosive charge creates a shock wave which propagates to the surface and, upon reflection from the ice-air interface, creates tensile loading in excess of the ice strength. Ice then spalls from the surface. This action is the conventional mode of operation of explosives in mining and construction. However, because of the good impedance match between ice and water, below-water reflective spalling is probably not significant. Second, an accumulation of pressure resulting from the gasification of a liquid or solid chemical deep within an iceberg would create an outward-directed stress field, which could cause a large-scale tensile failure of the iceberg. Such an explosion would separate the iceberg into a few large pieces. This much more unorthodox application of explosives is probably the more practical scenario for their use in iceberg fracture.

Explosive demolition of icebergs has, in fact, a demonstrated but limited degree of feasibility. Ice blasting, where carried out in the past on icebergs and other ice masses clearly has an effect. Adapting the method to the present context is primarily a matter of scaling the blast effect to yield fracture over linear dimensions of the order of one hundred metres, a feat not yet demonstrated. The primary attractiveness of explosives lies in their common usage, and hence in the fact that the technology is old and well established. In fact, however, in the cold ocean environment, explosives pose many novel technical and environmental problems. These include:

1. An unconventionally large charge is required.
2. Careful placement (probably deep within the iceberg) is necessary. Because of the hostile working environment posed by an iceberg at sea, perhaps in bad weather,

special problems arise in placing even small charges.

3. The environmental consequences of the detonation of such large charges are likely to be adverse; in consequence, regulatory approval is unlikely.
4. Safety; the handling of large quantities of explosives offshore will remain a major concern. An unusual and difficult problem would be posed by the misfire (failure to detonate) of an explosive charge on an iceberg. Such a misfire would leave a safety and environmental problem without civilian precedent, which would demand attention, and yet defy simple solution.

Thermite.

Thermite, in quantities of the order of several hundred kg, does not provide sufficient energy to disrupt an iceberg significantly, nor can the energy it does liberate penetrate deeply into an iceberg. The only reason for the attention paid to thermite is a set of publications by H.T. Barnes, whose observations and whose reasoning do not bear careful scrutiny, and whose work has not been independently substantiated.

2): Thermal Fracture.

Ice has a moderate heat capacity, moderate thermal conductivity, and a fairly high coefficient of thermal expansion. These factors combine to render ice amenable to mechanical fracture through thermal stress. Indeed, the environmentally induced temperature gradients normally present in icebergs undoubtedly play a significant role in accelerating an iceberg's eventual breakup.

It can be argued that an artificially induced thermal gradient *of sufficient magnitude* could induce the sudden fracturing or disintegration of an iceberg. Two general approaches to the problem of setting up a sufficient thermal gradient can be envisioned; first, heating through application of a heated fluid or an exothermic chemical reaction; second, cooling through application of a refrigerant fluid. Heating has the advantage of requiring smaller amounts of materials where the applied heat source is a strongly exothermic chemical reaction.

However, there is a fundamental limitation on the available temperature differences, and hence thermal gradients, which can be achieved by heating. The internal or core temperature of an iceberg probably does not range much below -25 ° C, the characteristic subsurface temperature of Greenland glaciers. Since an ice surface cannot be raised above 0 ° C, even momentarily[1], no temperature difference larger than 25 ° C can be induced in an iceberg through heating, so that only relatively small thermal gradients, at most a fraction of a degree per metre, can be induced through the bulk of the berg.

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[1] It is a peculiarity of first-order phase transitions that while gases and liquids can be supercooled, and a liquid can be superheated, a solid melts instantaneously if its temperature is raised above its equilibrium melting temperature at the applied pressure.

The problem of such small gradients relates as much to heat transfer as to the requirement of inducing thermal stress. A linear thermal gradient of 1 ° C/m will lead to a transfer by conduction of 2.2 W of heat (p.357 of Hobbs 1974) along a path of 1 m^2 cross-sectional area in ice. This amount of power will warm a cubic metre of ice by 1 ° C in just under 11 days. Since radiant heat transfer in iceberg ice is not operative over distances exceeding a few tens of centimetres, thermal conduction, even if very slow, must be depended upon to distribute heat throughout the bulk of the ice.

Cooling, on the other hand, permits in principle at least, a much larger thermal gradient to be established. If liquid helium were to be used, a temperature difference of 244 ° C could be achieved relative to the cold centre of the berg. This would of course be economically prohibitive, but it does give an upper limit on possible temperature differences. With liquid nitrogen, which is available in large quantities, a temperature difference of 171 ° C can be attained. This is 6.8 times that which can be achieved with heating. Furthermore, ice becomes more brittle and more amenable to fracture when it is cooled.

These elementary considerations make it all the more surprising that any attention is still given to thermite. Of course, in the 1920's, when H.T. Barnes did his work, liquid nitrogen was a rare and expensive laboratory curiosity; but no longer - it is now a widely used industrial material.

The key problem in thermally fracturing ice lies in the large quantities of materials required. This is true both for heating and cooling. Realistically, many hundreds of tons of coolant or tens of tons of reactive chemicals would be needed to establish the thermal regime in an iceberg necessary to precipitate its disintegration. For example, assume that in the process of thermally fracturing a one million tonne iceberg, it was necessary to change the average temperature of the ice by 0.1 ° C. This would require vaporizing over 1.2 million litres of liquid nitrogen, or reacting 55 tonnes of thermite. Of course, these numbers are conservative in the sense that inefficiencies in heat transfer would undoubtedly lead to much larger quantities of materials being required.

It is not easy to estimate the mean overall change in ice temperature that would typically precipitate the thermal fracture of an iceberg. Gold (1963) demonstrated that a sudden change in ice surface temperature of 6 ° C was sufficient to initiate fracture propagation inward from the surface. Hence one might infer that an overall temperature change of 6 ° C in a significant fraction, say 1%, of an iceberg's mass could induce a major fracturing event. Changes in temperature of less than 6 ° C would probably do nothing since the process of crack initiation would not commence. Similarly, modifying the thermal regime in less than 1% of an iceberg's mass is unlikely to precipitate large-scale disintegration. An intuitive conclusion is thus that the quantities of materials mentioned above are indeed quite likely to be minimum quantities and hence that the method of thermal fracture is impractical in the context of iceberg demolition.

3): Laser Cutting.

Infrared or visible radiation, concentrated in the form of a high power laser beam could be used to melt or vaporize ice along a narrow and precisely defined path. Such a beam, directed at an iceberg from a nearby vessel, would appear, in principle, capable of slicing pieces of ice from the above-water portion of an iceberg. Alternatively, a laser might be used to induce rapid heating or steam formation over a small portion of iceberg surface, thereby causing ice to chip or spall from that surface.

The attractiveness of using a laser to cut or fracture an iceberg lies in the apparent ease with which a large amount of highly-concentrated energy can be delivered from a vessel to a remote location (i.e. an iceberg). Since the laser could be turned on or off almost instantaneously and no high velocity projectiles or fluids are propelled from the vessel, the method also appears to offer certain safety advantages.

Two primary drawbacks affect the potential use of lasers for iceberg cutting. First, the size and power requirements are immense. The laser would have to produce a continuous beam output or an average pulse output running to several tens of thousands of watts. Electrical supply and cooling apparatus would be correspondingly very large with total continuous power requirements running into the multi-100 kW range.

The second major problem with laser cutting relates to aiming. Aim from a moving frame of reference (a ship) would have to be maintained within extremely narrow tolerances for time periods of many minutes, or hours. Failure to maintain precise beam alignment with the slot being cut would have the effect of entirely nullifying the advantage the laser offers in concentrating the radiation delivered to the ice. Laser power requirements would increase tremendously, beyond the megawatt (continuous) range and the method would be rendered unfeasible, since the laser would have specifications exceeding the present state of the art in high power lasers.

Overall, laser cutting may be termed the "Star Wars" approach to iceberg fracture. It requires similar technology to the Strategic Defense Initiative, the development of which is problematic[1] except insofar as it is certain to be astronomically expensive. In fact, in some regards, iceberg cutting with a laser is more difficult than missile interception; aim from a heaving, pitching, rolling, yawing ship is obviously more difficult than from a satellite in orbit, and the energy to be delivered to the target is enormously greater. For that reason, we can predict with assurance that laser cutting will *never* be used on icebergs; if the problems associated with it *could* be overcome (by the present authors, for example) the technology would immediately be sold to the appropriate military agency, for a far higher price than any civilian organization could afford, and would thereafter be kept a strictly guarded state secret.

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[1] For two differing viewpoints on the SDI see Yonas (1985) and Panofsky (1985).

4): Microwave Ablation.

Microwave radiation is absorbed efficiently by ice and thermalized, with penetration distances typically of the order of a few centimetres. Heating, melting and breaking of ice by a focussed microwave beam is feasible in principle. Microwaves, directed and focussed at an ice surface, would cause intense local heating, with a significant fraction of the heat being evolved several centimetres below the surface. The heat could give rise to thermal shock and spalling of ice (where the near surface temperature is significantly below 0 ° C), subsurface steam generation and pressure buildup leading to spalling, along with direct melting of ice.

High power microwave sources and associated reflectors and other beam control apparatus are clearly in the realm of conventional technology. Magnetrons, the microwave sources used in microwave ovens and other heating applications, are cheap, rugged, reliable, and relatively efficient. Large microwave reflectors, commonly used in the communications industry, are readily available and have been adapted to survive hostile environmental conditions.

There are two primary difficulties to be anticipated in considering the use of microwaves for iceberg fracturing. The first is simply one of scale, and hence technical feasibility. The quantity of microwave radiation which would be required to remove a substantial fraction of an iceberg is very large. Indeed, if it is assumed that a useful microwave ablation procedure is dependent upon vaporizing one kg of ice per second, then about 3 MW of absorbed microwave power would be required. Power delivered from source would have to be much greater, perhaps double, since a sizeable fraction of the energy would not be absorbed but would be reflected or scattered. Of course, the primary mode of action would have to be the spalling off of large chunks of ice under the effects of thermal shock and steam pressure buildup. To vaporize the entirety of a 1 million tonne iceberg with absorbed power of 3 MW would take over 30 years. Focussing the beam sufficiently to achieve the concentrated energy necessary could also prove problematic. An unfocussed beam would warm ice but would not induce the necessary mechanical action to make the method potentially feasible.

A second problem would relate to extraneous microwave radiation in the environment. This radiation would arise primarily from two sources. First, radiation would leak from the microwave generating equipment aboard the iceberg fracturing vessel. A second source of extraneous radiation is provide by reflection or backscattering from the target surface on the iceberg. Assuming 6 MW delivered to the target, and 50% reflection, then a power density of $50 W/m^2$ would be realized at a distance of 140 m from the target. Canadian standards for occupational microwave exposure set a limit of $50 W/m^2$ for one hour time-averaged exposure in the workplace. The exposure limit for the general public is $10 W/m^2$ (Michaelson 1983). This level would be realized 310 m from the target point. Keeping in mind that the overall exposure would be the sum of power reflected from the target and power leaked from the source apparatus, it is clear that careful shielding and other precautions would be required. The fact that the microwave field would be highly spatially nonuniform, giving peak power densities far higher than the average powers mentioned above, is a cause for further concern.

In overall assessment, microwave-induced ablation of icebergs appears to demonstrate a very limited potential. It is probably the most promising of the "beam" methods enumerated in this section. Nevertheless, huge technical problems, combined with significant environmental and safety problems, render the method clearly unattractive at this time.

5): Beams of Fluids and/or Small Projectiles.

Ice can be cut or broken with high velocity fluid jets or streams of small projectiles. Cutting ice with water jets is a demonstrated technology and is indeed one of the fastest possible ways to make holes or slots in ice. Fluid jets also tend to be quite efficient in terms of the volume of ice removed per unit of mechanical energy supplied to the cutting system.

A properly aimed jet of water or other fluid could in principle be used to slice sections of ice from the above water portion of an iceberg. An entire iceberg might be dismantled in this way, although major technical problems arise, even at the conceptual stage. Water jets interact strongly with air, tending to diffuse and then atomize. Their effective range is limited to at most a few metres. Hence, a cutting head would have to be brought into almost intimate contact with the iceberg surface, but an attempt to create long or deep slots would far remove the surface to be cut from proximity to the cutting head. Increasing the density of the cutting fluid would improve range, but would cause potential new environmental, safety and handling problems, depending on the nonaqueous liquid selected.

A jet of fluidized particles, as for example sand in air as used in sand blasting, has the same general characteristics as a fluid jet without solid inclusions.

A jet of small projectiles, perhaps pneumatically propelled, would, in concept, be able to cut ice in accordance with physical principles similar to those by which water jets operate. The particles would have to be relatively homogeneous in size and shape and moving at bullet-like velocities. Much greater range than could be obtained with fluid jets is realizable with sprayed particles. Practical range would be determined by velocity and ballistic considerations and by the ratio of particle cross-sectional area to particle mass. The design of a "gun" capable of launching the projectile stream would be problematic from an engineering viewpoint and would be considerably more difficult than designing a corresponding fluid jet system. Both fluid jets and sprayed particles sufficient for iceberg mass reduction would resemble naval ordnance in their capacity to cause serious damage to personnel and/or property if misdirected. Appropriate safety considerations would be imperative in planning for their prospective use. A critical aiming problem would dominate the development of any operational procedure to cut icebergs with beams directed from a ship (see the section above on laser cutting).

In conclusion, it is apparent that even with foreseeable extensions to foreseeable technology, fluid or jet cutting would remain impractical for large-scale iceberg fracturing.

6): Fluid Injection (non-self-sealing).

A solid mass can be fractured or split through application of pressurized fluid injected into its interior. The fluid forms a small cavity at its internal point of entry by elastically or plastically deforming the surrounding material. The cavity expands as further fluid is forced into it at accumulating pressure. Crack initiation from the cavity then commences, with the newly formed cracks rapidly becoming filled with pressurized fluid. This fluid provides a net diverging stress normal to the crack face, tending to open the cracks still further. When a crack or cracks reach the exterior surface of the solid body, pressure is released and the fracturing process terminates. Hopefully by the time that fracturing terminates, the body will be entirely split, or at least severely fractured.

Fluid injection is a demonstrated means for breaking large rocks, and the method holds clear potential for application in fracturing icebergs. Two basic categories of fluids can be envisioned for use as a pressurizing medium in iceberg fracturing. In one category are common, generally low viscosity fluids such as compressed gases, water, or hydraulic oil. These materials are easily handled and delivered under pressure; however, they present problems of difficulty of confinement when released within an iceberg where a leak-tight seal may be difficult or impossible to establish. In a second category are fluids of extreme viscosity, or those that freeze following delivery or that react with ice or water to form a solid. These so-called self-sealing fluids pose special problems, but on the other hand have special advantages, and are dealt with separately in the subsequent section.

Injection of gas or water into an iceberg can, in principle, lead to fracturing if pressure in the entry cavity and resulting cracks can be maintained. Iceberg ice is usually precracked, and may contain leak paths even before large pressure is accumulated. The hole surrounding the entry duct into the iceberg may also provide a leak path unless elaborate precautions are taken to seal it. Generally speaking, in order to fracture an iceberg by injection of a low-viscosity fluid, the flow resistance along the combination of all leak paths must be much greater than the flow resistance along the supply/entry line. This condition must be maintained until the iceberg is satisfactorily fractured.

A simple demonstration shows up some of the functional aspects and the problems inherent in the fluid injection method. A hypodermic syringe can, under ideal conditions, be used to fracture a potato. The needle is inserted in a single clean motion into the vegetable. The tip of the needle is positioned to lie at a point such that the nearest surface is actually a perimeter, encircling the potato such that points on the perimeter are roughly equidistant from the tip. When fluid pressure (either air or water but preferably water) is applied, the potato will crack along a plane passing through the tip of the needle and intersecting the surface along the perimeter closest to the tip.

If the needle is moved in the entry hole so that the fit is slackened in even the slightest amount, then leakage around the needle will preclude developing the necessary internal pressure (about 0.7 MPa) to cause fracture. If the needle is significantly off centre with respect to the perimeter nearest its tip, then a crack will open on one side only, and pressure will be relieved before full fracture is achieved.

Sealing the entry hole in an iceberg, while critical, is clearly problematic given the difficult operating environment and the high tolerances required. Even a small leak would lead to immense losses of pressurizing medium. Further problems of leakage stem from the fact that iceberg ice is generally precracked. In fact, deep waterfilled holes in icebergs have been observed to drain, suggesting the presence of significant leak paths operating at even very low pressures. In a leak-free situation, should this be established, there would still be problems akin to those observed when a needle is inserted off centre in cracking a potato. That is, major cracks induced by the pressure could reach the surface while the body of the iceberg remained intact. These cracks would provide large leak paths, causing internal pressure to drop and further fracturing activities to cease. It is clear that problems of fluid leakage and consequent loss of internal pressure would make the successful fracturing of an iceberg by injection of unconfined non-self-sealing fluid very improbable.

7): Injection of Self-Sealing Liquids.

Three classes of liquids can be labelled potentially self-sealing when injected under pressure into a somewhat leaky ice mass. First, there are fluids of high viscosity which will accumulate under significant pressure even as they flow along a leak path of substantial cross-sectional area. Glycerol is an example. Second, there are fluids which solidify by freezing at temperatures slightly above the melting point of ice. Cyclohexane, with a melting point of 6.55 ° C is an example. Third, there are a few materials which are liquid or gaseous at temperatures below 0 ° C but which react with water or ice to form a solid. Tetrahydrofuran is an example of this class.

Highly viscous liquids present problems when considered as iceberg fracturing media because of the enormous pressures that would be required to deliver them through a feeder line of appreciable length. Pressures ranging to hundreds or thousands of MPa could be envisioned. It would be assumed that as the fluid leaked towards the ice surface, it would flow appreciably only under pressures sufficient to initiate and propagate fractures in ice. Use of a thixotropic fluid such as drilling mud could offer significant advantages if the material was delivered in the fully fluid (low viscosity) state through a feeder line and then allowed to gel in the cracks formed in the ice. Extensive testing would be required to verify that this regime was realizable.

Liquids which freeze at temperatures slightly above 0 ° C are probably more practical than viscous liquids for use as an iceberg fracturing medium. A suitable liquid, possessing relatively low viscosity, would be delivered through a thermally insulated or heated feeder line at sufficiently elevated temperatures to prevent solidification. The liquid would then freeze upon contact with the berg ice or cold meltwater or seawater. The pressure induced cavity in the ice would fill with a mixture of liquid and solid pressurizing medium, while cracks or other extended leak paths would fill entirely with solid. A key source of potential problems would be the tendency for the liquid to freeze prematurely in the feeder line. Further problems could result if the liquid were delivered too rapidly, or at too high a temperature, or if leak paths to the surface were short or of large cross-sectional area. In such cases, liquid would escape without solidifying.

A small class of chemical substances are liquid or gaseous at temperatures below 0 ° C, but combine with ice or water to yield a solid which melts at a temperature above 0 ° C. Such substances are usually formers of clathrate hydrates: icelike materials in which foreign molecules are encapsulated by water molecules in a low-density hydrogen-bonded crystal. Many clathrate hydrates are stable only at elevated pressures and will decompose rapidly at atmospheric pressure, but a few, notably those formed with tetrahydrofuran or with ethylene oxide, are entirely stable at 1 atm. These substances will form a solid plastic-like skin on the surface of wet ice.

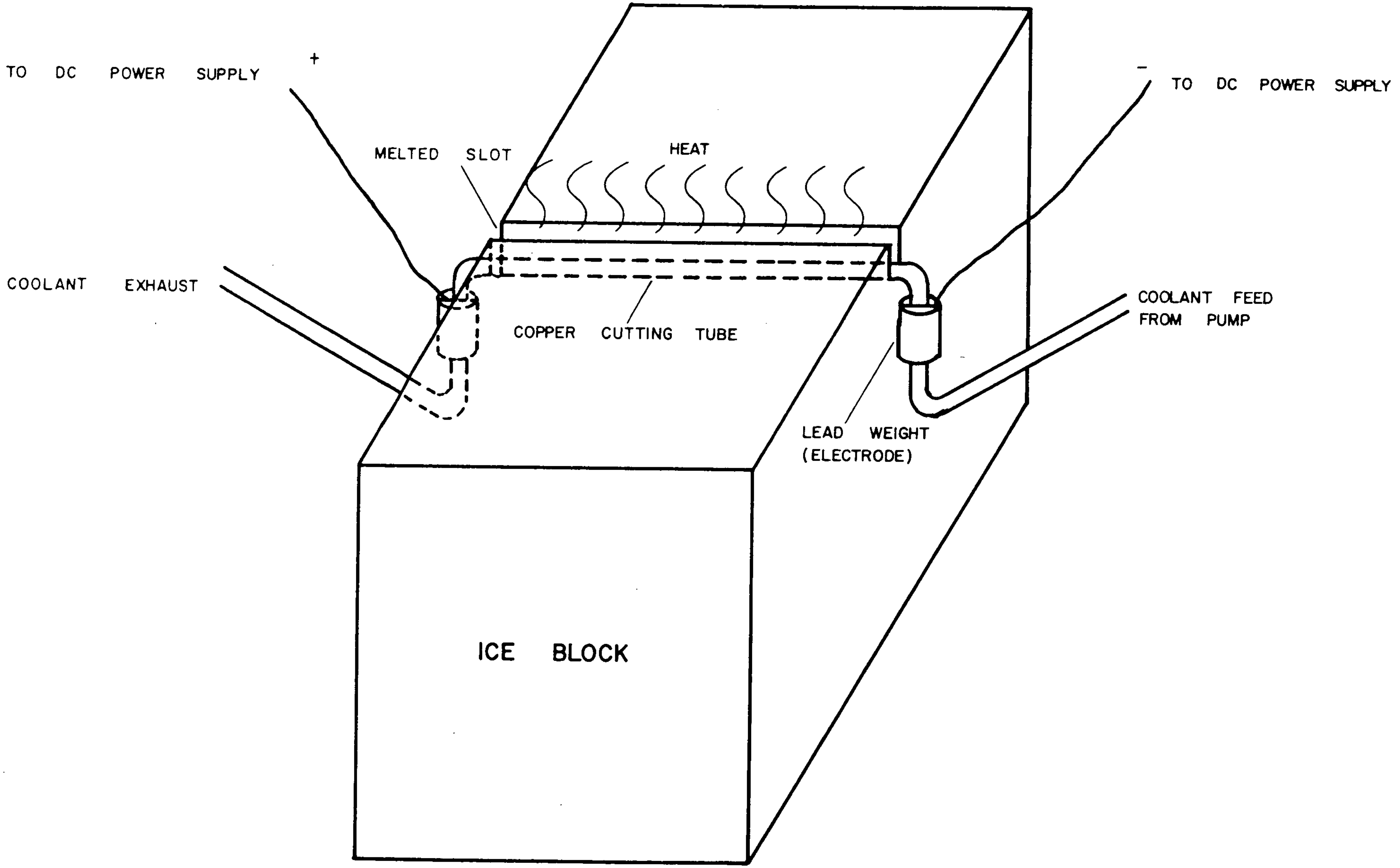
When injected into a cavity within an iceberg, a hydrate-forming liquid would form a skin, sealing the cavity, and would solidify almost instantaneously in cracks or other leak paths. Such liquids have low viscosity and would not freeze up in the feeder line. The advantages of using a hydrate-forming liquid as a pressurizing medium in iceberg fracturing are sufficiently great as to warrant such liquids being our sole focus in further discussions of this general approach.

8): Injection of Confined Fluids/Mechanical Fracturing: the Flat Jack.

While injection of unconfined self-sealing fluids offers clear potential in iceberg fracturing, mechanically confining the pressurizing medium might prove more practical. For instance, a hydraulic ram embedded deeply in ice would, when extended, prove highly disruptive and could lead to tensile failure over large areas. Problems of fluid leakage and consequent loss of pressure would not arise. The applied stress field would be highly directional and could be intentionally aligned with directions of small cross section or potential weakness in the iceberg.

A conventional hydraulic cylinder is probably not practical for iceberg fracturing. The cylinder would need to be very large, with linear dimensions of the order of several metres, and correspondingly very heavy, with a mass of the order of several tonnes. It would be difficult to deploy on an iceberg surface, let alone embed at depth. A more practical hydraulic loading configuration can be found in the flat jack, which is basically an envelope made with two initially flat pieces of metal placed together and sealed at their edges, incorporating a feed tube for pressurizing fluid (see Fig. 2 following p. 40). The jack bulges when pressurized and so exerts force on its surroundings.

An unexpanded flat jack is very narrow in one dimension and can be inserted into a narrow slit cut in the ice. A flat jack large enough to fracture an iceberg would have linear dimensions of the order of several metres and would be most readily embedded by causing it to melt its way into the ice edge on. The penetrating edge could be heated with hot fluid passed through a tube running along the edge. The jack would require embedding to a depth approaching 50% of the overall vertical thickness of the iceberg (i.e. draft plus sail height). Applied hydraulic pressures would range up to values of the order of 100 MPa, the ice loading area would be of the order of a few square metres or tens of square metres, and overall gross applied loads would range to 100,000 tonnes. A key potential problem in the method would be local, plastic failure of ice surrounding the jack, although deep embedding should render this situation improbable.



HOT WIRE METHOD FOR CUTTING ICE

Figure 1

9): "Hot-Wire" Cutting.

Ice has a low melting temperature relative to most common metals and hence can readily be melted by direct contact with a heated metal surface. In particular, a hot metal wire can cut through ice rapidly, continuing to penetrate so long as the temperature of the wire is maintained significantly above 0° C. This penetration occurs independently of applied mechanical force at a rate determined solely by the rate of heat transfer. Sufficient force to maintain the cutting line in contact with the ice is all that is necessary to sustain penetration.

A hot wire cutting through ice must be continuously supplied with energy, this energy being evolved as heat from the surface of the wire and thereupon transferred by conduction to the ice, causing melting. The latent heat of fusion of ice is large compared with most low melting solids. Accordingly, a wire penetrating at an appreciable rate must evolve heat very rapidly. The most practical method of rapidly and uniformly heating an extended length of wire is by passing a large current of electricity through it.

The notion of using an electrically heated wire to cut ice from an iceberg was first suggested by Weeks and Mellor (1977), who dubbed the requisite apparatus an "electrothermal knife". They suggested its use, not in the context of iceberg management, but rather for iceberg utilization: the cutting up of large Antarctic icebergs towed to desert locations to provide fresh water. Few details of the engineering design of the proposed knife were given, this in keeping with the very general approach taken in their article to the overall problem of iceberg utilization[1]. Nevertheless, the electrothermal knife was pointed out as one of the more feasible methods of dismantling an iceberg for subsequent melting and use as a water supply. It is clearly worth noting the engineering similarities between this aspect of the iceberg utilization problem and the problem of iceberg fracturing addressed in the present study.

An iceberg fracturing system based on an electrically heated wire initially laid across the surface of an iceberg could, in principle, afford the controlled splitting of the berg into two sections. Fig. 1 illustrates the functional aspects of such a hot-wire cutting system. The wire, starting at the top surface of the above water portion of the iceberg would melt its way down solely under the influence of gravity, eventually reaching the bottom of the berg and dropping out into the ocean. Assuming that precautions were taken to insure that the slot cut by the wire did not refreeze solidly after the wire had passed through, the sections of ice on either side of the slot would diverge due to natural forces. These forces would arise from ocean currents and winds and from the deviations from hydrostatic equilibrium of each of the two, now separated, floating ice masses.

The key potential problems in the "hot-wire" method relate to slot refreezing and cutting line burnout. A single conceptual approach can be taken to address both problems. Instead of using a wire, a tube of small exterior diameter can be used, through which fluid is forced under pressure. The fluid distributes the heat evenly along the tube, and prevents the formation of localized hotspots and subsequent burnout. The leakage or extrusion of this fluid through fine holes in the wall of the cutting tube

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[1] A concept which has not as yet been rationalized economically.

inhibits refreezing of meltwater in the slot, if the fluid selected is also a good antifreeze. The inherent simplicity of the "hot-wire" method, both in concept and in its subsequent analysis, renders it very attractive for consideration as an iceberg fracturing method.

CHAPTER 3.

DETAILED ANALYSIS
AND
ENGINEERING EVALUATION
OF
ICEBERG FRACTURING METHODS

3.1. Introduction

In the following section, four potential iceberg fracturing methods are selected for detailed analysis. Each of these methods shows some degree of promise. The use of explosives, particularly in the form of large bombs, cannot be discounted on any but environmental grounds. From a purely technical viewpoint, the method appears workable. Injection of pressurized fluids holds clear potential as an iceberg fracturing method. Two modes are considered in the following discussion; injection of unconfined self-sealing fluids being the approach which seems most likely to lead to a practical technique should serious development be undertaken. The alternative, fracturing with fluids enclosed in a confining envelope [the flat jack method] is less dependent on undeveloped technology, but is clearly problematic from a logistics viewpoint. The "hot wire" ice cutting method holds most promise for development into a fully operational iceberg management tool. The method is easily analyzed and tested and relies heavily on more or less conventional technology. No insurmountable obstacles, either technical, economic, or environmental, are foreseen in carrying the "hot-wire" method through to operational status.

In the following, we have maintained the numbering scheme used in the previous section.

3.2.1. Method 1: Explosives and Pyrotechnics.

Of the many possible methods for fracturing or demolition of icebergs, the one which has received the most thorough testing, indeed the only one to have received thorough testing, is the use of explosives and pyrotechnics. The first trials of that sort were carried out with military ordnance - in the words of Mellor and Kovacs (1972)

> "Numerous attempts have been made over a period of 60 years, but ... almost total lack of success has been reported. Most tests have been made under the auspices of the International Ice Patrol and the U.S Coast Guard, who have used gunfire, demolition charges, land mines, depth charges and bombs".

The report of the International Ice Patrol on their 1960 season (Bullard et al. 1961) contains a detailed description of one such test, in which 15 bombs of 1000 lb each were dropped on a medium-sized iceberg over a one-week period, resulting in a small change in orientation of the berg. Nevertheless, despite this lack of success, we argue below that very large bombs designed to penetrate deeply into an iceberg before exploding, should not be ruled out for use in emergency situations.

The numerous problems and failures encountered by many investigators of explosive demolition can be attributed to charge placement at or near the ice surface. Cratering studies in both ice and rock have shown that a much more effective approach involves the placement of charges more or less centrally inside the material to be blasted (Duvall and Atchison 1957).

The only tests to date of iceberg demolition which could truly be described as successful were those carried out by Mellor and Kovacs in 1972 for the Arctic Petroleum Operators' Association (Mellor and Kovacs 1972; Mellor et al. 1977; Weeks and Mellor 1977; Mellor 1985; see also the critique by Bauer (1972)). In these tests, the technique of bench blasting with multiple shotholes was used to break up a small ice island in Mackenzie Bay in the Beaufort Sea, and various supporting blasting tests were made in two other ice islands at the same location. Objects of the program were to study crater, bench, and controlled-splitting blasting and blasting in water under ice, to prove out a lightweight shothole drill for placing charges, to establish load factors for ice and to determine whether ice islands under shock loading become unstable.

An electrically-powered ice auger, then newly invented, made the drilling of the shotholes feasible. There was reason to expect that the yields of broken ice would be much greater for bench blasting than for crater blasting.

Three ice island fragments (approximately 37 m wide by 16.5 m thick with 7.5 m above the water level) grounded in 8 m to 9 m of water, were tested. Electrically driven augers with 83mm diameter bits were used to drill a total of 33 shot holes which were loaded with at total of almost 1400 kg of explosives. The main explosive used was a high-density Hydroflo (C.I.L. trademark) blasting slurry, which consists of ammonium nitrate, trinitrotoluene (TNT), water, and minor amounts of other important ingredients, with added aluminum (see the *Blasters' Handbook* (CIL 1980), for details), primed with TNT/PETN and detonated non-electrically. The Hydroflo is water-resistant, easily poured into shotholes of the diameters indicated, and, with a specific gravity of 1.45 gm/cm^3, readily displaces water from shotholes.

It is worthwhile at this point to compare the cratering characteristics of ice and rock. Livingston (1960) conducted systematic cratering tests on glacier ice and, although there are some inconsistencies in compiled data, the overall indication is that charges in ice can be set about 50% deeper than in rock. Also, ice charges realize a true crater radius (as opposed to apparent crater radius or open hole) about 30% larger than in rocks, while breaking approximately twice the volume.

Destruction of icebergs and ice islands by crater blasting involves the use of one or more cratering charges. The size, number, and proximity of the charges that can be placed depends on the thickness of the ice.

It should be noted that for the simultaneous breakout to the top and the bottom of the iceberg, charge depth should be adjusted for the confining effect of water surrounding the iceberg. This calls for a 1% increase in charge weight per metre of water depth. In terms of charge depth instead of weight, a water depth of 20 m requires a 6% decrease in charge depth.

Although bench blasting, using several shotholes, is considered the best method for breaking large volumes of rock, the results in iceberg ice were disappointing. In yield of volume of broken ice per unit mass of explosive, the ice was comparable to Carboniferous limestones such as are found in the north of England. The yield was given almost exactly by

$$\text{yield} = 1\ \text{m}^3/\text{lb} \equiv 2.2\text{m}^3/\text{kg} \tag{1}$$

of explosive charge. Several mechanisms may play a role in bringing about this unfortunate result: the high compressibility of ice relative to that of rock; phase transitions among the various high-pressure forms of ice, which would absorb energy; and inhibition of crack propagation by cracks, bubbles and other inhomogeneities present in the ice.

Using the above figure, the amount of explosive necessary for the demolition of an iceberg of 100,000 tonne using bench blasting is approximately **50 tonnes**. This of course is the amount necessary to break **all** of the ice. There is some conflict as to whether crater blasting would be more or less effective (Mellor and Kovacs 1972) but in any event it is not an order of magnitude more effective.

The amount of explosive necessary to fracture an iceberg into two or more large pieces is less, but still amount to several tonnes of charge weight.

Mellor's opinion was, and remains (Mellor 1985), that the optimal method for iceberg demolition is to use crater blasting in a few chambered shotholes, using a blasting slurry such as Hydroflo[1] which is water-insensitive and which has sufficient density to displace standing water from the shotholes, and which flows well when cold. In his view, yields are comparable to those obtained with bench blasting, and the charge emplacement is much easier. Nevertheless, the charge emplacement is nontrivial[2], and the charges required are massive. Indeed, careful charge placement is important for explosive demolition; but, while Mellor and Kovacs knew the geometry of their ice islands accurately, because of the bathymetric constraints, the routine operational determination of the geometry of floating, deteriorated icebergs remains far in the future.

In any event, the necessity of boarding the target iceberg, and working on it for one or more days, makes the method unsuitable for routine operational use.

The quantities of explosives required are prohibitive from a safety, environmental, and regulatory standpoint. The likelihood of environmental damage from the blast wave is significant when one considers the high acoustic coupling coefficient between ice and seawater: the ratio of acoustic impedances for ice to water is about 2 (Bauer 1972, Mellor

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[1] Possible alternatives include Aquagel, made by the Atlas Powder Company, and Tovex, made by DuPont Canada Inc.

[2] The drilling and chambering might best be carried out by chemical means.

and Kovacs 1972), so that the outgoing stress wave will experience little reflection back into the iceberg. The resulting shock wave will be highly deleterious to fish (Wright 1982). Unreacted explosive and chemical byproducts of the explosion, including oxides of nitrogen and partially oxidized nitro-organics, would probably prove noxious in the marine environment when present in tonne quantities. A serious problem would result from a misfire (failure to detonate or partial detonation), which would create an environmental and navigational hazard which would be very difficult to deal with.

Emergency Demolition of Icebergs

If an emergency situation arises in which the destruction of a large iceberg is of such urgency that normal environmental considerations and regulations are of diminished concern, then the conventional blasting methods outlined above will also be too slow. Fortunately (for our purposes at least) the problem of rapidly demolishing large objects has been considered before, and solutions have been found.

The requirement is for the rapid emplacement of high explosives in quantities of the order of 10 tonnes, deep within an iceberg, rapidly and under adverse weather conditions. To find a system or method answering these requirements we can turn to the history of World War II in Europe (Ford 1971, Frankland 1970, Morpurgo 1973). It was realized fairly early in that conflict that the "small" 250 kg bombs which were standard at the beginning of the conflict were completely inadequate for strong, relatively small structures such as viaducts, fortified emplacements, and E-boat pens. In consequence very large bombs were developed[1] with four characteristics: they were heavy, they were streamlined, they had angled tailfins so that they would spin, and they were designed for deep penetration into soil and even concrete. To achieve the necessary, supersonic terminal velocity they had to be dropped at altitudes in excess of 6100 m (20,000 ft). The two bombs developed were called "Tallboy" (5.5 tonne; 12,000 lb) and "Grand Slam" (10 tonne; 22,000 lb). Tallboys were used with great success against V1 launching ramps and storage facilities. At Wizernes, a 10,000 tonne concrete dome on top of a storage complex was shifted from its foundations and the tunnels below reduced to rubble. At Siracourt, a Tallboy penetrated the 5 m thick concrete roof of a V1 storage emplacement and exploded inside. One Tallboy penetrated 25 m of soil into a railway tunnel near Saumur, France, shortly after the invasion of Normandy; its explosion in the tunnel caused about 10,000 tonnes of earth to fall in. The deeply buried and heavily fortified V3 emplacement at Marquise-Mimoyesque was destroyed in a Tallboy attack, effectively ending the V3 program. This weapon was used to shatter the embankment of the Dortmund-Ems ship canal, rendering it unusable for the duration of the conflict. One Grand Slam demolished seven spans of a concrete viaduct near Bielefeld, Germany, which had withstood repeated attacks with more conventional ordnance, and even with Tallboys; it did so by "eradicating" the foundations of the pylons. Finally, last but not least, Tallboys were used in the destruction of the *Tirpitz*, the largest warship in the European theatre of operations[2]. One Tallboy dropped on 15 September 1944 struck the

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[1] By the English engineer Barnes N. Wallis, whose other achievements included the R100 dirigible, the Wellington bomber, and the bouncing bomb used to by 617 "Dambuster" Squadron, RAF, to destroy the Möhne and Eder dams in the Ruhr in 1943.

[2] The *Yamato* and *Musashi* were even larger.

ship's bows and did damage which was probably irreparable; it was, however, still possible to use her as a floating fortress. That possibility was eliminated when she was destroyed by two more Tallboys in an attack carried out on 13 November of the same year.

Here, then, we have a device which could be useful against an iceberg. It is clear from our previous discussion of conventional blasting that the amount of explosive contained by a Grand Slam is of the right order of magnitude to do the requisite damage. We will now make a rough estimate of the depth to which it might penetrate into an iceberg.

Under sufficiently high stress, any material will flow as a liquid. Assuming a quadratic drag law, then the vertical velocity $u(t)$ of the bomb in the target material is given by

$$\frac{du}{dt} = -A\ u^2, \tag{2}$$

where the coefficient A is given by

$$A = \frac{C_D\ \rho_{target}\ A_\perp}{M_{bomb}},$$

with M_{bomb} the mass of the bomb, $A_\perp$ its cross-sectional area, C_D its drag coefficient, and ρ_{target} the mass density of the target being penetrated. Taking the drag coefficient to be independent of velocity, eq. (2) can be integrated to give

$$u = \frac{u_0}{A\ u_0\, t + 1}; \tag{3}$$

the bomb enters the target with velocity u_0 at time $t = 0$. We suppose that the quadratic drag law breaks down, and the bomb comes to a halt, at some time t_ς when the velocity has fallen to a fraction ς of its velocity u_0. Thus

$$\varsigma = \frac{1}{A\ u_0\, t_\varsigma + 1}.$$

The depth of penetration D can be obtained by integrating eq. (3) above:

$$\begin{aligned} D &= \int_0^{t_\varsigma} \frac{dt}{A\ u_0\, t + 1}. \\ &= \frac{1}{A\ u_0} \ln\left(\frac{1}{\varsigma}\right). \\ &= \frac{1}{\rho_{target}} \cdot \frac{M_{bomb}}{C_D\ A_\perp} \ln\left(\frac{1}{\varsigma}\right). \end{aligned}$$

Hence, for two earthquake bombs of the same type, launched from the same height against two different targets, the ratio of the penetration depths will vary inversely as the ratio of the target densities:

$$\frac{D_1}{D_2} = \frac{\rho_{target\,2}}{\rho_{target\,1}}. \tag{4}$$

Applying eq. (4) to the railway tunnel near Saumur mentioned above; a penetration depth of 25 m (80 ft) was achieved. A typical density for dry earth (Table 1-110 of Bolz and Tuve (1973)) is 1.4 gm/cm^3, while the density for iceberg ice of 2.5% porosity is 0.894 gm/cm^3. Hence a Tallboy dropped at altitude could be expected to penetrate approximately 38 m (125 ft) into an iceberg. This calculation is most approximate, but it does indicate that penetration depths of the requisite order of magnitude can be achieved with the earthquake bombs.

The acoustic match between water and ice is sufficiently good that a large water-deployed bomb, say of the "Dambuster" bouncing bomb type (Brickhill 1977) might also prove effective.

While the use of earthquake bombs is of interest, it is not without problems.

Aircraft: In the first instance, Grand Slam was carried by specially modified Lancaster bombers, and no aircraft in use today is designed to carry it. Indeed, few aircraft available today could lift it. Surplus B-29 bombers may still be available; the B-29 did drop Tallboys on an experimental basis, and we have heard that the B-29 could be modified to carry Grand Slams on underwing mounts, although we have not verified this point. Of aircraft now in common use, the C-130 is the only realistic candidate. A bomb of the Grand slam type could perhaps be deployed from the cargo bay of a C-130 using a small drogue parachute, which would disconnect when the bomb was free of the aircraft. A similar system has been used to air-launch Minuteman ICBMs from the Hercules.

Accuracy: 617 Squadron, who were the RAF's precision bombing group and who did use the earthquake bombs, only achieved an average error of about 50 m from altitudes of 6700 m (Brickhill 1977), the preferred height for release of these bombs. The B-29 had a good bombsight and was presumably capable of similar accuracies. Dropping the bomb from a C-130 in the manner indicated above would be inherently less accurate, but that could probably be compensated for by flying slowly during the deployment; bombers and attack aircraft must fly fast to reduce their vulnerability to ground fire - hazardous though icebergs may be, their capacity to shoot back is very limited[1].

Aiming considerations alone dictate a requirement for several bombs per large iceberg, and reduce the usefulness of the approach for small icebergs. The aiming problem could be reduced if a bomb of "Dambuster" type were used, but the airframe modifications required would probably be greater. "Smart" bomb technology[2] of the sort introduced into service by all major air forces in the late 1960s would greatly increase the probability of a successful hit.

Explosive consumption: the explosive charge of the Grand Slam was approximately 7.5 tonne. It is clear from the work of Mellor and Kovacs discussed above that while such a bomb would do significant damage to a large iceberg, several would probably be required to destroy it.

Excessive penetration: it is clear from the figures given above that an earthquake bomb might pass right through an iceberg of shallow draft.

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[1] But not nonexistent! Massive chunks of ice have been observed to be thrown for considerable distances in the course of calving.

[2] To be precise, precision-guided munitions using laser designation of target, or munitions-mounted television guidance.

Number of aircraft required: the second, third, and fourth points above make it clear that a substantial number of earthquake bombs, of the order of ten, would have to be committed to the destruction of a single large iceberg. Even assuming that each aircraft involved flew multiple missions, it is evident that more than one aircraft would be required.

Training: training even of pilots experienced in ground attack to the use of the bomb system would be required, as nothing similar is in common military use today.

Expense: the above points make it clear that the development of an anti-iceberg capability based on earthquake bombs would be expensive; many bombs would be needed, substantial airframe modifications might be required, several aircraft would be needed, and a training program for pilots would have to be implemented.

Nevertheless, all of the problems with earthquake bombs, except cost, can be overcome, as they were overcome in the past. And, for the emergency demolition of icebergs, the fundamental point remains, that the design philosophy underlying the earthquake bombs: large explosive charges, penetrating deeply into the target, to be rapidly deployed under adverse environmental circumstances, is also the design philosophy for an effective operational iceberg demolition system.

Thermite

The following discussion on thermite is provided not because thermite presents a credible approach to the problem of iceberg fracturing, but rather because of the great claims which have been made for the method, initially by H.T. Barnes of McGill University (Barnes 1925, 1926a,b,c, 1927, 1928; Diemand 1984). Even cursory consideration of such claims makes discussion inevitable. Precise classification of what effects thermite does produce is difficult, but we have included thermite treatment of ice here rather than under "thermal methods" because any large-scale action it has must be due to blast effects from confined thermite in ice; indeed, two of the claims in the U.S. patent issued to Barnes in 1925 (Barnes 1925) makes reference to the explosive nature of the ice/thermite interaction.

Thermite consists of an intimate mixture of a strongly reducing metal powder, nearly always aluminum, and a metal oxide in powder form, usually manganese dioxide or ferric oxide. The aluminum "burns" in the metal oxide, generating large quantities of heat, producing aluminum oxide and liberating the reduced metal. Thermite made with ferric oxide has been extensively used for spot welding, while that made with manganese dioxide is a standard incendiary material.

Barnes published several articles on iceberg demolition (Barnes 1926a,b,c, 1927) which have been reviewed[1] in accessible publications (Diemand 1984, Mellor and Kovacs 1972). He has a lengthy discussion in his book "Ice Engineering" (Barnes 1928), as well as in his United States patent for the process (Barnes 1925). A short but interesting

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[1] Diemand (1984) gives a good account of Barnes's views; her exposition of the U.S. Coast Guard tests of thermite is incomplete; see below.

account of his approach to the National Research Council of Canada for support for his ice work is given by Thistle (1966). We will concentrate on Barnes's paper in the Proceedings of the Royal Society (Barnes 1927), partly because it is his only account of the subject which was published in a major archival scientific or engineering journal[1], and partly because all of his writings on the subject say much the same things and the article in Proc. Roy. Soc. provides, in our opinion, the best resumé of his position.

According to his article in the Proceedings of the Royal Society, Barnes attempted thermite demolition on three icebergs near Twillingate in 1926. For the first test, a 100 lb (45 kg) charge of thermite was set at a depth of approximately 1 m on the surface of a 500 ft sq free-floating berg that had a freeboard of 75 to 100 ft.

> "The result of firing was the emission of flame and fire to a height of 125 feet or more with a great explosion of the ice and the throwing off of great masses of the ice from the sides and ends of the main plateau treated. ... As anticipated, the effect of the intense heat in direct contact with the hard ice was to send a temperature wave into the mass which produced a great deal of cracking and visible disruption, apart from the explosive shock ... of the dissociated ice itself."

The iceberg subsequently fell apart over a two-day period. The second test was on a grounded berg of unspecified size; a 500-lb charge, apparently containing some high explosive, was placed at a depth of 4 ft.

> "The whole thing was a most wonderful sight when the mighty charge fired and roared, lighting up the iceberg and surrounding hills like Vesuvius in eruption. ... As before the real change in the berg did not take place until the next day, when most of the off-side nearly through the thermit hole came away... For two days after this berg continued to break away ...".

The third test was on a 100 ft diameter grounded berg described as of "mushroom type". Two charges, specifically stated to be of thermite, of 60 lb and of 100 lb, were fired on the surface.

> "Explosions came in both cases, but no visible sign of disrupting ice. On returning the next morning this berg could not be found for it had fallen away along the thermit hole, becoming honeycombed with cracks. A floating fragment was identified by marks of the molten thermit and the hole blown out by the reaction which was now on the water-line half hidden under the surface ...".

As a consequence of Barnes's work, the U.S. Coast Guard made major tests with thermite in 1959 and 1960 (Budinger et al. 1960, Bullard et al. 1961, Van Allen 1961), in which charges substantially larger than Barnes's were set off, with no significant destructive effect. In the 1959 tests, incendiary munitions were used, each of which broke up

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[1] It is worth noting that while Proc. Roy. Soc. is a journal of high repute and distinguished history, Barnes, as a Fellow of the Royal Society, could publish in it without being refereed.

into a number of bomblets; one type used powdered magnesium and napalm, while the other used thermite and a binder. The bomblets were scattered on the icebergs, rather than being deeply embedded. However, Barnes's hypothesis was that the effects of thermite were due to thermal shock, so that tamping would be irrelevant; in fact it would be expected, contrary to a recent criticism (Diemand 1984), that distributed charges would be *more* rather than less effective than a single charge of the same mass.

In the 1960 tests, three substantial charges were actually embedded and fired in two icebergs. In the larger, a medium-sized berg, 13 charges of 28 lb totalling 165 kg (364 lb) were fired on one day, and 20 charges totalling 250 kg (560 lb; gross weight in each case) were fired the following day. A few small growlers calved off, but "neither blast had any marked effect on the iceberg" (Van Allen 1961). The burial depths were comparable to those described by Barnes, and the charge weights in excess of his. A third thermite demolition was also attempted, using 6 charges of 28 lb, on a smaller iceberg. "The only result shown was a small crater, only a few inches deep, which was filled with melting ice cubes" (Van Allen 1961).

Thermite Energetics.

At no point does Barnes face the fact that ice cannot be heated above 0° C, so the high temperature of the thermite reaction is not of any particular use. And the total energy liberated by, say, 90 kg (200 lb) of thermite is not particularly remarkable. From the *Handbook of Chemistry and Physics* (CRC 1978) we have

$$2\,Al + Fe_2O_3 \rightarrow Al_2O_3 + 2\,Fe + 188.34\ \text{kcal}.$$

Hence a stoichiometric thermite mixture will liberate, if it undergoes perfect combustion (itself far from sure in view of the violence of the reaction and the probability of blowing reactants around), 881.5 cal/gm. Hence 200 lb of thermite will liberate, under ideal conditions, 8.014×10^7 cal. Now the specific heat of ice at -11° C is 0.4861 cal/gm/deg. Assuming that *all* of that heat penetrates the ice (10% would be a more reasonable estimate), then that amount of heat is sufficient to raise in temperature, by 10° C, a mass of only 16.5 tonnes of ice, an amount which could be contained in a small room, and which is utterly trivial compared with the mass of an iceberg. The data for this calculation were all available in Barnes's time - the value of the specific heat of ice quoted above was, for example, published in 1915. He apparently did make such a calculation, but dismisses it (p. 149 of "Ice Engineering" (Barnes 1928)):

> "The writer does not attach importance to the amount of ice which thermit actually melts for the heat liberated is small compared to the heat of fusion of ice. The important fact is the output of energy in a penetrating heat ray which overcomes the exceedingly small temperature effects, in the water responsible for the pranks and inconveniences caused by ice."

It is no wonder that, in Barnes's own words (Barnes 1926a), he had "suffered so much adverse criticism from eminent officials and even scientists of Europe and America"!

In fact, as our calculation of the radiative penetration depth below will show, all but a minute fraction of that heat would be absorbed in a small mass of ice, probably a good deal less than a tonne. The heat generated is certainly sufficient to vaporize a good fraction of such a small mass, and indeed to dissociate some of the resultant water vapour into hydrogen and oxygen; hence the copious quantities of steam reported both by Barnes and by the U.S. Coast Guard workers. Furthermore, if Barnes had in some way confined his thermite (+ high explosive?) charge, an explosion of real violence might well have resulted.

Calculation of the Penetration of Infrared, Visible, and Ultraviolet Radiation into Iceberg Ice.

Iceberg ice is filled with many small bubbles of air, typically a few tenths of a millimetre in diameter (ICE Engineering Ltd. 1982). These are sometimes spherical but are more often elongated to a greater or lesser extent. As a result of these bubbles, iceberg ice appears white or a very light blue-gray in sunlight, except for blue bands filled with nearly bubble-free ice presumably formed by the freezing of meltwater in crevasses. These blue bands, at any rate those more than a few centimetres in thickness, are usually heavily cracked. The cracking of the bubble-filled ice also increases its opacity. To estimate the depth of penetration of electromagnetic radiation of infrared and higher frequencies, such as would be produced copiously by an intense heat source, into iceberg ice, we will assume that the path of a photon striking a bubble is perfectly randomized; in the language of kinetic theory, its persistence of velocity is zero. Small though they are, the bubbles are still large compared to the wavelengths of radiation in the frequency range of interest, so that scattering from a bubble is described by geometrical optics; but owing to the impact parameter being random, and the imperfect sphericity of the bubbles, the assumption is reasonable. A non-zero persistence of velocity would in any event only modify our calculated depth of penetration by a factor close to unity.

An elementary application of random walk theory (Chandrasekhar 1943) then leads us to the conclusion that the intensity $I(\vec{R})$ of photons to be found at position $\vec{R}$ after traversing N mean free paths $\bar{l}$, when initially distributed isotropically at the origin with intensity I_0, is given by

$$I(\vec{R}) = I_0 \, e^{-\alpha \bar{l} N} \, W(\vec{R}), \tag{5}$$

where $W(\vec{R})$ is the probability density for a photon to reach position $\vec{R}$ after N steps, assuming no absorption, and $\alpha(\omega)$ is the absorption coefficient per unit length at frequency ω. After only a few steps, the probability density W is given to a good approximation by

$$W(\vec{R}) = \frac{1}{(2\pi N \bar{l}^2/3)^{3/2}} \exp\left[-3 \, | \vec{R} \, |^2 / 2N\bar{l}^2\right]; \tag{6}$$

which is a form of the Central Limit Theorem. Differentiating eq. (5) with respect to N, we obtain

$$\frac{\partial I}{\partial N} = -\alpha \bar{l} I_N + e^{-\alpha \bar{l} N} \, \frac{\partial W(\vec{R})}{\partial N}. \tag{7}$$

Introducing the elapsed time t by the relationship

$$t = N\bar{l}/c, \tag{8}$$

where c is the speed of light in the ice, eq. (7) becomes

$$\frac{\partial I}{\partial t} = -\alpha c I + e^{-\alpha \bar{l} N} \frac{\partial W(\vec{R})}{\partial t}. \tag{9}$$

The probability density W, in its asymptotic form (6), satisfies a diffusion equation:

$$\frac{\partial W}{\partial t} = D_e \nabla^2 W, \tag{10}$$

where D_e is the diffusion coefficient of the electromagnetic radiation in the ice in the absence of absorption. Substitution of eq. (10) into eq. (9), with use of eq. (8), yields the desired transport equation:

$$\frac{\partial I}{\partial t} = D_e \nabla^2 I - \alpha c I. \tag{11}$$

Eq. (11) holds over distances large compared to the mean free path of a photon in ice, and under conditions where the characteristic Beer's Law attenuation length $1/\alpha$ is also large compared to the mean free path.

The diffusion coefficient D_e can readily be obtained from eq. (6) with use of eq. (8). It is clear from the definition of the diffusion coefficient that

$$4D_e t = 2N\overline{l^2}/3. \tag{12}$$

Furthermore, for uniformly independently distributed scatterers, i.e. bubbles, we will have

$$\overline{l^2} = 2\bar{l}^2. \tag{13}$$

Even if this assumption is not exact, it will only affect the ultimate result by a factor close to unity. Using eqs. (8), (12) and (13), we find that the diffusion coefficient of the electromagnetic radiation is related to the photon mean free path $\bar{l}$ by the relationship

$$D_e = \frac{\bar{l}c}{3}. \tag{14}$$

Now the mean free path for photons in the absence of absorption can easily be estimated. If $\bar{a}$ is the mean bubble radius, then

$$\begin{aligned} \bar{l} &\simeq \frac{1}{n \pi \bar{a}^2} \\ &= \frac{\frac{4\bar{a}}{3}}{n \cdot \frac{4}{3} \pi \bar{a}^3}. \end{aligned} \tag{15}$$

In the above, n is the number density of bubbles in the ice. Clearly, the denominator of the second line of eq. (15) above is nothing but the volume of air per volume of berg ice, i.e. the porosity of the ice, which we will denote by f . Then eq. (15) becomes

$$\bar{l} \simeq \frac{4}{3} \cdot \frac{\bar{a}}{f}. \tag{16}$$

A reasonable value for $\bar{a}$ is 0.015 cm; a typical value for the porosity of berg ice is 2.5% (ICE Engineering Ltd. 1982). These values, when substituted into eq. (16), give

$$\bar{l} \simeq 0.6\,\mathrm{cm} \tag{17}$$

as a reasonable value for the mean free path of photons, without absorption, in iceberg ice.

For steady-state flow of radiation into a semi-infinite surface of iceberg ice, eq. (11) reduces to

$$D_e \frac{\partial^2 I}{\partial x^2} - \alpha c I = 0. \tag{18}$$

This has the rightward-decreasing solution

$$I = I_0\, e^{-x/\lambda} \tag{19}$$

where the characteristic penetration depth λ is given by

$$\lambda = \sqrt{\frac{D_e}{\alpha c}}, \tag{20}$$

whence

$$\lambda = \left(\frac{\bar{l}}{3\alpha}\right)^{1/2}. \tag{21}$$

Of course, if the Beer's Law attenuation length $1/\alpha$ is much smaller than the mean free path, then eqs. (20) and (21) grossly overestimate the actual penetration depth - radiation diffusion is then negligible because the photon has little chance of completing even one step of the random walk. Hence as an overall estimate of the penetration depth, we take

$$\lambda = \min\left[\frac{1}{\alpha}, \left(\frac{\bar{l}}{3\alpha}\right)^{1/2}\right]. \tag{22}$$

The absorption of electromagnetic radiation by ice is quantitatively similar to that of liquid water (Fletcher 1970, Hobbs 1974), though there are some differences which are insignificant for our calculations. The absorption spectrum of liquid water is succinctly but comprehensively described in a widely-used text on electromagnetism (p. 290-291 of Jackson (1975)). The absorption coefficient α is greater than 1 cm^{-1} for radiation between 1 cm and 1 Å in wavelength, except for a narrow frequency range centred around the visible, where the absorption coefficient dips to slightly less than $3 \times 10^{-4}\,\mathrm{cm}^{-1}$.

Hence the maximum value of the penetration depth λ as given by eq. (22) is 26 cm. Our own observations of light traversing iceberg ice indicate that 26 cm is definitely an **overestimate.**

For an absorption coefficient of 1 cm^{-1}, λ as given by eq. (22) is less than 0.5 cm.

At 10 μ, the absorption coefficient is approximately $10^3\,\mathrm{cm}^{-1}$; the maximum in the infrared is greater than $10^4\,\mathrm{cm}^{-1}$; and the maximum in the ultraviolet is approximately 10^6; these correspond to penetration depths of 10^{-3} cm, 10^{-4} cm, and 10^{-6} cm.

In short, infrared, visible, and ultraviolet radiation do not penetrate more than a few **centimetres** into iceberg ice. Over much of the infrared and ultraviolet spectrum, the penetration is only a *fraction* of a cm. So much for Barnes's "powerful rays" being "cast ... into the ice" (p. 162 of Barnes (1927)); so much for his "temperature wave" rolling into the berg (p. 167, op. cit.).

The calculation of radiative diffusion set out above is of use in giving us a good understanding of the phenomenon, but is really more elaborate than is necessary; to convince oneself of the correctness of our conclusions, one need only observe the amount of light which is transmitted through a 10 cm thick slab of iceberg ice, and then examine the graph of the absorption coefficient of water shown on p. 291 of Jackson (1975).

Of course, the heat generated by the thermite could also propagate into the ice by ordinary thermal conductivity, a process which is never remarkably effective in ice, as its temperature can never rise above zero.

Barnes's notion of a "temperature wave" is ludicrous. Heat conduction is described by a diffusion equation, and, as has been seen above, radiation transport within the iceberg in the infrared and above is described by a diffusion equation with a sink term. Heat propagation by a wave process is known in only one system: superfluid ^{4}He (the phenomenon called "second sound").

Other Remarks on Barnes's Views

It is difficult to reconcile Barnes's writings on iceberg demolition with what should have been expected of a professional physicist working in the second quarter of the 20th century. With Barnes, we are not dealing with a rather fanciful but essentially rational and informed natural philosopher of the late 18th century; Fourier's law of heat conduction is part of classical physics, having been formulated in the early part of the 19th century. The laws of electromagnetic propagation were worked out in the last third of the 19th century. Random walks were well understood by Rayleigh, if not by earlier workers, and by the 1920's radiation transport was fairly well understood, particularly in the context of stellar structure. Barnes's statement that "the natural colour of pure ice is a deep blue by the scattering of the light from the large ice molecules" (p. 161, op. cit.) betrays a lack of understanding of Rayleigh scattering, and of the structure of ice, which cannot be justified by the state of knowledge in the '20's. His statement that "pressure ice is deep green, and that it "rapidly weathers on the exposed surface under a bright sun", presumably owing to the "innumerable air bubbles which have been released in the ice by the sun's rays", is indicative of a marked inability to observe. The present authors have never, in their extensive experience of iceberg ice, seen deep green berg ice, though we have heard of its occurrence in Antarctica, probably due to inclusions of rock flour. And let it be said, once and for all: iceberg ice from Arctic glaciers is ***bubbly***, although not always uniformly so because of foliation, and of course not in filled-in crevasses. Note too, the inconsistency in Barnes's views; the berg ice is sufficiently ductile, he thinks, to permit the growth of bubbles within it (presumably in the same way that bubbles form in a carbonated beverage when the pressure is released) yet it is so brittle as to be readily susceptible to thermal fracture; the analogy to glass is repeatedly made[1].

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[1] Both of the authors have had some experience in working glass, and concur

What else can one say of Barnes's writings on icebergs? His description of iceberg ablation (Barnes 1927) is deficient in that solar heating is the only effect which he mentions. It is difficult to see how he could overlook the undercutting of ice by wave action at and near the waterline, which most authorities think is the dominant factor in berg ablation. Nor, indeed, can the subsurface ablation associated with melting and buoyancy currents be easily ignored: though its quantitative contribution to overall ablation is little understood to this day, it grossly determines the morphology of the those parts of an iceberg below the wave zone.

Barnes's determination of the porosity of iceberg ice is similarly defective. Once he had found that his samples were nearly pure water, as he did by letting some of them melt and evaporate, he should have determined the porosity by **weighing**. Instead he employed a messy and inaccurate volumetric method which led him to porosities three to five times too high.

Barnes's description of the ice-water phase transition (p. 236 of Barnes 1926c) is seriously defective (see Hobbs (1974)) for the appropriate molecular physics, and Callen (1960) or, for references available to Barnes, Planck (1945) and Gibbs (1875) on the thermodynamical aspects). The deficiencies in the molecular physics are perhaps justifiable by the state of knowledge in the 1920s (see p. 139 of Planck, op. cit.), but those in the thermodynamics are not.

In Barnes's descriptions of his thermite tests, it is surprisingly difficult to deduce what he actually did. He speaks of "burning ice" (Barnes 1927, p. 168); is this a rhetorical flourish, or did his thermite contain some magnesium metal, which *could* react violently with water under those circumstances? He states that his second test made use of "the high explosive, bermite" (op. cit., p. 168), but the same paragraph implies that thermite also was used. Did he perhaps employ a combination of thermite and high explosive in all of his tests?

Perhaps the best, last word on Barnes's publications was written by Mellor and Kovacs (1972):

> "Unless he was merely triggering inherent instability, his results are quite fantastic in terms of energetics."

Hazards of Thermite.

Thermite is classified as an incendiary rather than as an explosive, and its unconfined reaction ordinarily is attended with little hazard. However, in ice, as a consequence of the inefficiency of the radiative and thermal transport mechanisms, its energy is absorbed by a rather small amount of ice, as discussed above; and this ice is not only melted, but vaporized and probably to some extent decomposed into its constituent elements, which in turn probably react to some degree with the thermite and the metallic iron which it produces. The result is spectacular indeed. Photographs of the U.S. Coast Guard tests of large embedded thermite charges in the season of 1960 (Bullard et al.

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that Barnes underestimated the toughness of massive pieces of glass.

1961, Van Allen 1961) clearly show a shower of molten iron and thermite, which extended, according to the authors, about 100 m from the charges. Barnes was well aware of the violence of the reaction, as previous quotes make clear, and in fact the "explosive reaction" between the thermite and the ice figures importantly in Claims 1 and 2 of his U.S. patent (Barnes 1925). In one of his articles (Barnes 1926c), a picture is shown of a 41 kg (90 lb) canister of thermite rocketting 40 m (125 ft) up from an ice jam. To modern eyes it suggests nothing so much as a Submarine-Launched Ballistic Missile (SLBM). The picture is reproduced on p. 161 of his book "Ice Engineering" (Barnes 1928), which contains two other spectacular pictures of thermite in ice (p. 150 and p. 159). We do not lend much credence to Barnes's writings on the whole, but we do believe some of his photographs. We will leave this subject with a quote from Van Allen (1961):

> "Thermite, a mixture of powdered aluminum and iron oxide, is an incendiary charge. When it burns it can produce a temperature of 4,000 F. degrees (half of the sun's surface temperature) and molten iron is released which acts as a heat reservoir for the combustion of related materials. Actually it is not an explosive. Ignited on ice, however, thermite is extremely dangerous as it reacts in a unique way resulting in a great explosion of steam and hot molten iron."

Feasibility Criteria for Explosives and Pyrotechnics.

Of the various approaches potentially taken to explosive demolition of icebergs, the use of large bombs stands out as eminently the most practical. Accordingly, the feasibility criteria are applied to this method only.

a): Feasibility of the relevant physics and chemistry: the likelihood of success for the method is judged as approximately 80% since the deployed charge is large, logistics although clearly military in scope are straightforward, and multiple bombings can be applied to those bergs which do not succumb to a single assault. The key, of course, to successful application of the method lies in the use of **large** bombs.

b): Engineering feasibility: the engineering aspects of this method will be left in the hands of military authorities.

c): Marine considerations: the handling of iceberg demolition bombs would be carried out entirely from aircraft. Hence ship-related marine considerations do not arise. The method would appear to be useable under quite a wide range of weather conditions.

d): Safety: the method is no more dangerous than the handling of heavy military ordnance in other contexts. Extensive notification to marine traffic (including submarines) potentially in the area would have to be provided. In event of a misfire (failure to detonate) a second bomb would probably suffice to eliminate the hazard.

e): Costs: the design of the appropriate bomb and the requisite adaptations to existing aircraft to facilitate bombing would undoubtedly be expensive. These costs would have to be considered in the context of the potential effectiveness of the method.

f): Environmental considerations: the environmental effects of setting off a very large explosive charge in a medium as well-coupled to the ocean as iceberg ice are unacceptable in all but extreme scenarios. Such a scenario could arise should an unmanaged iceberg intrude or threaten to intrude into an area where a large oil spill was likely to be precipitated. Potential damage to other structures, such as the oil production facility itself, would also have to be considered in this case.

3.2.2. Method 7: Injection of Self-Sealing Fluids

Three classes of self-sealing fluids have been enumerated previously as having potential for use as unconfined pressurizing media in iceberg fracturing. Of these classes only one, the hydrate-forming liquids, will be subject to detailed analysis in this section. Highly viscous liquids, and liquids which freeze near 0 ° C, while both showing potential as fracturing media, appear clearly inferior to the hydrate-forming liquids in terms of the overall practicality of their use. In any event, much of the discussion below is applicable to all three classes of self-sealing liquids. Environmental and safety considerations associated with a particular hydrate-forming chemical (there are very few to choose from) would be the only factors potentially warranting a return to serious consideration of the alternative classes of liquids.

Of the various hydrate-forming chemicals known, only two appear sufficiently inexpensive and sufficiently effective to merit serious study. These two are ethylene oxide (C_2H_4O) and tetrahydrofuran (C_4H_8O; henceforth usually abbreviated THF). Both are common industrial intermediates and can be purchased in bulk.

Ethylene oxide is, however, volatile and flammable. It can detonate, and is used as a monopropellant for rockets. It is dangerously toxic, and its release, controlled or otherwise, near the support vessel would constitute a hazard to the ship's personnel, quite apart from its environmental toxicity.

Tetrahydrofuran, on the other hand, does not present an explosives hazard, and in toxicity and flammability is similar to diethyl (common) ether, although its normal boiling point (67 ° C) is higher. Its flashpoint is -14 ° C, and 200 ppm in air is considered acceptable for breathing. The chemical thus requires caution, but is not so dangerous as to preclude its use.

Operationally, the fluid injection method of iceberg fracturing would be carried out in two stages. First, a narrow hole would be drilled deep into the iceberg. Second, a pressurizing fluid would be delivered into the hole through a narrow tube. It will be assumed that fluid leakage around the outside of the entry tube would be controlled by rapid solidification of hydrate in this region.

The first step of the fracturing procedure, the ice drilling process, must be fast, efficient and logistically convenient. Efficiency of drilling is conventionally defined for thermal drills to be the ratio of the diameter of the hole drilled to the diameter required, and we follow the same usage for chemical drilling. For purposes of admitting highly pressurized fluid of low viscosity, an entry hole with diameter 0.5 cm would be sufficient. A larger hole would present greater problems of sealing. The tighter the fit, the better. The logistical convenience of drilling is determined primarily by the complexity of the drilling procedure. More complex procedures such as mechanical auguring or drilling with a fluid jet would necessitate the placement of complex equipment at the iceberg-ocean interface. Furthermore, such methods add an extra stage to the fracturing procedure. Different equipment is required for the drilling and for the pressurization, and once the drilling is completed, it is likely that the insertion of the pressurizing tube into the hole will prove to be a nontrivial operation.

Chemical or thermal drilling could, in principle, eliminate the tube insertion stage, since drilling would be done with the fluid delivery tube itself. In what would be a reasonably practical scenario, a stainless steel tube of outside diameter 0.635 cm and inside diameter 0.305 cm would be held firmly against the surface of an iceberg while a chemical drilling medium was supplied through the tube's bore. The tube would be allowed to penetrate several tens of metres into the iceberg before the drilling fluid was replaced with the self-sealing pressurizing fluid (assumed here to be THF).

Some possible, but clearly less than ideal, fluids include: steam, hot water, anhydrous ammonia, and anhydrous hydrogen chloride. All of these materials would yield an inefficiently drilled hole. Hot water is the least likely candidate owing to the large thermal losses along the entry tube widening the entry hole in the ice excessively. Such losses would be lessened with high pressure steam drilling, but would still present a significant problem. Anhydrous ammonia or hydrogen chloride could be delivered to the berg cold, but would yield very fluid, mobile reaction products. These reaction products (ammonium hydroxide solution or hydrochloric acid respectively) are strong freezing point depressants, and would probably therefore also yield unacceptable widening of the entry hole. The high toxicity of gaseous ammonia or hydrogen chloride further militates against their use.

Highly reactive liquids which solidify or become viscous upon contact with ice or water show promise as chemical drilling media in the present application. Such liquids are usually chlorides of tetravalent elements (e.g. $SiCl_4$, $SnCl_4$, or $TiCl_4$), or solutions or suspensions of bivalent or trivalent halides (e.g. a solution of $AlBr_3$ in benzene or a suspension of $MgCl_2$ in cyclohexane). These materials all have large heats of reaction with water, and all with the exception of $MgCl_2$ yield solid reaction products (in the case of $MgCl_2$ the carrier, cyclohexane, would be expected to solidify and hence bind the soluble reaction product, $MgCl_2 \cdot 6H_2O$.

Of the substances listed above, only $AlBr_3$ and $MgCl_2$ are self-initiating in their reaction with ice. The tetravalent chlorides react rapidly with water at elevated temperatures but, at low temperatures, tend to form an impermeable skin of reaction product (the oxide or oxychloride) which segregates the drilling liquid from the water and ice and prevents further reaction. Ejection of the drilling liquid from a small bore tube at high pressure might reduce or eliminate this problem by breaking the oxide film as it forms. Tests would be necessary to confirm this.

Aluminum bromide powder reacts violently with ice. It dissolves while doing so, and the reaction product precipitates aluminum hydroxide upon cooling. Whether or not a solution of $AlBr_3$ in benzene would react analogously is unknown and would require experimental investigation. If the reaction of the $AlBr_3$ solution does run in a manner similar to the reaction with powdered $AlBr_3$, then the solution should prove a nearly ideal chemical drilling medium for ice. Possible environmental and safety problems (benzene, though a common industrial chemical, is carcinogenic; $AlBr_3$ is a strong respiratory irritant and reacts explosively with water) would need to be addressed.

Anhydrous magnesium chloride reacts vigorously with water or ice and is a highly effective drilling medium when poured onto ice in powder form. However, the reaction product is very soluble in water and is a strong freezing point depressant. Furthermore, $MgCl_2$, unlike $AlBr_3$, is not soluble in a nonpolar liquid and would have to be delivered either fluidized in a gas stream or suspended as a slurry in a liquid carrier. The second alternative is clearly the more attractive, especially when the carrier is chosen to have a freezing point slightly above 0 ° C, permitting it to freeze around the entry tube and so immobilize the soluble reaction product. Tests would be required to investigate the effectiveness of the apparently promising $MgCl_2$ - cyclohexane drilling system. Both of these chemicals are well tolerated in the environment and would not pose any major hazards to personnel. Indeed, the magnesium chloride is a natural constituent of seawater.

Binary chemical systems are also of potential usefulness; though their use necessarily increases the complexity of the equipment, it might be possible to use the same system both for drilling and for the subsequent pressurization. A lengthy search of the chemical literature has indicated that the most likely of such binary systems is H_2O_2 - $SnCl_2$.

With any chemical drilling method, design of an appropriate drilling head (termination of the penetrating tube) would be a critical factor. The head would be required to bring the chemical agent into intimate contact with ice and then to permit the clearing of the reaction products. The head ideally should not exceed the diameter of the penetrating tube. The head, which would be fixed on a drilling tube of 0.635 o.d., would likely consist of a small bore (less than 1 mm) nozzle and a series of axial grooves or cuts in the outer wall of the tube. Considerable design and experimentation would be necessary in order to realize an optimal embodiment of the chemical drilling head.

Deployment of the penetrating tube into an iceberg could be carried out remotely from a standby vessel, given successful development of a chemical drilling system as described above. The tube is small, lightweight and extremely rugged. A remotely operated underwater vehicle could be employed to carry it or a line feed system could be set up using an anchor point on the target iceberg. Such an anchor point could be established by ballistically deploying an ice grappling device on the berg. Lines extending from this device back to the ship would then be used to feed the pressure tubing to the iceberg surface.

After drilling the iceberg to a depth of several tens of metres, the chemical ice melting agent would be replaced with the self-sealing pressurizing liquid. As discussed above, THF is the most attractive candidate. THF forms a stoichiometric clathrate hydrate with cold water, consisting of 8 THF molecules to 136 water molecules. The hydrate is 1 part THF to 4.25 parts water by weight, or 1 part THF to 3.78 parts water by volume.

The reaction to form THF clathrate hydrate runs rapidly, and the hydrate is precipitated even when the water-THF mix differs substantially from the stoichiometric ratio. The hydrate is almost as tough as ice and adheres strongly to ice at temperatures near zero. Liquid THF in the absence of water has a freezing point of -108.3° C, and thus will not solidify in the feeder line or the entry tube under any conditions. THF is a strong solvent for ice and liquid THF, immediately upon contacting ice, dissolves enough to precipitate a solid skin of the clathrate hydrate. THF in fact can be used as a *glue* to join together pieces of ice, even when they are wet.

During an iceberg fracturing operation, THF would be injected at pressures ranging up to a few tens of MPa. At the outset of the procedure, pressures would be lower as considerable leakage around the entry hole would undoubtedly occur. Flow of THF would be monitored closely and a cessation of flow, indicating blockage of leaks by precipitated hydrate, would warrant increasing the pressure towards the operating limits of the system. Full design delivery pressure must be sufficient to maintain continuous breaking of ice, thereby expanding the cavity at the termination of the entry hole. As cracks develop, loading will occur over larger and larger surface areas, so that, if pressure is maintained, the net mechanical forces on the berg will increase until large-scale failure of the iceberg ice ensues. If a crack reaches the surface before fracturing is complete, reduction in THF flow would probably lead to the blockage and consequent sealing of the crack by the hydrate, after which the THF pressure could be reestablished.

The overall requirements for materials in iceberg fracturing with an unconfined fluid cannot be determined without experimentation, although they can be estimated. Assuming reasonable drilling efficiency, a few tens of kilograms of chemical drilling agent would be sufficient to produce the entry hole for the pressurizing tube. THF requirements could run to a few thousands of kilograms. The overall costs for consumable materials would probably be less than $10,000 per iceberg fracture attempted.

A conventional high pressure piston-type pump would be suitable for supplying pressurized THF to the fracturing system. The pump and associated fluid connections would not be able to utilize most common plastics in their construction since THF is a very powerful solvent[1]. Metal and polytetrafluoroethlylene (TFE) components would be allowable. Fluid delivery rates of the order of 0.5 l/sec would be envisaged. The time taken to fracture the iceberg would be of the order of a few hours.

Feasibility Criteria.

a): Feasibility of the relevant physics and chemistry : the likelihood of success is adjudged as 30% since the method cannot be verified in laboratory testing, and pressure accumulation/fluid-leakage parameters, while critical, are difficult to scale or predict. They will also be strongly specimen-dependent. The drilling system, considered essential for operational use of the method, was not configured within the context of our preliminary analyses.

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[1] It dissolves all common lubricants, epoxy cement, rubber, most plastics including nylon, and rubber. It will dissolve Scotch tape, both adhesive and backing.

b): Engineering feasibility: the method is feasible only with a sophisticated drilling/leak-sealing system which has not as yet been configured. Pumping and transmitting large volumes of exotic solvents[1] at moderately high pressures presents substantial engineering problems. Conventional rubber hydraulic hosing would not be usable; instead, it would be necessary to use corrugated stainless steel hose, or braided stainless steel over polytetrafluoroethylene (TFE) hose. These are more expensive and difficult to procure than rubber.

c): Marine considerations: the application of the method could require support from a helicopter or tethered submersible. The requirement of either of these platforms places sea state/weather limitations on the deployability of the system.

d): Safety: the safest chemicals so far found to be feasible from a chemical and physical point of view in the drilling and/or leak sealing stages still present non-negligible toxic and flammability hazards.

e): Costs: the method has the potential to be relatively inexpensive - indeed, perhaps the least expensive of the methods considered in this study. However, such low costs, particularly operating costs, could be realized only through the development of new technology, particularly in the area of chemical drilling and leak sealing. The potential costs of this development form a major component of the cost of applying this method.

f): Environmental considerations: some of the chemicals used in drilling and/or leak sealing/pressurizing will be detrimental, to a degree, to the marine environment. The optimal pressurization/sealant liquid found in the course of this study, tetrahydrofuran, is not extremely toxic. However, the total volume of liquid necessary to effect fracture is not amenable to *a priori* prediction, and could indeed be quite large. Accordingly, a complete assessment of the potential environmental effects of the method cannot be carried out prior to field trials.

3.2.3. Method 8: The Flat Jack.

A flat jack is a metal envelope consisting of two relatively thin plates welded together around their common perimeter. A small-bore connecting tube admits fluid under pressure to the space between the plates. A general arrangement drawing of a flat jack in ice is shown in Fig. 2. The use of a flat jack for ice strength testing has been described recently (Masterson 1983). A larger jack could, in principle, be employed to induce iceberg fracture.

The general strategy of fracturing an iceberg with a flat jack would involve placing the jack at a very substantial depth in the berg. The ideal location would be at the centre of the iceberg, with the plane of the flat jack lying parallel to the plane of minimum

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[1] The preferred pressurizing/sealing liquid, as indicated above, would be tetrahydrofuran.

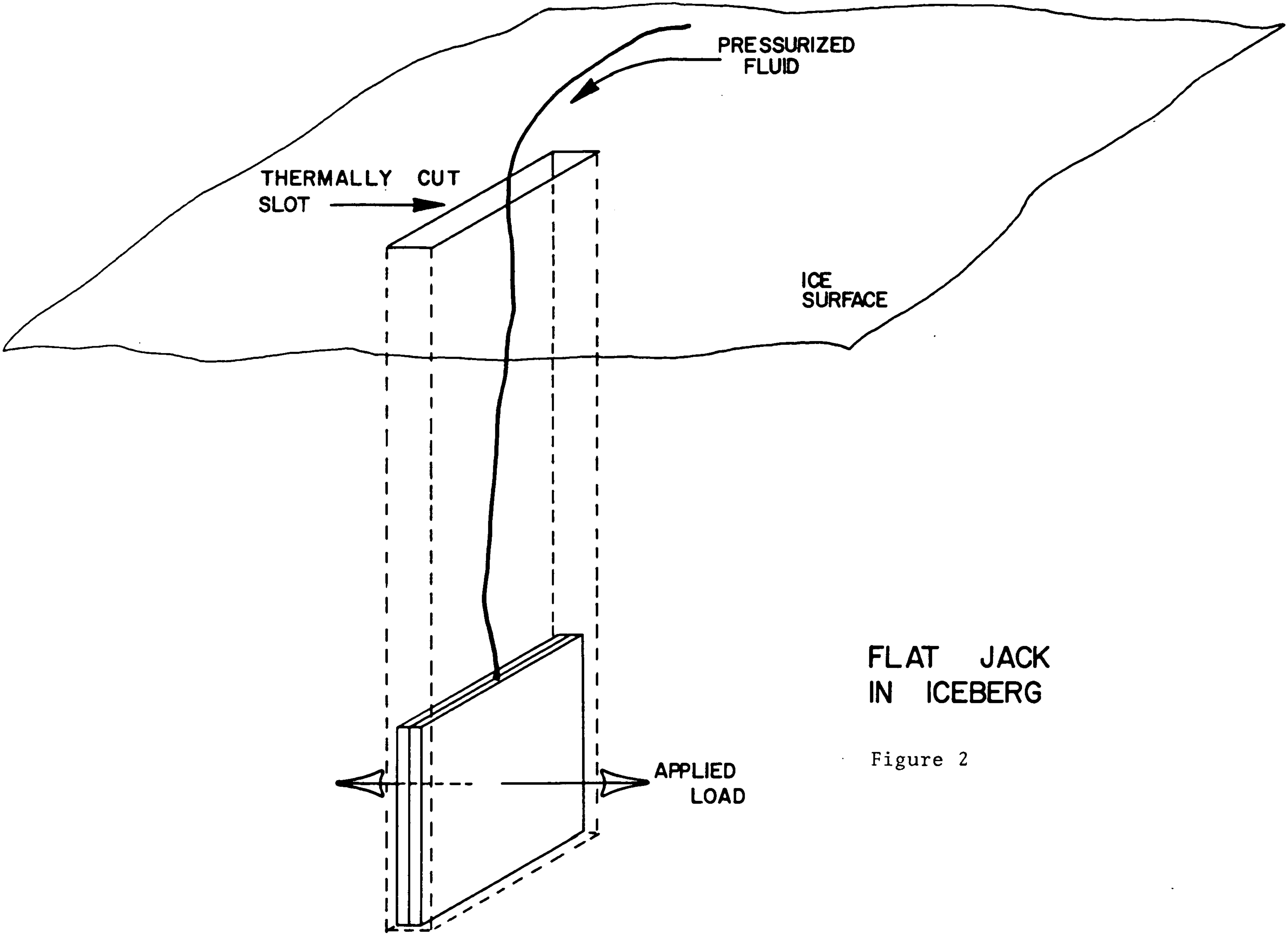
PRESSURIZED FLUID
THERMALLY CUT SLOT
ICE SURFACE
APPLIED LOAD
FLAT JACK IN ICEBERG

Figure 2

ice cross section. The purpose of the flat jack would be to prevent leakage of pressurizing fluid (compare with unconfined fluid fracturing described in the previous section) and to give directionality to the applied loading.

Considerations of the feasibility of deploying the flat jack on a berg, and controlling it during implantation, particularly under windy conditions, would limit the size of an operational flat jack to about 3 m by 3 m. Use of several such jacks, deployed in a single plane and pressurized simultaneously, would be recommended to achieve greater gross loading without requiring extreme pressures. The weight of a steel flat jack with dimensions 3 m X 3 m X 0.00635 m (two 1/8 in steel plates welded together) would be 450 kg, easily handled by a large helicopter of the type used in the offshore for supply purposes (450 kg is, however, too heavy for a Bell 206L).

Fabricating a flat jack from nonferrous metal, such as aluminum or magnesium, would yield a substantial weight advantage but at the expense of making the requisite leaktight edge seal somewhat more difficult to weld; hence, at the expense of increased fabrication costs. Even with modern MIG and TIG apparatus, it is still much harder to achieve a bubble-free weld with aluminum than with iron or stainless steel.

The embedding of a large flat jack in an iceberg would best be carried out by causing the jack to melt its way in edge on. This could be accomplished by running a copper tube along one edge (the tube would be silver soldered in place) and heating the tube with circulating hot fluid. Insulated feed and return lines would run along the two vertical edges of the jack.

In an operational deployment scenario, the jack would be flown by helicopter sling to an iceberg and laid on the above-water surface, supported by a simple but sturdy stand. The stand would maintain position and orientation of the jack during penetration and would allow the jack to slide through unobstructed, eventually dropping free of the stand as the top of the jack reached the ice surface. Hot fluid for penetration would be generated by a chemical reaction on the iceberg near the jack. The reaction vessel would comprise part of the support stand. The flat jack would require sufficient heat supply to allow penetration to a depth of several tens of metres before the chemical reactants were exhausted, and the jack allowed to freeze in.

For purposes of evaluating the pressure and fluid requirements of a flat jack used in iceberg fracturing, it is useful to consider a medium-sized specimen iceberg. As discussed above, extension of the method to large icebergs would require the use of more than one jack. The logistics of such multiple deployments may or may not be feasible. This aspect will not be analyzed in detail here.

Consider a specimen iceberg which is perfectly tabular and of medium size. We will take it to be a rectangular parallelopiped, with a sail height of 3 m, a draft of 21 m, a breadth of 48 m and a length of 60 m[1]. Such an iceberg has a mass of 69120 tonne, and

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[1] Hence its "waterline width" and "waterline length" as conventionally defined in iceberg surveying are 75.0 m and 76.8 m respectively. The waterline length is the largest diameter of the waterline section of the iceberg, and the waterline width is the width of the projection of the waterline section perpendicular to waterline length.

a cross-sectional area of 1152 sq. m. through its breadth, i.e. perpendicular to its long axis. Assuming that the tensile strength is 1.5 MPa, a reasonable value for small samples of iceberg ice, then the total force required to split the berg along such a cross section is 1728 MN, or 176,000 tonne force. Such a force virtually guarantees the destruction of a berg; in fact the tensile strength tends to decrease with increasing specimen size, according as the occurrence of cracking favorable to the breakup of the sample; in a series of tests, it was shown by Jellinek (1958) in small ice samples that the tensile strength declines as sample volume increases.

Upon pressurization of a flat jack of area 9 m^2 embedded centrally (i.e. to a depth of 12 m) in the specimen iceberg, a net tensile loading of 1728 MN is realized with an applied pressure of:

$$1152/9 \times 1.5 \text{ MPa} = 192 \text{ MPa} = 192 \times 145 \text{ psi} = 28\,000 \text{ psi} = 1900 \text{ atm}. \qquad (23)$$

This gives a guaranteed split, unless plasticity occurs to such an extent that the plate bulges and breaks; probably 1/2 of the above pressure, i.e. 14,000 psi (97 MPa) or roughly 1000 atm, would in fact suffice.

Provision of such high pressures is by no means a trivial matter; thus, for example, commercial gas cylinders are pressurized only to a maximum of 2200 psi (15 MPa). Furthermore, substantial volumes of the pressurizing fluid are required. If, for example, the plates are to be separated by 1 cm on average, then 90 &l& or 3.2 cu. ft. are required. In fact, greater mean separations would almost certainly be required, so that the fluid capacity of the expanded ram could run to hundreds of litres.

Provision of such quantities of gas would require large numbers of gas cylinders. One standard cylinder of nitrogen contains 110 cu ft at **1 atm**, which which would reduce to 0.25 cu. ft. (7.1 &l&) at 1000 atm (and 0 ° C). Hence 13 cylinders would be required to separate the plates by 1 cm on average, at 1000 atm. Assuming that in fact at least 2 cm mean separation would be required, and that pressures higher than 1000 atm might be needed, then 40 cylinders appears to be a reasonable estimate of the minimum number, without taking into account reserves or backups. Substantial pumping capacity would be needed, of course, to raise the gas pressure to the required 14,000 psi (97 MPa).

In addition, a gas-driven flat jack would probably fail explosively; it can readily be calculated that 0.62 MJ is stored in the ram for each cm of mean displacement, per 1000 psi of pressure. This implies that about 18 MJ of mechanical energy would be released when the ram fails. About 10 kg of nitroglycerine would yield an equivalent blast effect.

Pressurization with fluids is also possible and indeed probably desirable. For example, pumps of the kind used in water-jet drilling are commercially available, and can supply substantial volumes of water at pressures ranging up to 200 MPa. Water is a convenient pressurizing medium in that it presents no environmental problems following berg breakup and rupture of the jack. Conventional hydraulic oil could not be used because of the resulting oil slick, but hydraulic pumps of more or less conventional design could likely be used with a biologically innocuous fluid as pressurizing medium.

Pressurizing liquid could be delivered from a standby vessel to the iceberg through conventional high pressure hydraulic hose. If pressurizing with gas, it might be preferable to use standard 0.3175 cm o.d. (1/8 in), 0.0762 cm wall (0.030 in) stainless steel tubing as the feed line. This tubing is light, cheap, very durable, and is rated with a working presure of 70 MPa and a burst pressure three times higher.

Another method for effecting pressurization is to connect the flat jack to a pressure vessel containing confined liquid nitrogen, which is then allowed to thermalize to ambient temperature. This has several advantages over the two methods described previously:

1. Pressurization is rapid, indeed, and could be made near-explosive, thus minimizing the chances for failure in creep;
2. Heavy-duty pumping equipment is not required;
3. Fluid handling lines to the support ship are not required.

Furthermore, liquid nitrogen is cheap, it is available in large quantities, it is fireproof, it is of low density, and it is not difficult to handle. However, the on-iceberg containment vessel connected to the jack must have a capacity of several hundreds of litres, and must withstand at least 1000 atm (101 MPa); its design requires consideration.

The form of containment vessel easiest to make and easiest to handle would be a large coil of tubing, capable of withstanding at least 1000 atm, connected to the flat jack and fitted with a valve at the other end. On the iceberg, the valve would be opened and the coil would be immersed in a liquid nitrogen bath. The bath would be light, and could be inexpensively manufactured from wood and styrofoam. When the coil was cooled and filled with liquid nitrogen, the tubing would be allowed to thermalize. Rapid thermalization could be effected by pulling the coil into the sea.

The amount of liquid nitrogen necessary to pressurize 90 l of expanded flat jack, plus the containment vessel itself, is 53 l (i.e. the total system volume is $90+53 = 143$ l), which would weigh 45 kg. Assuming that the coil was made out of 0.635 cm (1/4 in) carbon steel, for cheapness, with walls of 0.124 cm (0.049 in) thickness; then the volume of the coil is 1.171 l per 100 m. Hence nearly 4580 m (15,000 ft) would be required. This would weigh 700 kg, in addition to support and fixtures. Lighter tubing might be used, in particular 0.635 cm (1/4 in) carbon steel with 0.0889 cm (0.035 in) walls; this contains 1.51 l per 100 m, so that only 3500 m (11,500 ft) would be required, but the burst pressure of this tubing is only a barely sufficient 102 MPa (14805 psi), and the coil would still weigh 360 kg, plus support and fittings.

Generally speaking, there is a tradeoff between jack size and the capacity of the pressurization system; the system described above is close to optimal; even so, it is barely feasible under field conditions.

The flat jack has two important advantages over the liquid-injection method discussed above:

1. The fluid is confined; less is therefore required, and control during pressurization is easier;

2. The jack applies a directional splitting force, which can be chosen along the minimum cross section. As the energy required is a function of crack area, control of the cracking plane is a desirable feature.

Drawbacks and potential drawbacks of the method:

1. The principal drawback of the method is that it requires deployment of substantial quantities of heavy-duty high-pressure equipment on the iceberg. This does not completely rule out the method for demonstration purposes, on small icebergs, under optimal weather and sea-state conditions; however, it does mean that the development of the method into an operational iceberg management tool will be very difficult.
2. The side channels created by the thermal embedding might lead to failure of the jack before fracture of the iceberg occurred. Localized failure of the ice around part of the jack might have the same effect.
3. There could be substantial problems with the unheated sides of the jack freezing in during penetration.

Feasibility Criteria.

a): Feasibility of the relevant physics and chemistry: the likelihood of success is adjudged as 30%. The method cannot be verified in laboratory testing and several critical parameters such as ice strength and pressure/force accumulation rates are difficult to scale. Probabilities of local failure of the iceberg leading to failure of the flat jack prior to and instead of generalized failure of the iceberg cannot be estimated and are almost certainly highly sample-dependent, i.e. vary significantly from iceberg to iceberg and even from one part of an iceberg to another.

b): Engineering feasibility: the engineering feasibility of the method is severely limited. The key problem is the size of the required jack and the fact that many jacks, perhaps ten, might be required to fracture an iceberg larger than a million tonnes. The method also involves the handling of large volumes of fluid at high pressures. The necessary equipment to do so is heavy, cumbersome, and accordingly problematic from an engineering/logistics viewpoint.

c): Marine considerations: the method can be deployed under general marine conditions only with the aid of a helicopter. Light winds and good visibility are required. Linking a ship and an iceberg with high pressure fluid conduits of high capacity is problematic.

d): Safety: the method presents safety problems associated with handling large volumes of fluid at high pressure, which is inherently dangerous. If gas is used, the jack will probably explode violently following fracture. In addition, one might envision deployment requiring the placing of a boarding party on an iceberg for several hours. Iceberg boarding, and working on an iceberg, can be very difficult, depending on the shape of the berg. It is generally unsafe, and can be extremely so, if the berg is only marginally stable. For these reasons, iceberg boarding cannot be part of a routine operational procedure; any method which requires iceberg boarding cannot be used routinely.

e): Cost: all parts of a large high pressure apparatus are necessarily heavy and strong, and therefore expensive. Particularly expensive are high pressure pumps capable of delivering fluid at high capacity.

f): Environmental considerations: considerations of environmental impact rule out the use of hydraulic oil as the pressurizing medium. Using high pressure gas, the only environmental problem would come from the explosion of the jack following (or instead of) iceberg fracture. The method would probably result in large amounts of metal fragments being left on the seafloor.

3.2.4. Method 9: "Hot-Wire" Cutting.

The method of slicing an iceberg into two pieces using a thin electrically heated wire is clearly an attractive approach to the problem of iceberg fracturing. There are three key reasons for its becoming the primary focus of this study. First, the method is simple. When compared with other approaches to fracturing, the hot wire method stands out as being easy to configure, analyze and scale. Laboratory tests appearing almost trivial in their simplicity can clearly demonstrate the potential functionality of the method in the field. Second, the method is cheap. Necessary equipment, especially for the limited field demonstration carried out in the course of this study, is conventional and available off the shelf. The key large-capital components can readily be rented. No other method enumerated in this report is amenable to the conduct of a credible field demonstration within the allotted budget of $30,000. Third, the method is safe. Any strategy that purports to offer a realistic chance of fracturing an iceberg must necessarily involve the release of enormous amounts of energy in a short span of time. The release of this energy within a closed electric circuit affords an inherent high degree of safety. Dangerous pressures, exotic chemicals with exotic toxic properties, powerful explosives and incendiaries, lethal high energy beams; all are avoided in the configuration of the hot wire method.

In the following discussion, three embodiments of the hot wire iceberg fracturing system will be presented. First, there will be a discussion of the principles underlying such a system, and the introduction of a basic or generalized version of it. Engineering details will not be treated at this stage. Second, a detailed engineering description of a version of the system configured specifically for a field demonstration on a medium-size iceberg will be presented. This presentation, comprising Appendix 1 of this report, will lead to the finalizing of the design of the system actually taken into the field as part of the present study. Third, a full-scale operational version of the fracturing system will be described. This description, included in the present section of the report, is intended to serve as a blueprint for the further development of a hot wire fracturing system towards commercial operational status.

The Hot-Wire Iceberg Cutting Method: Basic System

The electrical components of the basic hot wire ice cutting system consist of a power supply, a major resistive element (the cutting line) and a minor resistive element (the circuitry connecting the cutting line with the power supply). These components are connected in a simple, purely ohmic, series circuit. Operating in parallel with the cutting line is an effective leak resistance, this being the flow of current through the ocean between the two immersed ends of the cutting line. Fig. 3 on the following page shows the layout of the basic circuit.

The electrical action of the circuit is straightforward. Electrical energy from the power supply is dissipated as heat in the various resistive circuit elements. It is necessary for system efficiency that the resistance of the cutting line substantially exceed the series resistance of the connecting circuitry. Furthermore, the resistance of the ocean leak path must greatly exceed the resistance of the cutting line. These criteria dominate the electrical aspects of system design.

All versions of the cutting system utilize a direct current (DC) power source. There are several reasons for this. DC voltages (and hence insulation requirements) are 40% lower than alternating current (AC) peak voltages for a given rate of energy delivery. DC presents less of a shock hazard than AC for a given voltage level. Also, since some components of the circuit are to be immersed in an electrolyte (seawater), important electrochemical considerations arise. Polarization effects lead to a seawater conductivity which is a minimum at zero frequency (i.e. DC). Hydrogen bubble formation at the negative electrode enhances this effect when currents are high. It is generally easier to control electrolytic corrosion in a DC circuit than in a low frequency (e.g. 60 Hz) AC circuit. It is necessary only to keep all vulnerable circuit components at a negative potential relative to nearby seawater. A sacrificial electrode (or electrodes) is held at positive polarity and is allowed partially to dissolve under electrolytic action. With low frequency AC, a similar arrangement could be used, but it would be necessary to superimpose a DC bias on the circuit to prevent corrosion of the sensitive components.

The voltage/current regime in which the iceberg cutting circuit operates is dictated by the energy requirements of the cutting line, the resistance of the cutting line and the resistance of the connecting circuitry. Energy requirements tend to be of the order of tens or hundreds of kilowatts (see further discussions of thermodynamics in this section and in Appendix 1). There is a clear advantage in operating at elevated voltages and reduced currents to the greatest extent possible. This minimizes energy losses in the connecting circuitry and permits the use of electrical supply cables that are not unduly cumbersome. If the ocean is to be utilized as an electrical conductor for the return link, further emphasis must be placed on keeping the current low. Not only do ohmic losses become significant when multihundred ampere currents are passed through the ocean, but the accompanying electrolysis can consume large amounts of metal in relatively short periods of time.

A current of the order of 200 A to 500 A is appropriate for cutting ice with a small diameter wire (a few millimetres in diameter). Lower currents tend to yield insufficient power dissipation in wires[1] made from commonly available materials. Higher currents

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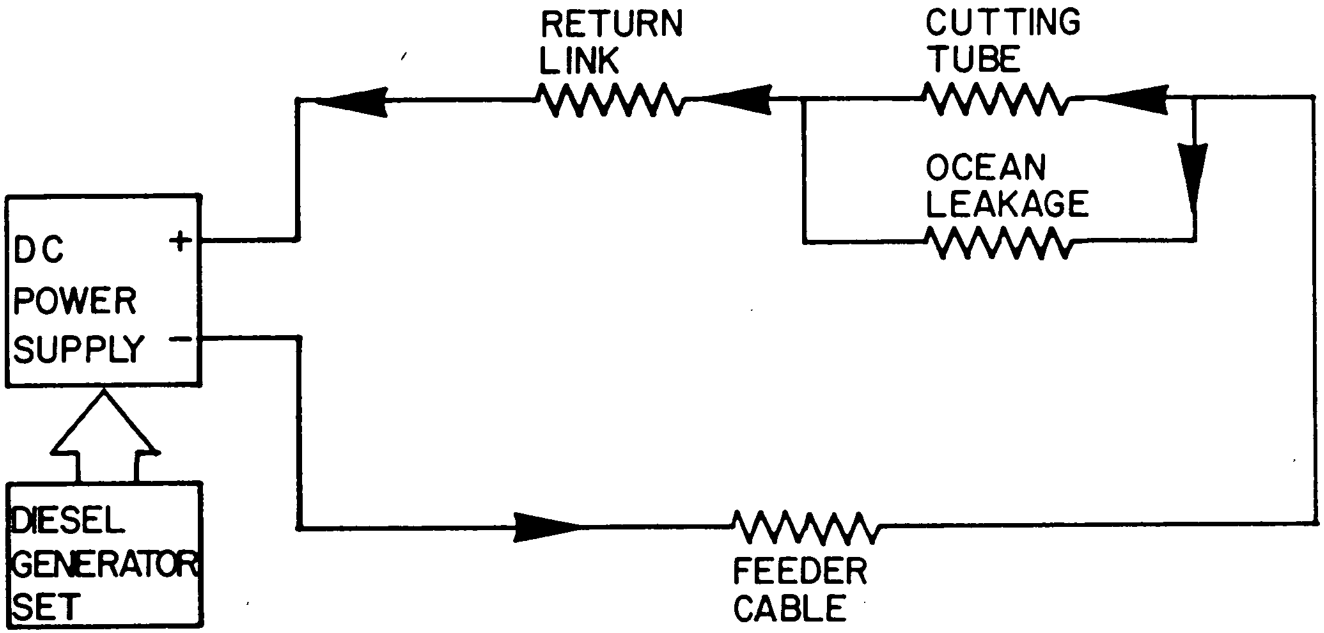
[1] Actually, as subsequent analysis will show, a fluid-filled tube rather than a solid wire is necessary.



NOTE: Arrows indicate the direction of electron flow.

ICEBERG CUTTING SYSTEM
BASIC CONFIGURATION

Figure 3

result in unacceptable line losses except where very heavy cables are used; cables which would be unmanageable in the marine environment.

Typically, connecting circuitry used in a hot wire cutting system will have a total series resistance of the order of a few tenths of one ohm. Cutting line resistance is a function of line dimensions and of the metal from which the line is made. Resistivities of common metals range over about two orders of magnitude with copper at the low end of the range, and various types of stainless steel at the high end. Limitations on line geometry are imposed by thermodynamic and mechanical requirements. The thicker the cutting line, the greater the power needed to melt the ice in the cut, or, alternatively, the longer the time required for the cut. Power and/or time requirements become unacceptable for a cutting line much over 0.635 cm (1/4 in) in diameter. A 0.3175 cm (1/8 in) diameter line is much preferred in terms of system energetics.

An overly thin cutting line would lack the mechanical strength necessary to make it reasonably durable in the marine environment. The tensile strength of a line is determined by its cross-sectional area and by the material from which it is made. Strengths for a cutting line of diameter 0.3175 cm (1/8 in) vary from approximately 100 kg force for copper to 1000 kg force for the strongest stainless steel. Strengths less than 100 kg force would not be acceptable, but our field demonstration indicated that greater strength is not necessary.

For these reasons, a cutting line of outside diameter 0.3175 cm (1/8 in) has been chosen as our standard for all further analyses in this report. The resistance of the standard cutting line is proportional to its length, and is a function of its composition. A copper line sufficient to cut a large iceberg would have a resistance of the order of 1 Ω, comparable to the resistance of the connecting circuitry and hence not overly efficient. An equivalent stainless steel line would have a resistance of the order of 40 Ω, necessitating the use of very high voltages (several kilovolts) to provide adequate energy dissipation. Other materials such as aluminum or carbon steel have intermediate resistances.

The thermal aspects of the hot wire iceberg cutting system are determined primarily by the properties of ice itself. Ice has an unusually high heat of fusion for a low melting solid, making it particularly difficult, in terms of energy requirements, to cut by melting. Accordingly, a wire which is designed to melt its way rapidly through ice must evolve large amounts of heat. In consequence, an ice cutting wire which is not held in intimate thermal contact with ice will rapidly overheat and burn out. Inherent in the geometry of the hot wire method are sections where the cutting line does not touch ice or water. These sections, comprising sections of the line at the edges of the iceberg where the line drops into the ocean, and sections overlying depressions and concavities in the iceberg, are present at the outset of cutting, though eventually all parts of the line come in contact either with water or ice. The sections not in contact with water or ice must be cooled independently of those that are in contact; the thermal conductivity of copper, large though it is, is not sufficient for the latter to cool the former.

The most practicable way to regulate the temperature of an ice cutting line which is cooled in a very nonuniform manner is by pumping fluid through the line. The fluid accumulates heat from undercooled sections of the line by warming or, in extreme cases, by boiling. This heat is then redistributed to those sections of the line which **are** in contact with ice. In the ice - or water - cooled sections, the fluid cools (or in extreme cases condenses), giving up accumulated heat. The moving fluid increases cutting line efficiency by transporting heat to sections where it is the most useful and, given adequate flow rates and a reasonable percentage of the line in contact with ice or water, precludes line burnout.

Suitable coolant fluids include water, with or without solutes therein, and a wide range of organic liquids. From a purely thermal viewpoint, water is clearly the fluid of choice, owing to its high heat capacity, very high heat of vaporization, good thermal conductivity, and relatively low viscosity. These properties are not matched by any other commonly available liquid. The lower monohydric aliphatic alcohols, in particular methanol, have properties sufficiently similar to those of water as to make them acceptable alternative coolants without significant changes in system design parameters.

The surface temperatures of icebergs often approximate 0 ° C and hence a cutting line laid on an iceberg surface need not be prone to rapid refreezing of the slot melted by the line. However, icebergs, particularly large icebergs, can be expected to have significant temperature gradients from the exterior to the interior, with cold interiors. These low internal temperatures are remnants of the low temperatures occurring in the great Arctic glaciers of Greenland and northern Canada which are the sources of icebergs found off the East Coast of Canada. The thermal diffusivity of ice is such that a large iceberg, with linear dimensions of the order of hundreds of metres, will thermalize only over time periods of the order of tens of years.

At temperatures several degrees below 0 ° C (to be expected in the interior of even a small iceberg) a slot of width 0.3175 cm (1/8 in) as made by a thermal cutting line[1] would rapidly refreeze when left filled with meltwater. While cutting the above-water portion of an iceberg, the slot would undoubtedly drain, making refreezing less of a potential problem, though the plastic deformation of the iceberg in certain stress distributions might tend to force the cut faces into contact with each other. However, when cutting below the waterline, the difference in density between meltwater and seawater is sufficiently small, and the slot sufficiently narrow, that buoyancy forces would have little effect in clearing the meltwater. In consequence a bond of newly formed ice could rapidly develop above the cutting line, effectively defeating the objective of the cutting procedure.

In light of the above considerations it is clear that an antifreeze material must be introduced into the slot formed by a thermal cutting line used in an iceberg fracturing operation. Since the line is already carrying pressurized liquid coolant, the most practicable means of preventing refreezing is to use a coolant which is itself an effective antifreeze, and to leak controlled amounts of it from the cutting line into the slot. Several compounds which are both effective coolants and effective antifreeze agents do exist, one of which is methanol. It is also possible to use water as a coolant, with an antifreeze material such as urea dissolved in it.

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[1] Our experience indicates that the slot is not observably wider than the outside diameter of the cutting line.

It is not necessary to release large quantities of antifreeze into a slot cut in ice so as to prevent entirely the resolidification of the meltwater. All that is required is to prevent formation of a mechanically strong bond between the two ice surfaces bounding the slot. Indeed, allowing the material in the slot partially to refreeze to a mechanically weak slush is probably desirable in that it prevents or inhibits the washing-out of the antifreeze and possible replacement with fresh water. Antifreeze concentrations of only 10% of that necessary totally to prevent freezing will lead to loose slush formation. This slush tends to be stable for time periods of the order of weeks or months - in other words, the same time scale that is necessary for the hardening of first year sea ice.

To supply enough antifreeze to produce even a dilute antifreeze solution in a long slot cut across an iceberg requires substantial volumes of liquid to be leaked. In fact, antifreeze requirements tend to dominate thermal requirements in determining the volumes of coolant which must be injected into the line. Use of a cutting line with a bore significantly narrower than the 0.165 cm which is standard for 0.3175 cm (1/8 in) tubing is precluded by antifreeze delivery requirements and supply pressure limitations.

The mechanical configuration of the basic hot wire iceberg cutting system is simple since the primary mode of action is electrical and thermal. It is necessary only that there be sufficient mechanical force applied to the cutting line to maintain it in contact with the ice surface. Note the contrast between this situation and the common classroom demonstration where an unheated wire is used to cut through an icecube. In this demonstration, mechanical force applied to the wire gives rise to pressure melting (the slope of the fusion line for the ice-water system being negative), allowing the wire to sink through the icecube. Since very little heat is gained by the combined wire-ice-water system from gravitational potential energy, the penetrating wire does not form a slot. Rather, the water freezes in behind the wire as the wire progresses downward. The rapidity of the process is strongly dependent on the applied force or, more accurately, on the contact pressure between the cutting wire and the ice.

For the hot wire iceberg cutting system, on the other hand, thermal considerations govern the rate of ice penetration. Increasing the mechanical force applied to the line beyond that necessary to maintain contact with the ice does not lead to a significant increase in penetration rate, unless the applied force is impracticably large. The weight of the cutting line itself is in fact all that is required to move it through the iceberg. A thermal cutting line cuts at a uniform rate along its length and thus cuts a flat bottomed slot rather than the convex or arc form which would perhaps intuitively be expected. This is clearly desirable in cutting an iceberg, as no time is lost waiting for a slower central portion of the line to reach the bottom of the berg.

Although the energized cutting line will sink into the ice under its own weight, additional small weights (of the order of 10 kg each) should be attached at either end of the line so as to give it a clear vertical trend in its cutting. Otherwise, the relatively small forces arising from cable hookups to the ship could pull the line horizontally or obliquely, with consequent reduction in cutting efficiency.

In summary, the basic hot wire cutting system consists of a metal tube of small diameter laid over the upper surface of an iceberg, with weighted ends hanging over the sides of the berg; the tube is heated with a large electrical current and the heat is redistributed along the tube by antifreeze/coolant pumped along its length. The heated tube melts the ice of the iceberg to form a long thin slot into which the tube sinks under its own weight. Such meltwater as does not drain from the slot (above water) or stream from it (below water) is kept from refreezing solidly by antifreeze leaked from the cutting tube into the slot. When the slot reaches the bottom of the iceberg, the two ice masses bounding the slot separate under natural forces.

The Hot-Wire Iceberg Cutting Method: Demonstration System

In configuring a version of the hot wire ice cutting system for a field demonstration, several factors beyond those presented in the preceding analysis were taken into consideration. The demonstration was to be medium scale; that is, a small iceberg, grounded or trapped in inshore waters, was to be cut. Hence the overall system logistics and, in particular, power requirements, were substantially less onerous than would be the case for cutting a multi-million tonne iceberg lying well offshore. Corresponding to the limited objectives of the field demonstration was a strict budget allocation of Can$30,000, which in large part determined the apparatus, marine logistics, and the time which could be made available for the conduct of the work.

The essential factors governing the configuration of the demonstration system were:

A): The power supply must be available off the shelf, preferably locally and preferably by rental.

B): In consequence of A), the power supply was chosen to be a heavy duty welding machine supplied by a 75 kVA diesel generator. The welding machine voltage output was 65 V maximum, under load. The maximum sustained power output was about 40 kW.

C): Project funds were sufficient for only one day's ship time. Since deployment and cutting had to be completed entirely between dawn and dusk of one spring day, the overall cutting time could not exceed about 8 hours.

D): In consequence of B) and C), system energetics precluded cutting a slot in the ice more than 30 m long. To cut a longer slot would have required more power or more time.

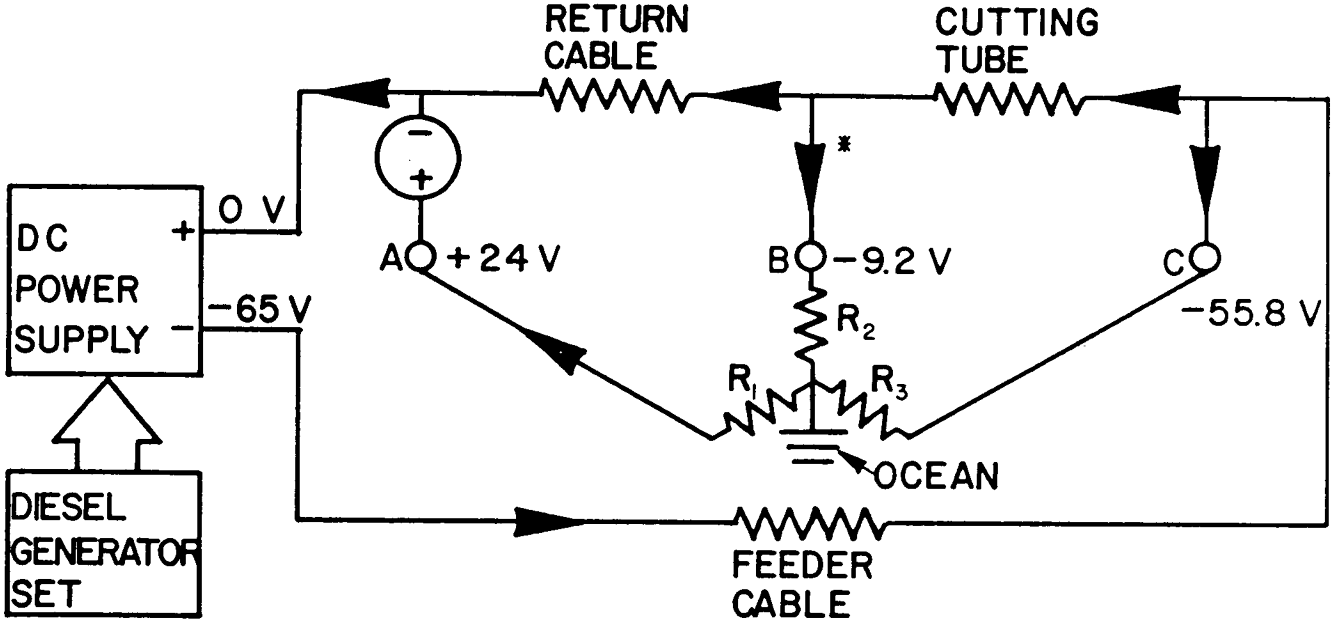
E): A copper cutting line was necessary. Any other metal would give a circuit resistance too high to yield adequate energy dissipation, given the limited voltage available.

F): With the copper cutting line, the system would run at about 500 A maximum current.

G): Given the high operating current and the fact that extra voltage to compensate for line losses was not available, very low resistance cabling (and hence thick and heavy; AWG 0000) was necessary throughout the circuit. An ocean return link could not be used.

H): Because of the low resistance of the cutting line relative to the leak path through the ocean, electrical insulation on the cutting line was unnecessary.

I): Coolant and antifreeze pumping pressure was limited to 1.72 MPa (250 psi), this being the pressure of a pumping system already on inventory at ICE Engineering



NOTE: Arrows indicate the direction of electron flow.
* This is the DESIRED direction of electron flow in this branch.

ICEBERG CUTTING SYSTEM
DEMONSTRATION CONFIGURATION

Figure 4

Ltd.

The above guidelines formed the basis for designing the demonstration version of the hot wire iceberg fracturing system.

A circuit diagram illustrating the main aspects of the system is shown on the preceding page (Fig. 4). This diagram is discussed in detail in Appendix 1, which contains the complete engineering design aspects of the demonstration version.

The Hot-Wire Iceberg Cutting Method: Operational System

In configuring the demonstration version of the iceberg cutting system, maximum use was made of locally available off-the-shelf components so as to minimize the cost of the system and the time required for its procurement. While it was possible to put together a functional system for use under controlled conditions in this way, many of the components are clearly far from optimal, or indeed even suitable, for use under general marine conditions. The following aspects of the hot wire system design require major upgrading before the system could be considered as acceptable for general operational use on East Coast icebergs:

1): **Power Supply Design:** The combination of low voltage and high current used in the demonstration version causes line loss considerations to dominate system design. These considerations lead to unacceptably heavy cables, unfeasibility of using the ocean as a return conductor, and severe limitations on the maximum resistance (and hence length) of the cutting line. Accordingly, the power supply must be configured to yield higher voltage at more moderate currents. A welding machine will not be adequate as a power supply since regulations governing shock hazard limit open circuit voltages to 90 V maximum. A full load voltage of more than 900 V will be required to run the operational hot wire cutting system.

2): **Power Requirements:** The demonstration version of the iceberg cutting system delivered about 20kW (net of line losses) to a 30 m length of cutting line. This yielded a cutting rate of 2.3 m/hr. Both line length and cutting rate must be increased in the operational system. Accordingly, delivered power must be raised to at least 250 kW. Power available at source should be 300 kW or better. This is four times the generating capacity (75 kVA) utilized in the demonstration version of the system.

3): **The Cutting Line:** The cutting line used in the demonstration version of the system was a tube of 3.175 mm outside diameter made from electrical grade copper. The resistance of this tubing is too low to permit the requisite power dissipation for the operational version without going to unacceptably high currents. The copper tubing must therefore be replaced with carbon steel tubing having a resistivity of $1.0 \times 10^{-6}\,\Omega \cdot \mathrm{cm}$ (in contrast to the resistivity of $1.7 \times 10^{-6}\,\Omega \cdot \mathrm{cm}$ for electrical grade copper). The length of the cutting line must be increased to at least 150 m to permit the cutting of larger icebergs. The overall resistance of the cutting line is then 2.6 Ω (assuming a wall thickness of 0.762 mm), yielding a power dissipation of 250 kW when supplied with 310 A at 806 V.

4): **Electrical Insulation:** The demonstration version of the system did *not* utilize electrical insulation on the cutting line. The higher voltages required to power the operational version will necessitate the use of a fully insulated line. Because of the thermal insulating characteristics of all common plastic electrical insulators, the cutting line will run considerably hotter when electrically insulated than when bare. Heat shrinkable polyolefin or TFE will probably prove suitable at the moderately elevated cutting line temperatures (estimated to be between 100° C and 200° C). Insulation sufficient to prevent arcing to the ocean at 1000 V will be needed.

5): **Cabling:** The heavy 4/0 electrical supply and return cables used in the field demonstration of the iceberg cutting system proved clumsy and generally difficult to handle in the marine environment. The operational version of the system must employ much lighter cabling. Current can be fed through a copper tube of 6.35 mm diameter and 1.65 mm wall thickness with tolerable line losses. This tubing has an electrical resistance of 0.0007 Ω/m, yielding, for a length of 300 m (ship to iceberg) a line loss of 65 V when carrying a current of 310 A. The small diameter, thick walled copper tubing is rugged, flexible, and totally immune to kinking; its flexure is closer to that of a bar than that of a thin-walled tube. This thick-walled tubing would serve a dual role in supplying both electric current and coolant/antifreeze to the thinner cutting tube.

6): **Ocean Ground:** An ocean ground (i.e. return path for current from the cutting line) was not feasible in the demonstration version of the cutting system, because of the significant finite resistance of the electrical path through the ocean. Overall energy losses on this leg of the circuit where intolerable at the strictly limited low voltages and high currents utilized. The operational version of the system would use an ocean ground electrode on the far side of the iceberg to carry the return current. This would eliminate the need for a cable loop deployed over the iceberg and would reduce the system to just one line extending from the support vessel. The electrode at the berg end of the line can be made from 3.175 mm thick aluminum sheet, rolled to form a cylinder 78 cm in diameter and 122 cm long. This electrode would weigh 25.5 kg.

At the ship end of the circuit, a heavier aluminum sacrificial electrode would be deployed in the ocean. This electrode, operated at positive polarity, would gradually dissolve electrolytically in the ocean, while maintaining all other immersed components at a net negative potential. In this way, electrolytic corrosion of system components, which terminated the field test of the demonstration version, would be entirely prevented. The ship side of the ocean ground would also be a cylinder 122 cm long and 78 cm in diameter, but rolled from plate 2.54 cm thick. Its weight would be just over 200 kg. The resistance of the electrical path through the ocean between the electrodes would be approximately 0.078 Ω, assuming their separation to be 500 m. This resistance would give rise to a voltage drop of 24 V when the system was operated at 310 A.

7): **Coolant and Antifreeze:** As in the demonstration version, the full-scale iceberg cutting system would utilize pressurized methanol as a coolant and antifreeze. Flow rates would have to be about 10 times greater than the approximately 15 *l*/hr realized in the field test of the demonstration system since the line is five times longer, and the ice penetration rate sought is about twice as great. The viscosity of methanol in the operational design is about four times lower than in the original design, owing to the higher internal operating temperature of the plastic-insulated cutting line (150° C as opposed to 10° C). This would give a fourfold increase in flow. A further gain in flow can be achieved by increasing the supply pressure, although the fact that the line is operating in the turbulent flow regime imposes a square root dependence of the flow rate on pressure. Feeding the line with methanol pumped to a pressure of 13.8 MPa (2000 psi) would increase flow by a factor of about 2.8 relative to the rate achieved with the demonstration system. The combined effect of lower fluid viscosity and higher pressures will yield adequate methanol flow for coolant and antifreeze purposes in the 150 m long line envisioned in the operational configuration.

The distribution of leak holes for supplying antifreeze to the cut will have to be determined empirically for the operational version of the cutting line, as it was for the demonstration version. The intermediate and rapidly spatially varying Reynolds numbers characterizing flow in the line render very difficult any *a priori* analysis of line flow characteristics. It is envisioned that the appropriate number of leak holes would be in the range 10 to 15.

Major Components for the Operational Hot-Wire System.

The operational version of the iceberg cutting system, while similar in general layout to the demonstration version, includes four key components with very significantly altered specifications. These components are: the DC power supply, the AC power source, the insulated cutting line and the coolant pump. However, while these are significantly different from those used in the demonstration version, all fall within the realm of standard, proven technology. Indeed, quotes for each of these major components have been obtained from suppliers in North America. A description of each key component, including possible sources, is given below.

The major components of the iceberg cutting system are as follows:

a): Power Supply:	A custom manufactured DC power supply for this application would have: 500 kW of power available at the output (1.25kV at 400 A), variable voltage and current limiter. The required supply is 600 kVA (600 V at 1000 A) 3 phase AC with a power factor of 0.9. The unit would weigh approximately 1000 kg and would measure 0.9 m × 0.9 m × 2.3 m. The unit could be supplied in 14 to 16 weeks at a cost of under $20,000 by Inverpower Controls Ltd. of Burlington, Ontario.
b): Generator Set:	In order to supply the AC power input to the DC power supply, the Caterpillar model 3508 heat exchanger cooled diesel generator set appears satisfactory. The 3508 has an output power rating of 815 kVA, 600 V, 3 phase AC with a power factor of 0.8 or higher; it consumes 160 l/hr of diesel fuel at 600 kVA output. The unit weighs 5896 kg (13000 lb) and measures 3.68 m × 1.70 m × 1.80 m (145 in × 67 in × 71 in).

The generator set can be supplied, within 8 weeks of ordering, by the Newfoundland Tractor and Equipment Ltd., St. John's, Nfld., at a cost of under $200,000, or $16,000 (8%) per month in the case of a lease of 6 months or longer.

c): Coolant Pump:

To supply the feeder and cutting lines with methanol coolant/antifreeze, the Monarch MP 1306-7P piston type pump was selected. The pump is belt driven with a 5.2 kW (7 hp) Briggs and Stratton engine. The unit weighs 39 kg and delivers 10.2 l/min at 12750 kPa. The MP 1306-7P is available for under $2000 from W.N. White and Co. Ltd., St. John's, Nfld.

d): Cutting Tube:

The actual cutting tube would be a 150 m length of 3.175 mm o.d. (0.125 in), 0.762 mm (0.030 in) walled mild steel tubing, the first 30 m of which is to be electrically insulated with 0.254 mm (0.01 in) of TFE.

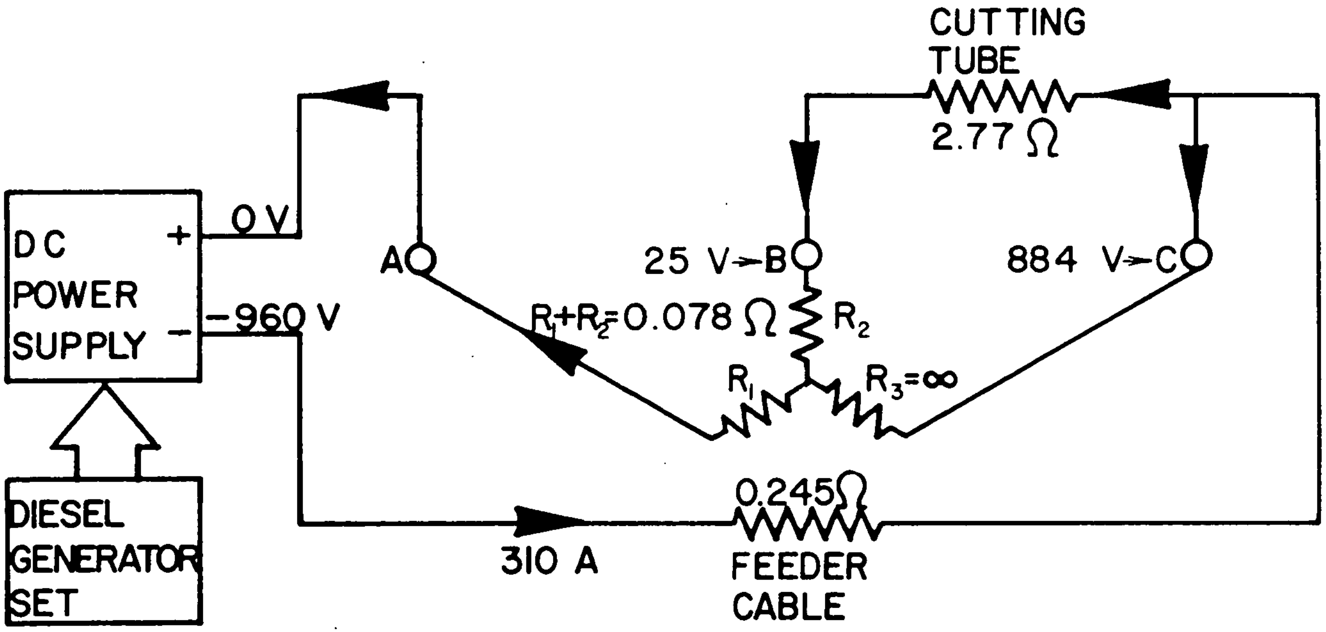
The cutting line can be supplied with TFE insulation to a specified thickness by Parker Hannifin Corp. in Ravenna, Ohio.

TFE has been found to possess all of the necessary characteristics for use as electrical insulation on the cutting line. It has a high dielectric strength (18900 V/mm = 480 V/mil), a high maximum service temperature (260° C), adequate thermal conductivity (2.43 mW/cm/deg) and is deemed to have good resistance to abrasion. With these characteristics the cutting line can be insulated electrically with 0.254 mm (0.01 in) of TFE coating to 4800 V while still allowing adequate heat transfer to the ice. In addition there is little problem with the insulation melting or being rubbed off.

A circuit diagram showing the basic electrical layout of the operational version of the iceberg cutting system is given in Fig. 5.

Scenario for the Operational Cutting of an Iceberg

For the purposes of describing the functioning of the proposed operational iceberg cutting system, assume that a target iceberg has been located by aerial reconnaissance about 5 days drift from an area of offshore operations. The iceberg is tabular and roughly rectangular in water line shape, measuring 230 m on its largest axis and 140 m a perpendicular axis through its center. The iceberg has an average surface elevation of 13 m above sea level and a corresponding overall thickness of about 100 m. The estimated mass of the iceberg is approximately 3 million tons and the decision is made to cut it into two roughly equal pieces.



NOTE: Arrows indicate the direction of electron flow.

ICEBERG CUTTING SYSTEM
OPERATIONAL CONFIGURATION

Figure 5

A workboat equipped with a fast rescue craft is dispatched to the iceberg, carrying the iceberg fracturing system (electric generator, coolant pump, cutting line, coolant supply, electrodes, line throwing apparatus), and several light weight ocean ground electrodes for use at the far end of the cutting line. The workboat used is capable of iceberg towing, conventional apparatus probably being satisfactory.

Upon arrival at the site a more or less conventional iceberg tow is set up but with a configuration specifically intended for fracturing. The workboat establishes the tow connection and uses it to take up and maintain station at a distance of 300 m from the edge of the iceberg. The stern of the vessel points towards the approximate center of the iceberg along a line which defines the estimated minimum iceberg cross-section. The vessel is thus in line with the short (140 m) axis of the rectangular berg.

The fast rescue craft is deployed and takes up station on the opposite side of the iceberg to aid in retrieval of a light line launched from the workboat. With both vessels on station and the workboat brought up on its towline with gentle thrust, a line throwing rocket is used to shoot a light line from the workboat across the approximate center of the iceberg. This line is retrieved from the water by the support vessel on the far side of the iceberg and is used as a leader line to haul the cutting line across the iceberg. The cutting line consists of 150 m of polyolefin-insulated 3.175 mm diameter steel tube and is connected to 350 m of 6.35 mm diameter copper feeder line. The total weight of the cutting line and the feeder line is about 90 kg. When the cutting line has been pulled across the berg and its end retrieved on the far side, the light (26 kg) aluminum ocean ground electrode is connected. This electrode is then dropped into the ocean near the support vessel and pulled back near the side of the berg by the weight of the supply line which hangs in a catenary between the fracturing vessel and the iceberg. The fast rescue craft is now no longer required and is retrieved by the workboat.

The heavy aluminum sacrificial electrode is then deployed over the side of the workboat in preparation for the system being energized. Circuit and fluid connections are completed, with both the 13.8 MPa (2000 psi) methanol pump and the 1 kV, 350 A power supply being readied for startup. The circuit, comprised of the cutting line (2.77 Ω), feeder line (0.245 Ω), and ocean return link (.078 Ω), has an overall resistance of 3.09 Ω and will draw 310 A when supplied with direct current at 960 V. The feeder line and the cutting line are given negative polarity.

Delivery of methanol is commenced and verified prior to the electrical supply being switched on. Along the cutting line, methanol is leaked from a series of 15 holes of 0.342 mm diameter at an overall rate of 0.7 l/min prior to startup but which increases to 2.8 l/min after the line is energized. The fourfold increase in flow is the result of the reduction in methanol viscosity accompanying the raising of the cutting line temperature from near zero to 150° C.

Electric current is turned on at an initial supply voltage of 240 V so as to allow the line to sink a small distance into the ice to ensure adequate cooling before full power is applied. Thirty minutes after startup, full power is brought up and the cutting line commences sinking into the ice at a rate of 5.6 m/hr. The power dissipated by the cutting line is 16.6 W/cm.

The cutting system is operated for 16 hr during which time the line penetrates 90 m. At this point the iceberg divides into two major sections and sheds a number of bergy bits. At the instant fracturing is observed to commence, the workboat is brought to full thrust, breaking a 40 tonne weak link in the tow hawser near the boat. The cutting line also parts and the vessel steams away from the breaking iceberg dragging the feeder line. The feeder line is retrieved on board the workboat and, after the broken iceberg fragments have stabilized in the water, the workboat returns and recovers the tow hawser. The cutting line and the light weight ocean ground are not recovered.

During the cutting operation, the following materials have been consumed and/or lost.

- line throwing rocket and leader line
- 2700 litres methanol for coolant and antifreeze
- 1000 litres diesel fuel for electric generator
- cutting line
- light ocean ground (26 kg aluminum)
- heavy ocean ground (200 kg aluminum)
- 1 day workboat time (fracturing vessel on site)
- 0.5 day fast rescue craft time (support vessel on site)

Feasibility Criteria for the Operational Hot-Wire Iceberg Cutting System.

a): Feasibility of the physics: the method is adjudged to have an 80% chance of succeeding in its operational embodiment. Laboratory tests can and have verified the cutting rate. Scaling of the process to icebergs of any size is straightforward. The refreezing of the thin cut is the only significant uncertainty in the physical processes, and a size - and sample - dependent one, but it can be controlled by leaking sufficient antifreeze into the slot.

b): Engineering feasibility: the method utilizes standard, although heavy-duty, electrical apparatus. While the circuit configuration is novel, the electrical specifications, power supply, cables and so forth are standard. Most key components of the system are available off-the-shelf.

c): Marine considerations: the system is deployable using a standard supply boat as the sole platform. No boarding of the iceberg is required. All apparatus deployed over the side is simple and rugged.

d): Safety: the primary hazard associated with the system is electrical shock. Voltages to be used are high but this hazard can readily be controlled with appropriate precautions. The cooling fluid to be used, methanol, is not strongly toxic unless swallowed in quantity, and no contact of the fluid with personnel is envisioned during operations. While methanol is inflammable, it is not very volatile, and the design of the apparatus does not lead to significant release of methanol near the ship. Dilution with water removes its flammability. Overall, the flammability hazard it presents is much less than would obtain with an equal quantity of gasoline and, with routine carefulness, is not a problem.

e): Cost: the method is inherently inexpensive, both in terms of consumables (primarily diesel fuel and methanol) and capital equipment required.

f): Environmental impact: the method poses no threat to the environment except in the release of methanol into the ocean. Alternative, totally environmentally benign coolants (e.g. ethanol) could be employed with only minor loss of effectiveness.

APPENDIX 1:

Design of the Field Demonstration Version of the "Hot-Wire" Method.

1.0. Introduction.

The engineering details of the demonstration version of the hot wire iceberg fracturing system are presented in the following discussion. Since only a single opportunity to conduct a one-day field program was available, all system parameters were finalized without the benefit of even limited field experience. Following completion of the field program, hindsight can be used to infer that while not all of the selected parameters were optimal, they were clearly within reasonable bounds.

Optimization of the parameters of the demonstration version of the system, using the results of the field program, has not been undertaken within the context of the present study. Rather, efforts beyond the field program have been focused on redesigning the system more towards an operational configuration. Accordingly, the following document remains basically as it was originally written[1], a planning document. The analysis quite closely resembles the strategy which was actually undertaken in carrying out the field program.

An illustration showing the general arrangement of the apparatus deployed in the field program is given on the following page (Fig. 6).

2.0. Physics of the Hot-Wire Cutting Tube

2.1. Thermodynamics

The thermodynamics of the process is simple. Heat evolved in the wire by the electricity is used to raise ice to the melting temperature and then to melt the ice. The heat required to melt ice is 79.72 cal or 333.5 J per gram. At a density of 0.90 (ice with 1.8 % porosity) the heat required per cm^3 is 300.2 J.

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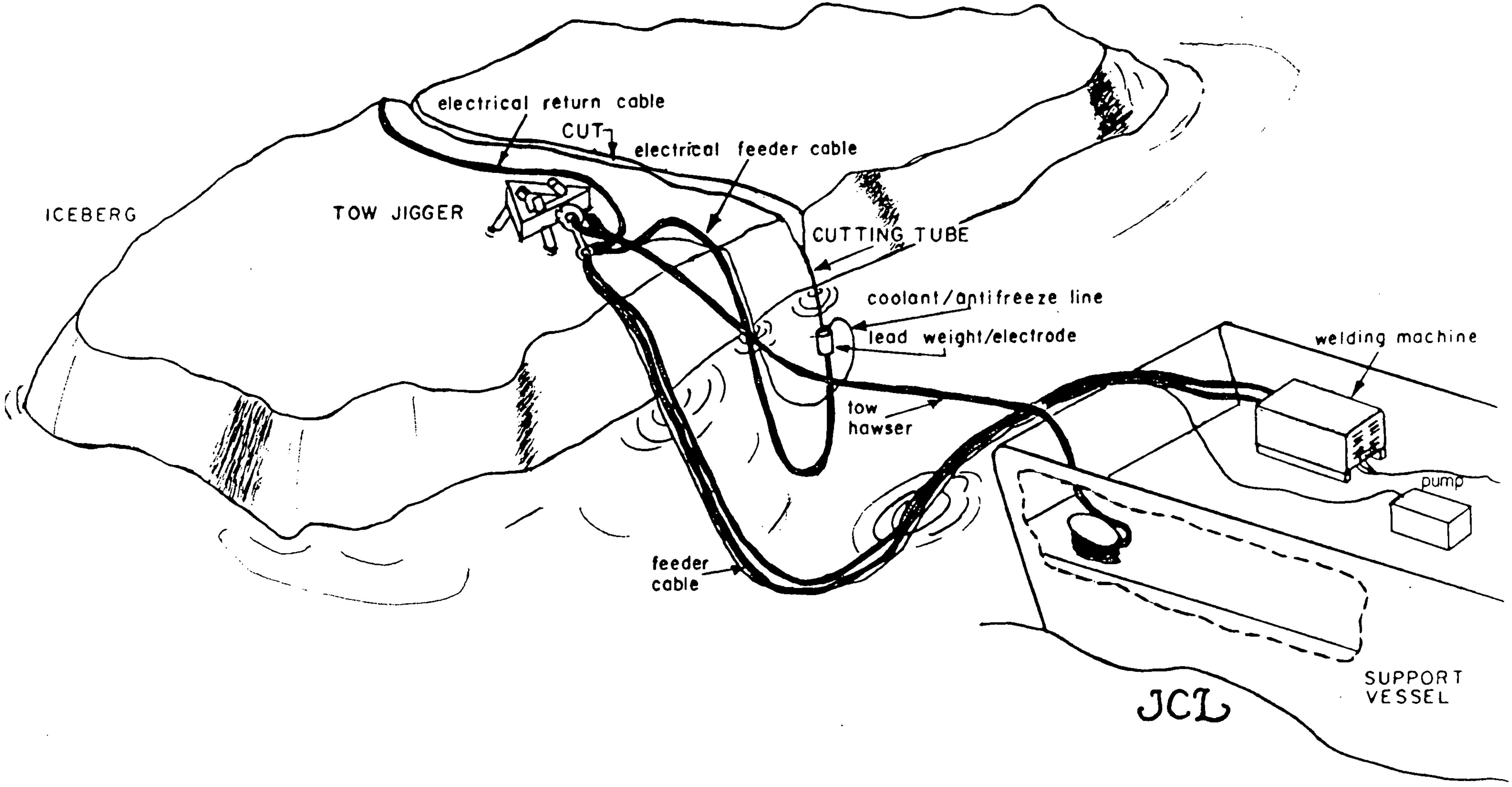
[1] This volume is a modified version of an interim report of the study, submitted March 18, 1985, prior to conducting the field program.



DEMONSTRATION VERSION OF ICEBERG CUTTING SYSTEM GENERAL ARRANGEMENT

Figure 6

2.2. Efficiency of Heat Transfer.

Because the wire is envisaged as made of copper, an excellent heat conductor, there will not be large temperature differences between the top and bottom of the wire. The bottom of the wire is separated from the ice by only a very thin layer of water and hence is maintained near 0 ° C. The temperature of the top of the wire probably would not exceed 10 ° C while ice cutting is taking place. Hence heat transfer to the water in the crack above the wire is minimal and a high percentage, approximately 90% or better of the thermal energy of the wire goes into heating and melting of the ice.

Now the heat capacity of ice is small, approximately 0.5 cal/gm/degree. More precisely, using values from p. D-211 of the *Handbook of Chemistry and Physics* (CRC 1978), we have

Table 1.
Temperature Dependence of the Specific Heat of Ice.

Temperature deg C	Specific Heat cal/gm/deg
-31.0	0.45
-21.0	0.467
-11.0	0.486
-2.2	0.502

so only a little of the heat is used in raising the temperature of the ice to 0 ° C; precisely, to raise the temperature of 1 gm of ice from -20 ° C to 0 ° C is 10 cal, as opposed to the 80 cal necessary to melt the ice.

2.3. Equation for the Cutting Rate

The cutting rate can be determined from the dissipated power per unit length, the geometry of the cut, the assumed efficiency of melting, and the latent heat of melting of ice. Let E_{cut} be the energy dissipated per cm of cutting tube per cm depth of ice penetration. Let l_f be the latent heat of melting of ice in joules per gm of ice, let ρ be the mass density of the ice in gm/cm^3, let d_{tube} be the outside diameter of the cutting tube in cm, and let ϵ be the efficiency with which heat is utilized in melting. Then

$$E_{cut} = \epsilon \; l_f \; \rho \; d_{tube} \tag{24}$$

If the power dissipated per unit length is H in watt per cm, the cutting rate C in sec/cm is given by

$$C = E_{cut}/H. \tag{25}$$

Consequently, substituting eq. (24) into eq. (25) and multiplying numerator and denominator by L, the length of the cutting line, we obtain

$$C = \frac{\epsilon\, l_f\, \rho\, d_{tube}\, L}{85.97P} \ (\mathrm{hr/m}) \tag{26}$$

where: L is measured in metres and P is the power dissipated in kW.

Assuming that

$\epsilon = 0.9$,
$l_f = 79.72 cal/gm = 333.5$ J/gm,
$\rho = 0.9\mathrm{gm/cm}^3$,
$d_{tube} = 0.3175\mathrm{cm}$,
$L = 30\mathrm{m}$,
$P = 20\mathrm{kW}$,

then $C = 0.238L/P$, and so the cutting rate is about 2.8 m/hr. This is comparable to the cutting rate observed in our field tests.

2.4. Electrical Properties of the Copper.

The cutting tube in the optimal configuration is electrical-grade copper, outside diameter 0.125 in (0.3175 cm), wall thickness of 0.030 in (0.0762 cm). The cross-sectional area of the copper in the tube wall is, therefore, 0.0578 cm^2.

The quoted manufacturer's tolerances on the o.d. are +0.0020 in and -0.0020 in; the quoted tolerances on the wall thickness are +0.0030 in and -0.0030 in.

The resistivity of electrical-grade copper is $1.7\times10^{-6}\ \Omega\cdot\mathrm{cm}$. Only silver has lower resistivity. For purposes of comparison, we note that the resistivity of 304 stainless steel is $72\times10^{-6}\Omega\cdot\mathrm{cm}$. Hence the resistance of the design tubing is, therefore, 0.0000294 Ω/cm, while for stainless steel tubing of the same dimensions the resistance would be 0.00125 Ω/cm.

From eq. (26), the cutting rate is inversely proportional to the power dissipated which is, in turn, linearly proportional to the resistance. Hence the cutting rates for tubes of differing resistances, given the same geometrical configurations and voltages, would be

$$C_1 = (R_2/R_1)\, C_2\,. \tag{27}$$

Hence the ratio of cutting for stainless steel and copper would be 17.4:1. In fact, the lower thermal conductivity of the stainless steel, and the nonnegligible ocean losses of emf would lower the cutting rate still further. Copper is the clearly preferred choice for the cutting wire given the constraints on applied voltage from commercially available high current power supplies.

3.0. Coolant and Antifreeze Flow

Without cooling, **at a power of 7 W/cm, the temperature of the cutting tube will rise at the rate of 35 ° C/sec.** The melting point of copper (1084 ° C) would be reached in about 30 sec. Coolant is therefore required to keep the cutting tube from melting (or vaporizing).

The energy transferred from the tube by the coolant flowing through the tube can be calculated by the number of cm^3/sec transferred through the tube, together with the specific heat and latent heat of vaporization of the coolant.

3.1. Velocity equation.

The flow velocity of coolant through the tube is given by the Hagen - Poiseuille equation, in which V_{vol} is the volume flow rate of fluid in cm^3/sec, r_{id} is the radius of the tube bore in cm, L is the length of the tube in cm, P is the pressure differential in the tube in dyne/cm^2, and η is the viscosity of the coolant in poise:

$$V_{vol} = \pi P r_{id}^4 / 8L\eta \tag{28}$$

(Batchelor 1970, Giles 1962).

The pressure differential provided by the pump to be employed is 250psi $= 250 \times 6.895\ 10^4$ dyne/cm^2 $= 1.72\ 10^7$ dyne/cm^2.

3.2. Temperature Dependence of the Viscosities of Water and Methanol.

The viscosity of methanol is given to 2.05% or better from -98 ° C to +50 ° C by the expression

$$\log \eta = -1.6807 + \frac{354.876}{T - 48.585} \tag{29}$$

where the viscosity η is given in centipoise and T is the absolute temperature in K (Table 9-13 of Reid et al. (1977)). Similarly, the viscosity of water is given to 0.51% or better from -10 ° C to +160 ° C by the expression

$$\log \eta = -1.5668 + \frac{230.298}{T - 146.797} \tag{30}$$

(Table 9-13 of Reid et al. (1977)).

Some representative values of the viscosity of water are:

0 ° C, 0.0179 poise;
5 ° C, 0.0152 poise;
50 ° C, 0.00547 poise;
100 ° C, 0.002818 poise.

Some representative values of the viscosity of methanol are:

0 ° C, 0.0082 poise;
50 ° C, 0.00405 poise.

The temperature of the cutting tube in contact with the ice will, on the basis of laboratory tests, run at 5 ° C to 10 ° C. Parts of the tube in air may run with the coolant boiling. The decrease of viscosity with increasing temperature is advantageous, as it means that for constant head, the more coolant will circulate the hotter the tube.

3.3. Pressure Dependence of Viscosity.

While temperature variations in the viscosity of the coolant are important, pressure variations are not. The viscosities of liquids such as methanol and water show significant pressure variations over 10000 atm [1] but not over 20 atm (see Fig. 9-16 of Reid et al. (1977)). As 20 atm is comparable with and slightly greater than the highest pressure which the coolant/antifreeze pump can provide, pressure variations in viscosity will not appreciably affect the operation of the iceberg cutting apparatus described herein.

3.4. Dependence of Viscosity of Methanol/Water Mixtures on Composition.

While the viscosity of methanol is substantially lower than that of water at the same temperature, methanol/water mixtures are highly nonideal, and, for mixtures less than 85% methanol by weight, have viscosities substantially higher than water, let alone pure methanol. This more than offsets the advantage in higher boiling-point, specific heat, and latent heat of vaporization which would be obtained by use of a methanol/water mixture for coolant/antifreeze.

The viscosity of methanol/water mixtures are set out in Table 2 below, in which η/η_0 is the relative viscosity, i.e. the ratio of the absolute viscosity of the mixture at 20 ° C to the absolute viscosity of water at 20 ° C. The data are from p. D-265 of the *Handbook of Chemistry and Physics* (CRC 1978).

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[1] The variation in the viscosity of water is much less than that for methanol.

Table 2.
The Viscosity of
Methanol/Water Mixtures at 20 ° C
Relative to the
Viscosity of Pure Water at 20 ° C
as a Function of the
Percent Weight of Methanol

% weight methanol	η/η_0
1.00	1.038
10.00	1.326
20.00	1.601
30.00	1.791
38.00(max)	1.835
40.00	1.833
50.00	1.757
60.00	1.597
70.00	1.365
80.00	1.126
90.00	0.859
96.00	0.694
100.00	0.585

3.5. Spacing of the Antifreeze Supply Holes in the Cutting Tube.

The smallest commercially available drill is a size 80, which is 0.0135 in in diameter. Finer holes are now usually made with lasers. Much finer holes would not in any event be particularly desirable, as chances of fouling would be correspondingly increased. The size 80 hole is approximately 300 microns in diameter. A 100 micron filter will be installed immediately downstream of the pump. While a finer filter could be used, the probability of clogging the **filter** also rises with fineness.

However, the fluid leakage with size 80 holes is sufficient that only a small number, less than 10, can be used. Hence the concept of a **linear hole density** is not applicable to this system, and a discrete approach to the positioning of holes must be used. A definition sketch is shown in Fig. 7 below.

The N leak holes are numbered sequentially, with hole i being located at the low-pressure end of the cutting tube, just downstream of the second electrode. The pressure at leak hole i is denoted by P_i, $i=1,2, \cdots ,N$. The pressure at the inlet to the cutting tube is denoted by P_N.

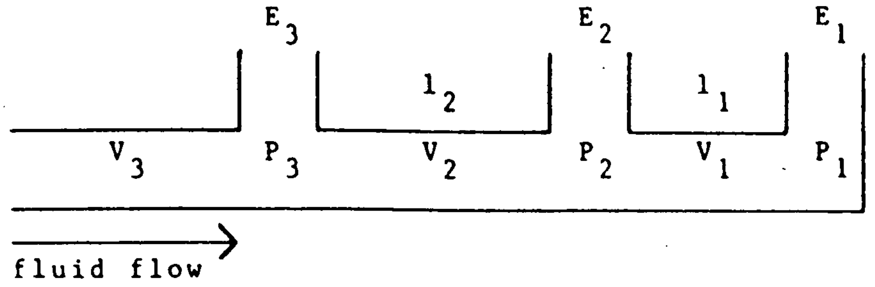

Figure 7: Definition Sketch for Antifreeze Supply Hole Distribution.

The pressures at adjacent holes are given by the expression

$$P_i = P_{i-1} + \frac{V_{i-1} l_{i-1}}{\kappa_T}, \quad i=2,3,\ldots,N, \tag{31}$$

where V_i is the volume rate of fluid transport through the tube immediately upstream of hole i, l_i is the separation between hole i and hole $i+1$, with l_N the distance from the hole farthest upstream to the inlet of the cutting tube, and κ_T is the fluid resistance of the tube. For laminar flow, κ_T can be calculated from eq. (28) above. It is given by

$$\kappa_T = \frac{\pi r_{id}^4}{8\eta}. \tag{32}$$

For methanol at 10° C and $r_{id} = 0.0826\text{cm}$, this expression yields

$$\kappa_T = 0.00268 \text{ gm}^{-1}\cdot\text{cm}^5\cdot\text{sec}. \tag{33}$$

The volume escaping from hole i, E_i, is given by

$$E_i = k_L P_i, \tag{34}$$

where k_L is the fluid resistance of the leak. This resistance was determined empirically for the 0.0171 cm radius holes drilled in the line and found to be 0.00000394 $\text{gm}^{-1}\cdot\text{cm}^4\cdot\text{sec}$. Hence the fluid flow through a leak hole at a given pressure is equivalent to the fluid flow through 680 cm of the tube at the same pressure.

In terms of V_i and E_i, the the equation of continuity for the tube and leak holes is

$$V_i = V_{i-1} + E_i \tag{35}$$

To obtain constant linear fluid leak density, the holes must be placed so that

$$l_i = \Gamma E_i - l_{i-1}, \tag{36}$$

where Γ is a constant, and l_i is the spacing between leak hole i and leak hole $i-1$. This equation differs from eqs. (31), (34) and (35) above in that it is a design choice rather than an application of the principles of hydraulics.

As a consequence of the above equation, the rate of supply of methanol to the cut, per unit length of cut, is given by $2/\Gamma$, with convenient units of $(\mathrm{cm}^3/\mathrm{sec})/\mathrm{cm}$.

In addition to eqs. (31), (34), (35) and (36) above, the distances l_i must obey the sum rule

$$\sum_1^N l_i = L, \tag{37}$$

where L is the length of the tube.

These equations are coupled and nonlinear. However, they are readily solved iteratively. With **seven** holes, the solution is given in Table 3 below.

Table 3.
Leak Hole Spacing
in the
Cutting Tube.

Hole no.	Pressure P_i psi	Leak Flow E_i $\mathrm{cm}^3 \cdot \mathrm{sec}^{-1}$	Spacing l_i cm
1	1.60	0.44	79.0
2	1.79	0.49	97.4
3	2.27	0.62	127
4	3.33	0.90	202
5	5.99	1.63	391
6	14.6	3.97	1052
7	60.3	16.4	1052
inlet	200	-	-

For the given solution, we obtain

$$\frac{2}{\Gamma} = 0.0055\ (\mathrm{cm}^3/\mathrm{sec})/\mathrm{cm} \tag{38}$$

It is noteworthy that most of the fluid in fact escapes from the first hole. More than seven holes does not significantly improve the distribution of fluid, as the holes at the low-pressure end are clustered tightly together.

The total fluid flow arising from the above configuration of holes will be 24.5 cm^3/sec with a pressure of 13.8 dyne·cm^{-2} (200 psi).

The loss of pressure on the methanol feeder line can be calculated for a flow rate of 24.5 cm^3/sec using eq. (28). For a feeder line of length 170 m, with an inside radius of $r_{id} = 0.238$cm (3/16 in i.d.), the pressure drop is found to be $2.7 \cdot 10^6$ dyne·cm^{-2} (39.1 psi). The methanol temperature for this calculation has been assumed to be 0 ° C, since the majority of the feeder line will be unheated and lying in the ocean (see Fig. 6). Hence the inlet pressure assumed in Table 3 can be realized with the specified pumping system.

3.6. Boiling Temperatures of Water and Methanol Under Pressure.

Water in uncooled parts will be 100 ° C or higher. The boiling points of water and methanol under pressure can be obtained from the Antoine equation (see Ch. 6 of Reid et al. (1977)). For water, this gives

$$\theta = \frac{3816}{14.36 - \ln P} - 227.0 \tag{39}$$

where P is the pressure in psi, and θ is the boiling temperature in degrees Celsius. For methanol, the Antoine equation gives

$$\theta = \frac{3626}{14.64 - \ln P} - 238.86 \tag{40}$$

Some typical values for the boiling point of methanol are:

64.9 ° C at 1 atm (the normal boiling point);
159 ° C at 250 psi, the pump pressure;
105 ° C at 60 psi, the mean line pressure.

We note that the critical temperature and pressure of methanol are 513.2 K (240.1 ° C) and 7.95 MPa, versus 647.3 K (374.2 ° C) and 22.1 MPA, respectively, for water (Table A.7 of Van Wylen and Sonntag (1976)). These are, then, the highest temperatures at which any heat can be removed by boiling these liquids.

3.7. Heat Transfer to the Cooling Fluid.

The total heat transfer to the fluid can be calculated as follows: calculate first the volume of the tube; compare with the volume flow rate V_{vol} as obtained above, to calculate the time necessary to replace all the fluid in the tube; then deduce the heat content of a tube full of fluid, assuming that the fluid is heated from the temperature just upstream of the first electrode, to the operating temperature of the cutting tube between the electrodes. The former will be close to 0 ° C owing to ocean cooling. The fluid will absorb significant heat only in those portions of the tube which are not in contact with ice or seawater. Hence the use of the coolant flow is efficacious in preventing runaway but it does not interfere with the cutting.

At a temperature of 10 ° C, and using methanol as coolant, the volume flow rate at the inlet to the cutting tube, V_7, is 24.5 cm^3/sec. In consequence, the tube's entire contents of fluid (64.2 cm^3) will be replaced every 2.63 sec.

Relevant properties of liquid methanol:

> At 25 ° C, its specific heat, at constant pressure, is 0.609 cal/gm/deg (p. D-212 of the *Handbook of Chemistry and Physics* (CRC 1978)).
>
> At 20 ° C its density is 0.791 gm/cm^3 (p. C-376 of the *Handbook of Chemistry and Physics* (CRC 1978)).
>
> The specific heat per unit volume is, therefore, 0.482 cal/cm^3/deg.
>
> Its heat of vaporization at 1 atm is 279 cal/gm (p. D-78 of the *Handbook of Chemistry and Physics* (CRC 1978)).

Table 4.
The Depression of the Freezing Point of Water by Methanol as a Function of the Percent Weight of Methanol

% weight methanol	Depression ° C
5	3.02
10	6.60
15	10.53
20	15.02
30	25.91
40	38.6
68	96.3
100	93.9

The heat transfer rate into the tube by methanol flowing at the rate of 24.45 cm^3/sec, and changing in temperature by 5 ° C, is 250 W. To change the temperature of the methanol by 100 ° C thus requires 5000 W. As the tube is intended to run at approximately 20kW, as much as 1/4 of its length could be exposed to the air before **any** of the methanol were to boil. Even in the final section of the tube (from leak hole 1 to leak hole 2), 630 W is required to boil all of the liquid methanol. As only 550 W will be generated in this section, even the small flow rate obtaining in this final section is quite sufficient to keep the tube from melting. The power absorption of 630 W is in fact an underestimate, as the viscosity of methanol decreases rapidly with increasing temperature (see eq. (29)), with consequent decrease in flow impedance and corresponding increase in flow rate.

3.8. Freezing Point Depression as a Function of Cutting Rate.

The depression of the freezing point of water by methanol is summarized in Table 4 above. The data are taken from p. D-284 of the *Handbook of Chemistry and Physics* (CRC 1978).

The concentration of methanol in the slot formed by the cutting tube is found by calculating the ratio of methanol leaked into the slot to the mass of fluid in the slot. This fluid mass is a combination of leaked methanol and meltwater from the ice. The volume of the slot per cm of penetration is 730.3 $\mathrm{cm}^3/\mathrm{cm}$ for a slot of 30 m length using the tube dimensions specified previously. The mass of the meltwater released is therefore $0.9 \times 730.3 = 657$ gm per cm of penetration. The mass concentration of methanol is therefore given by

$$\%\ \text{methanol concentration by weight} = \frac{1930}{657/C + 19.3}, \tag{41}$$

where C is the cutting rate in sec/cm as defined in eq. (25) above. For a cutting rate of 15.5 sec/cm (0.43 hr/m), the methanol concentration in the slot will be 31%, which will give a freezing point depression of about 26 ° C (Table 4). This is comparable with, and indeed likely significantly colder than, the temperature at the centre of a large iceberg.

4.0. The Electrical Supply.

Electrical cabling of very low resistance is necessary to carry power to a fixed point on the iceberg, namely the ice jigger, and from there to the cutting tube. The cable is connected to the cutting tube by 5 kg electrodes, constructed mainly of lead. These electrodes are fastened at either end of the cutting tube. The electrical cabling and the electrodes have in fact a second function in addition to the supply of power. That function is to provide sufficient **weight** to pull down the tube, and to balance the mechanical tension on either side of the berg. To achieve the latter, the cables from jigger to electrodes will hang in catenaries in the water. If the line should slide longitudinally toward one side of the iceberg, the effect is to reduce the weight of the cabling on that side, and hence to reduce the tension on the cable on that side relative to the tension on the other, and thus to centre the overall position of the line. Approximately 30m excess cable will be allowed on each side for this purpose.

The cable chosen is "Superflex" 4/0 welding cable, supplied by Canadian Liquid Air. It is nominally of 15mm o.d. It is a stranded cable, a 7 by 7 by 108 bundle. The internal strands are gauge 34 wire. The cable contains 3mm thick insulation, which is probably high density Neoprene. The electrical resistance calculated from its known structure (see below) is 0.157 Ω/km.

The weight per unit length is not provided by the manufacturer. However, a good estimate can readily be obtained. AWG no. 34 wire has a diameter of 0.00631 in (0.0160 cm), so that the cross-sectional area of each strand is 0.000202 cm^2. The cumulative cross-sectional area is, therefore, 1.068 cm^2. The actual area will be slightly greater because of the nonzero helicity of the strands in the twisted cable.

Neglecting the effects of twisting, the volume of copper in the cable is 106.8 cm^3 per metre of cable, compared with which the weight of the insulation can be ignored. Hence a good value for the weight of the cable per unit length is 0.955 kg/m. In fact, taking insulation and twisting of the strands into account, 1 kg/m is a reasonable value.

4.1. Weight on the Cable.

Each end of the cutting tube will be bearing one 5 kg electrode, and at most 15 kg cable so that the loading on each end of the cable will be 20 kg. This will drop to 5 kg at a depth of 30m, at the end of the cutting process. Care will be taken that the cables do hang over the iceberg into the sea, and do not snag on sills. The length of the cutting wire will be at least 30% greater than the estimated maximum width of the iceberg to allow for errors in that estimate, and also to allow for the slanting of the cutting tube in a possible oblique cut.

The tensile strength of annealed copper (of which our cutting tube is made) is 32 000 psi (220 MPa). The cutting tube cross section is 0.0578 cm^2, so that the tensile strength of the tube can be estimated as at least 130 kg. The 0.2% irreversible yield strength of copper, 10000 psi (69 MPa) for annealed Cu, is approximately 1/3 of the tensile strength, so that the tube will undergo small irreversible stretching, followed by work-hardening, at a load of 41 kg. Both of these figures are well above the design loads.

The tensile strength of the electrical supply cable can similarly be calculated to be 2400 kg.

4.2. Electrical Losses to Seawater

The electrical resistivity of seawater has been calculated from data in the *Handbook of Chemistry and Physics* (CRC 1978) to be 23.81 ohm cm. The calculation of current flow through the ocean based on the anticipated electrode configuration is difficult. We have instead chosen to approximate the electrodes and exposed sections of the line with spheres of equivalent surface area. Based on the assumption that two metres of line are exposed at each side of the iceberg, the anticipated current flow through the ocean can be found as follows: The surface area of 2m of tube is $\pi d_{tube}\ l$, where l is 200 cm and d_{tube} is 0.317 cm. Hence the surface area is 199.5 cm^2. The radius of an equivalent sphere is found by setting $4\pi R_{equiv} = 199.5$, giving $R_{equiv} = 3.98$ cm. The resistance between two spheres immersed in a uniform conducting medium of resistivity r is given by Smythe (1968) as

$$R = \frac{r}{2\pi} \left[\frac{1}{2A} + \frac{1}{2B} - \frac{1}{S} \right], \tag{42}$$

where A and A are the radii of the two spheres and S is the separation of their centres. Since the electrodes are symmetric in the present configuration, the radii A and B can be each set equal to R_{equiv}, and the equation reduces to

$$R = \frac{r}{2\pi R_{equiv} S} (S - R_{equiv}). \tag{43}$$

Setting $S = 80$ ft, which is equal to 2438 cm, and R_{equiv} equal to the above value of 3.98 cm, yields an effective resistance between the two immersed electrodes of

$$R = \frac{23.81}{2\pi} \times \frac{2438-3.98}{2438 \times 3.98} = 0.95\ \Omega. \tag{44}$$

The voltage applied to the electrodes is determined by subtracting the voltage drop anticipated across the feeder and return lines from the power supply voltage (65 V). At a line current of 500 A (see scenario below), the voltage at the electrodes will be 65 - 24 = 41 V. Hence the current flow through the ocean will be 43 A. The above calculations reflect an optimistic viewpoint; that is, the anticipated losses to the sea will likely be higher if no precautions are taken to insulate the exposed portions of the circuit. The assumption that the surface area of the line is distributed spherically results in a higher than actual current density in the water near the electrodes. Hence the value calculated for the resistance is undoubtedly too high. Even the calculated loss of 43 A to the ocean is unacceptable. This loss increases voltage drop on the feeder lines and will reduce the cutting rate significantly. Precautions will therefore be taken to insulate all exposed components of the circuit. The cutting tube itself cannot be insulated since thick materials such as tape impede thermal ice cutting while thin materials such as paint, varnish, or silicone grease are rapidly removed by electrolytic action (see below).

5.0. Electrolytic Effects; Corrosion Control

Direct current flowing through an electrolyte causes an accompanying transfer of dissolved ions between immersed electrodes. Seawater is a good electrolyte and electrolytic transfer of metal ions from the immersed portions of an iceberg cutting line is to be expected. Copper ions are generally monovalent (Cu^+) and accordingly are released into solution at the rate of 2.37 g/hr when a current of 1 A flows. Since typical DC currents leaked through the ocean during cutting are estimated to be in excess of 40 A (see above), complete dissolution of portions of the cutting line can occur in a relatively short time period unless precautions are taken.

Electrolytic dissolving of a metal electrode occurs only when the electrode is at a net positive potential relative to nearby solution. The transfer of electrons from the positive electrode to external points in the circuit is accompanied by the release of metal into solution as positively charged ions (cations). An electrode at a net negative potential relative to nearby solution tends to reduce hydrogen, which is given off as bubbles (with seawater as the electrolyte, hydrogen is always reduced at the negative electrode; other solutions may precipitate reduced cations).

Painting, varnishing or greasing an exposed electrode immersed in seawater will not generally protect the electrode from electrolytic corrosion when significant DC potentials are applied. Very small currents leaking through such thin dielectrics result in minor electrolytic action. At the negative electrode, small bubbles of H_2 form under the protective coating, gradually expanding preexisting microscopic perforations and eventually lifting the coating from the metal surface. At the positive electrode, bubbles of O_2 or Cl_2 cause much the same effect, except that these more reactive elements tend to attack chemically the coating, rapidly destroying it. The effect is all the more intense in that the oxygen and chlorine are in fact initially formed as the strongly reactive atomic species, rather than as the less reactive diatomic molecules. Thick layers of plastic or rubber insulation would prevent this effect, but would also impede heat transfer to ice, thus potentially causing the cutting line to overheat. A critical thickness of TFE insulation could eliminate corrosion while still permitting adequate heat transfer (see the description of the proposed operational system in Chapter 3 above). However, time and budget constraints precluded having an insulated cutting line manufactured to the required specifications, and an alternative, less costly approach to corrosion control was adopted.

All that is required to eliminate electrolytic corrosion is to keep the cutting line at a net negative potential relative to contiguous and nearby seawater. A sacrificial electrode, deployed near the positive end of the cutting line and raised to a positive DC potential relative to all portions of the cutting circuit is the sole necessary modification to the system. Fig. 4 (following p. 50) shows the circuit diagram for the cutting system including a corrosion control circuit. The corrosion control potential is provided by two battery chargers each rated for 12 V and 30 A as shown in the diagram. In the actual cutting system used in the field demonstration, terminal A corresponds to a cylindrical sacrificial electrode 17.8 cm in diameter and 60 cm long, machined from a single block of aluminum. This sacrificial electrode was deployed over the side of the iceberg.

The "Y" configuration of the three resistances, R_1, R_2, and R_3 shown in Fig. 4 corresponds to the electrical paths through the ocean connecting the sacrificial electrode and the two ends of the cutting line. Resistance R_1 represents the internal resistance of the battery chargers, the resistance of the line connecting the battery chargers to the sacrificial electrode, and the ohmic loss in the ocean as current flows to the sacrificial electrode from both ends of the cutting line. Resistances R_2 and R_3 denote ohmic losses in the ocean along current paths to the positive and negative ends of the cutting line respectively.

The actual electric potential of the ocean, and in consequence the current density, in the region of the cutting operation is a complicated function of position. The potential of a given point in space is determined by the proximity of that point to the various electrodes, by the contact area of each electrode with the salt water, by the shapes of the electrodes and by their respective electric potentials. Analysis leading to the determination of the space-dependent ocean potential function is not feasible within the context of the present work. Indeed, the ocean potential also becomes a function of time as the cutting line progresses through the iceberg, since the line changes both in position and in area exposed to the salt water. Hence an accurate prediction of the potential would require a good knowledge of the underwater shape of the iceberg.

The electric potentials indicated on the circuit diagram (Fig. 4) are potentials calculated relative to the positive terminal of the welding machine. This terminal is defined to have zero potential. The two vulnerable points on the cutting line are represented by terminals B and C. Clearly, terminal C, the negative end of the cutting line, is safe from electrolytic corrosion since all immersed circuit components are at a lesser negative potential. Terminal B, however, lies in water which could have a net negative or positive potential, depending on the relative proximities and contact areas of the sacrificial electrode and the negative end of the cutting line.

The key to preventing corrosive destruction of the cutting line at the positive end is to ensure that the nearby ocean potential is net positive. Electrons will then flow from the copper line to the ocean, in the direction indicated by the arrow marked "*" in Fig. 4, and hydrogen will be reduced rather than copper oxidized. The potential in the water near B is controlled by the positioning of the sacrificial electrode (the closer the better provided that a short circuit is avoided), the potential of the sacrificial electrode, and the position and immersed area of the negative end of the cutting line. The potential of the sacrificial electrode is 24 V less ohmic losses developing in the circuit as current rises. Clearly, too much current in the corrosion control branch of the circuit can nullify the effect of the sacrificial electrode, and cause the potential of the ocean near electrode B to go net negative[1]. It is difficult on an *a priori* basis, without experiment, to quantify the magnitudes of the various factors in corrosion control discussed above and thereby design a failsafe corrosion control circuit. This difficulty remained, up until the time of the field program, a key weakness in the design of the demonstration version of the iceberg cutting system.

6.0. A Scenario for the Demonstration Cutting of an Iceberg.

The following is regarded as the most practicable scenario. The cutting line chosen across the iceberg will be approximately 23 m, so that allowing for an extra 30%, the length of the cutting tube will be 30 m. The jigger will be located as centrally as possible. The lengths of cable from the jigger to the electrodes are, on each side, 12m to the side of the berg, 3m to the water, and 20m to form the catenary and to allow complete cutting of the berg. Allowing for 30% extra for contingencies, the cabling from jigger to electrodes is 90 m. In addition, twice 100m is necessary to bring power from the ship to the jigger, if the ship is to remain at a safe distance from the iceberg. Hence the total length of electrical supply cable necessary is 290m.

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[1] Indeed, this happened during the field demonstration, and resulted in a premature termination to the cutting.

The resistance of the supply cable, at 0.157 Ω/km, is 0.046 Ω.
The resistance of 30 m of cutting tube is 0.0883Ω.
Hence the total resistance of the circuit is 0.134Ω.

The welding machine delivers 65 V.
Hence the current delivered is 485 A.
Hence the power dissipated in the tube is $485^2 \times 0.0883 = 20770$ W,
which comes to 6.92 W/cm.

Hence, in the scenario, the cutting tube delivers 6.92 W/cm, which gives a cutting rate of **0.43 hr/m**, or 8.6 hr to cut an iceberg 20 m thick.

7.0. Iceberg Fracturing System Components.

1): Power Supply:	Miller Electric Mfg. Co. welding power supply model MP-75E. Output 750 A at 100% duty cycle. Open circuit voltage = 80 V. Supplied by Canadian Liquid Air Ltd., St. John's.
2): Electric Generator:	Diesel powered, 3 phase, 575 V, 75 kVA. Supplied by Flygt Canada Ltd., St. John's.
3): 3 Phase Cable:	To link generator to welding machine. 50 ft, 4 No. 2 conductors. Supplied by Flygt Canada Ltd., St. John's.
4): Iceberg Jigger:	Helicopter deployed electrothermal ice anchor. 25 ton capacity. Supplied by ICE Engineering Ltd., St. John's.
5): Iceberg Cutting wire:	130 ft long copper tube. Made from electrical grade copper with O.D. 0.125 in. and wall 0.030 in. The tube wall is drilled with a sequence of fine holes for leaking antifreeze. Holes spaced to yield evenly distributed density of fluid flow through tube walls. Supplied by Small Tube Products Ltd., Altoona Pa.; customized by ICE Engineering Ltd., St. John's.
6): Coolant Feeder tube:	170 m of "Synflex" 3/16 in inside diameter plastic and nylon pressure tubing. Supplied by Tubecraft Atlantic Ltd., St. John's.
7): Feeder and Return Cable:	2 lengths No. 4/0 welding cable. Two lengths of 150 ft each run from an attachment point on the ice anchor to the ends of the cutting line. The other lengths of 330 ft each run from the ship to the jigger attachment point. Cable supplied by Canadian Liquid Air Ltd., St. John's.
8): Coolant and Antifreeze:	45 gal. industrial grade methanol. Supplied by Eastchem Ltd., St. John's.
9): Pump:	250 psi, 1.5 hp water pump with regulator 0-250 psi. Supplied by ICE Engineering Ltd., St. John's.

10): Hawser:	600 ft. 2 1/16 in diameter "Karat" twisted high-density polypropylene towing cable. Breaking strength, 50 tons. Manufactured by Elkem a/s, Norway. Supplied by IMP Ltd., St. John's.
11): Cutting Monitor:	To monitor the cutting rate, a thin plastic tube was connected to the upstream electrode, and connected on the support vessel to a tank of compressed air fitted with a pressure gauge. The cutting rate could be determined by reading the pressure with mild bubbling. With this arrangement the gauge can show the pressure of the tube exit, and hence the depth of the electrode in the ocean.

Backups

No backups were available for the welding machine. A 50 psi water pump was available to back up the coolant/antifreeze pump. Sufficient electrical-grade tubing was available for 10 cutting tubes of the proposed length. Welding cable was available in about 50% excess of anticipated requirements. Tow hawser was also available in about 100% excess of requirements.

As backup for the ice jigger, a Mark 3 ice anchor and support system, as tested by ICE Engineering Ltd. in 1984 off Flat Rock, Newfoundland, was available, although it was not mobilized. While this system has significantly greater logistics requirements than the ice jigger, and is somewhat slower, its bearing capacity is significantly greater, being rated at 125 tonne.

APPENDIX 2:

The Iceberg Fracturing Field Program

PRELIMINARY TESTING

A series of preliminary tests were carried out to confirm certain key aspects of the functionality of the hot wire system. The tests are enumerated and described briefly below. Results of the tests were not critical in system planning, as for the most part they simply confirmed parameters which could readily be calculated from standard tabulated data. The primary benefit of the tests was the familiarity gained with the major system components.

Initial test of cutting concept: an automobile battery was used to supply approximately 70 A to a 1.5 m long section of stainless steel cutting tube of diameter 0.3175 cm (1/8 in). The tube was supplied with tap water for coolant at a pressure of 0.27 MPa (40 psi). The tube showed no tendency to overheat even with no additional external cooling. When placed on the surface of a 1 m × 1 m × 0.5 m ice block the tube cut into the ice at a rate of approximately 3.5 cm/min.

Electrical test of full-scale cutting system: The welding machine selected for use in the field program was used to energize a 30 m length of non-electrical grade 0.3175 cm (1/8 in) copper tubing. The tubing was coiled and immersed in a test pool filled with brackish water for heat dissipation. Up to 30,000 W of electrical power was supplied to the tube. The system was cooled with water at 1.72 MPa (250 psi) pressure supplied by the jet pump selected for use in the field program. The system operated stably for a time period of approximately one hour, and the test was terminated at the end of that time without incident. During the test the ultimate 3 m of the line was removed from the pool and used to cut pieces from a large ice block. The line carried a mixture of water and steam in this section, and was observed to cut ice at rates as high as 30 cm/min.

Pond test: the welding machine powered by a 75kVA diesel generator was used to energize a 38 m (125 ft) section of cutting tube laid straight out on the flat surface of a frozen pond. Lead electrodes/weights were deployed in holes augured in the ice at either end of the cutting line. When the line was energized it cut at a rate of 5.1 cm/min (2 in/min, 10 ft/hour) through the ice cover of the pond, which was about 41 cm (16 in) thick. The line was cooled with methanol/water mixture (50/50). This test indicated that the line would sink uniformly into the ice, i.e. with the bottom of the slot flat rather than arched.

Antifreeze test: a 10% methanol - water solution was left in a freezer at -26 ° C and checked first at hourly intervals, then at daily intervals, and finally at weekly intervals. The material froze rapidly to form a soft slush. The consistency of this slush was preserved over a time period exceeding one month.

Corrosion control test: a piece of copper tubing equivalent to that in the cutting line was immersed in a 10 *l* bucket of seawater. A +12 V DC potential was applied to the piece of copper tubing and an aluminum bar served as the negative electrode. The copper was observed to dissolve entirely by electrolytic action, in less than five minutes. Silicone grease and paint were found to be completely ineffective in preventing the electrolytic destruction of the copper. A three-electrode configurtion was set up using two aluminum bars: one bar held at a potential of 0 V; one bar held at a potential of +24 V; and a piece of copper tubing held at a potential of +12 V. The copper underwent no electrolytic corrosion in this configuration. Hydrogen was evolved at the copper electrode indicating that it was at a net negative potential relative to the nearby solution.

Ocean ground test: Two 1.2 m ×2.4 m × 0.3175 cm aluminum sheets were immersed in the ocean about 7.6 m (25 ft) from shore at Middle Cove Beach, near St. John's. The water depth was about 1 m. Three plate separations were used. In each case the plates were laid flat on the seafloor.

Case 1: Plate separation, 24 m; voltage, 12.5 V DC; current, 25 A; hence a resistance of 0.5Ω.

Case 2: Plate separation, 12 m; voltage 12.5 V DC; current, 35 A; hence a resistance of 0.36Ω.

Case 3: Plate separation, 1 m; voltage, 12.5 V DC; current, 50 A; hence a resistance of 0.25Ω.

It was found that the current readings were not a function of the orientation of the plates in the water. The current was a weak function of immersed plate area; with one plate entirely immersed and the second plate 90% out of the water, the current was 70% of that obtained when both plates were fully immersed.

It was concluded that the ocean resistance is too high to permit the use of an ocean ground as a return link in the cutting system circuit for the field demonstration version.

ICEBERG FRACTURING SYSTEM COMPONENTS.

Components:

1): Power Supply:	Miller Electric Mfg. Co. welding power supply model MP-75E. Output 750 A at 100% duty cycle. Open circuit voltage = 80 V. Supplied by Canadian Liquid Air Ltd., St. John's.
2): Electric Generator:	Diesel powered, 3 phase, 575 V, 75 kVA. Supplied by Flygt Canada Ltd., St. John's.
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6): Coolant Feeder tube:	170 m of "Synflex" 3/16 in inside diameter plastic and nylon pressure tubing. Supplied by Tubecraft Atlantic Ltd., St. John's.
7): Feeder and Return Cable:	2 lengths No. 4/0 welding cable. Two lengths of 150 ft each run from an attachment point on the jigger to the ends of the cutting line. The other lengths of 330 ft each run from the ship to the jigger attachment point. Cable supplied by Canadian Liquid Air Ltd., St. John's.
8): Coolant and Antifreeze:	45 gal. industrial grade methanol. Supplied by Eastchem Ltd., St. John's.
9): Pump:	250 psi, 1.5 hp water pump with regulator 0-250 psi. Supplied by ICE Engineering Ltd., St. John's.
10): Hawser:	600 ft. 2 1/16 in diameter "Karat" twisted high-density polypropylene towing cable. Breaking strength, 50 tons. Manufactured by Elkem a/s, Norway. Supplied by IMP Ltd., St. John's.
11): Cutting Monitor:	To monitor the cutting rate, a thin plastic tube was connected to the upstream electrode, and connected on the support vessel to a tank of compressed air fitted with a pressure gauge. The cutting rate could be determined by reading the pressure with mild bubbling. With this arrangement the gauge will show the pressure of the tube exit, and hence the depth of the electrode in the ocean.

Backups

No backups were available for the welding machine. A 50 psi water pump was available to back up the coolant/antifreeze pump. Sufficient electrical-grade tubing was available for 10 cutting tubes of the proposed length. Welding cable was be available in about 50% excess of anticipated requirements. Tow hawser was also available in about 100% excess of anticipated requirements.

As backup for the ice jigger, a Mark 3 ice anchor and support system, as tested by ICE Engineering Ltd. in 1984 off Flat Rock, was available but was not mobilized. While this system has significantly greater logistics requirements than the ice jigger, and is somewhat slower, its bearing capacity is significantly greater, being rated at 125 tonne.

PERSONNEL FOR THE ICEBERG FRACTURING FIELD PROGRAM.

"I" indicates that the person was part of the iceberg boarding party during the iceberg fracturing field program, "D" that he was part of the boarding party for the demobilization.

1): Project Manager: Dr. P.H. Gammon (I,D);
2): ESRF Scientific Advisor: Dr. Langley Muir (D);
3): Project Scientist: Dr. J.C. Lewis (I,D);
4): Senior Technician: J.R. Youden (I,D);
5): Technicians: Dave Parsons, James Lee, Robert Power (I,D);
6): Assistants: Gary Dinn (D), R.E. Gagnon, T. Sheppard.

RECONNAISSANCE.

A week prior to the iceberg fracturing field program, an iceberg which was located in Witless Bay[1], Newfoundland, was surveyed from a light Zodiac boat and then boarded. It was verified to be suitable for the demonstration of the hot wire method; that is to say, it had a place suitable for a helicopter to land, its shape was such that a 30 m cutting line was sufficient to cut off a sizeable portion from the iceberg, and no

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[1] Witless Bay is a bay and a small fishing village approximately 30 km SSW of St. John,s, Newfoundland. It is readily accessible by road from St. John's. The bay is roughly in the form of a thin wedge, partly blocked across its mouth by a substantial island, Gull Island. The subsea topography makes Witless Bay a good iceberg trap: one deep and comparatively narrow channel leads into the bay from the NW, and terminates in relatively shallow (though navigable) water between Gull Island and the southern headland of the bay. The iceberg was located approximately 500 m from Gull Island at the time of the field demonstration. It had been observed to move in the days prior to the demonstration, and was subsequently observed to shift its position again, so that it probably was not grounded.

large underwater sills or rams were evident, which might hang up the weights on the ends of the cutting line, and so impede or prevent its penetration. A small ice anchor, consisting of a 3/4 in thick steel disk 6 in in diameter and with a 3/8 in diameter wire rope attached to the centre of the disk, was inserted into an auger hole 1.1 m deep. This hole was then packed with ice chips and filled with water.

An aerial reconnaissance was flown on the 7th of April, the day before the planned field program. The iceberg in Witless Bay was boarded again from a helicopter, the proposed position of the cutting line was confirmed, and a target circle for emplacement of the ice jigger was sprayed on the ice. A nearby but much larger iceberg was also boarded during the same reconnaissance. Although in our judgement its larger size rendered it less suitable than the first iceberg for the fracturing demonstration, a small ice anchor as described above was inserted into it as well, so as to provide an alternative to the first.

MOBILIZATION.

The mobilization of the apparatus for the iceberg cutting system took place on the 8th of April, 1985, the day before the field program. The apparatus was separated into two lots, one of which was loaded on the *M.V. Fogo Isle*, docked at St. John's, and the second which was loaded on several trucks and driven to Witless Bay on the morning of the field program. To supply the energy for the cutting line a Miller welding machine and a Flygt generator were placed on the rear deck of the *Fogo Isle*. The source of coolant and antifreeze for this line, four 45 gallon drums of methanol, along with the two pumps necessary to feed the methanol were also placed on the vessel. Three 30 ampere battery chargers were included for the corrosion prevention system. The pumps and the battery chargers were powered by a smaller Flygt generator. All of the above apparatus was secured to the deck of the *Fogo Isle*. A VHF radio was also located on the rear deck in order to provide communication with the other personnel involved in the program, namely those on the iceberg, on the shore, in the light "Zodiac" boat, and in the helicopter.

The remainder of the apparatus was transported over land to Witless Bay. This included all the equipment which was to be flown to the iceberg: the iceberg jigger, the cutting lines, the feeder cable bundle, the electrical cables and tubing to make the connections between the feeder cable bundle and the cutting line, and miscellaneous items and tools necessary to complete the setup as explained below.

COMMENCEMENT OF THE PROGRAM.

The *Fogo Isle* departed St. John's for Bay Bulls on the evening of the 8th of April. Personnel and observers boarded the *Fogo Isle* in Bay Bulls at approximately 05:00 on the 9th of April, while the remaining personnel met at the helicopter launch site in Witless Bay.

DEPLOYMENT OF THE EQUIPMENT.

At 06:00 the *Fogo Isle* arrived at the berg site in Witless Bay. Meanwhile the crew on the shore prepared to transport the apparatus to the iceberg. Firstly, the ice jigger was flown to the berg, then the boarding party of four persons, followed by four bundles of equipment. These loads contained the 4/0 electrical cable to connect the cutting line to the feeder cable bundle, the feeder cable bundle, two large boxes of smaller items (including tools, the cutting lines, the methanol line, the lead and aluminum electrodes, and extra lengths of 4/0 electrical cable), and finally the tubing for the depth measuring device and the buoys for the feeder cable bundle. Each of the four bundles was secured to an ice anchor with polypropylene rope before being released from the helicopter. All the the required equipment was on the iceberg by 07:30.

The feeder cable bundle was deployed by first laying it along the surface of the iceberg and attaching the No. 10 wire for the electrolytic corrosion system and the buoys. The buoys were separated by approximately 8 meters, so as to provide slightly less than neutral buoyancy, thus enabling the cable to sink below the action of the surface waves. A polypropylene rope was tied to the end of the feeder cable bundle and ferried from the berg to the *Fogo Isle* by the Zodiac crew. This rope was then used to haul the feeder cable bundle from the berg to the vessel.

Next, the cutting line was laid along the surface of the iceberg and the connections between it and the feeder cable bundle were made. A lead electrode was attached to each end of the cutting line, and then two lengths of 4/0 Superflex welding cable were used to complete the circuit. One end of each cable was bolted to an electrode while the other end was bolted to the 4/0 cable of the feeder cable bundle. The negative electrode was located on the high side of the berg so that it would remain out of the water longer and therefore aid in the reduction of the amount of electrolytic corrosion. The electrodes on the cutting wire were then insulated with PVC electrical tape. A 50 meter length of Shawflex tubing was connected to the methanol feed line in the feeder cable bundle and to the end of the cutting wire which was on the high side of the berg. Lastly, 60 meters of Parflex tubing was connected to the air line on the feeder cable bundle and then taped to the electrode at the lower side of the iceberg. This was intended to be used as a depth measuring device, simply by recording the hydrostatic pressure at the electrode.

After all of the connections had been made, the electrodes were lowered over the edge of the iceberg, along with the attached 4/0 cable, the Shawflex, and the Parflex tubing, which all hung in catenaries.

For the corrosion prevention system, a No. 10 wire was attached to a cylindrical aluminum electrode with diameter 19 cm and length 38 cm. The electrode was suspended over the edge of the iceberg near the positive electrode using a polypropylene rope which was threaded through a hole along the axis of the aluminum cylinder. This rope was secured to the small ice anchor.

This completed the deployment of the iceberg fracturing system. Then, all of the tools, reels, extra cables, and other miscellaneous items were gathered together and placed in two slings which were then carried to the *Fogo Isle* by the helicopter. The only pieces of apparatus left on the iceberg were the various cables and tubing running from the end of the feeder cable bundle to the cutting system, and the iceberg jigger which was used by the *Fogo Isle* to maintain station. The distance between the *Fogo Isle* and the ice jigger was approximately 100 meters. At about 11:25 the four person iceberg boarding party disembarked the iceberg by helicopter and returned to the *Fogo Isle*.

CONNECTIONS ON THE SHIP.

On the ship the methanol and power supplies were connected to the feeder cable bundle. For the former, a small 50 psi pump was used to pump methanol from a 45 gallon drum, through a 100 micron filter, to the 250 psi, 1.5 hp pump. The output of the high pressure pump was connected to a 100 micron inline filter and then to the methanol feed line on the feeder cable bundle. For the latter, the diesel powered generator was connected to the welding machine using a 3 phase cable consisting of four No. 2 conductors. In turn the output of the welding machine was connected to the two 4/0 cables in the feeder cable bundle using ground clamps. Any extra cable in the feeder cable bundle was eliminated thus reducing the amount of electrical resistance in the circuit.

COOLANT BLOCKAGE.

At about 12:00 the pumping system was turned on. However, no flow of methanol through the line in the feeder cable bundle ensued. The first diagnosis of the problem was that it was due to an ice blockage of the cutting line, since no power had yet been delivered to it. In fact, this had occurred on a preliminary field test on lake ice, where water in the cutting tube froze before it was energized, thus preventing fluid circulation. In this previous case, the line was energized for short periods of time (from 20 to 60 seconds) until the ice in the tube melted. A similar procedure was followed in the current case. However, in this instance, powerup resulted in a burnout of the copper cutting line. In consequence, it was decided to reboard the berg to lay another cutting line. The helicopter, which had returned to St. John's to refuel, was contacted by radio. Meanwhile, further inspection of the feeder cable bundle showed that it was badly crimped where it was tied to the rail of the ship. The cable was then secured in another position, and the rope around the crimped portion was removed.

RETURN TO THE ICEBERG.

The helicopter returned at 13:22 and the same four person field party that had boarded the iceberg that morning returned to deploy another copper cutting line. Once on the berg, the flow of methanol at all junctions was confirmed. The electrical cables which hung over the edge of the iceberg were hauled back onto the berg. The PVC insulation was removed from both electrodes and after the old cutting line had been removed from them, the new one was laid along the berg and secured to the electrodes. The methanol line was connected to the cutting line and the flow out of the end of the tube was confirmed. The electrodes were insulated again and then lowered over the edge of the berg. At 14:45 the crew on the *Fogo Isle* was notified to energize the cutting line, at a low power level, while the boarding party remained on the iceberg to ensure that no further problems existed with the coolant supply. At this point the positive terminal of the welding machine was connected to the deck of the *Fogo Isle* to assist in maintaining the cutting line at negative potential. Subsequently, two 12 volt battery chargers, which could supply up to 30 amperes, were connected in series to the aluminum electrode to raise it and the surrounding ocean to a 24 volt positive potential relative to the positive side of the cutting line. After approximately 40 minutes, all personnel on the berg returned to the ship. Since the sea had become too rough for the helicopter to land on the deck of the *Fogo Isle*, the field party was flown to a nearby beach, and then ferried to the ship in the Zodiac.

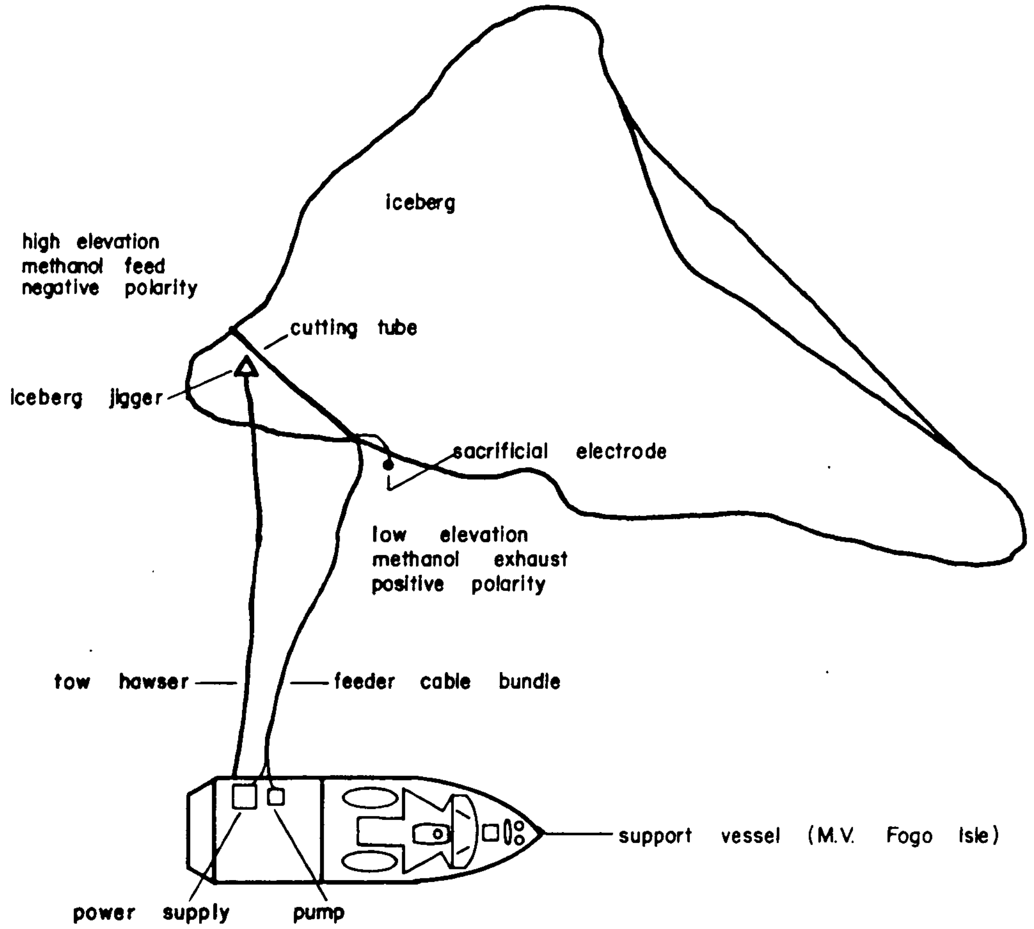
CUTTING THE ICEBERG.

A plan view of the ship and iceberg during the cutting, drawn to scale from photographs, is shown in Fig. 8.

While the line remained above the waterline, the system was operated at less than full power to reduce the possibility of the line overheating. At about 15:00 the system was running at 30 volts and 230 amperes, and the power level was increased in stages until the wire reached the waterline at 17:00, whereupon the welding machine was turned up to deliver maximum power, approximately 65 volts and 500 amperes. The amount of penetration up to this point can be estimated given that the iceberg was approximately 3 m and 10 m above the waterline at the two points where the cutting line hung over the edge of the berg. Full penetration by the cutting line of the above water portion of the high side of the iceberg, which was not visible from the vessel, was confirmed by the Zodiac crew.

CORROSION AND TERMINATION OF CUTTING.

The system ran for approximately another two hours, after which the copper cutting tube parted near the positive electrode due to electrolytic corrosion. The corrosion occurred after the current through the battery chargers supplying the corrosion control electrode exceeded their limit and an internal breaker tripped, thus shutting down the corrosion prevention system. The gradual accumulation of current on the corrosion control circuit corresponded to the cutting line breaking through the underside of the iceberg at the positive (near ship) end. As the line broke through, the surface area of copper exposed to the ocean increased, thereby reducing the resistance of the electrical path between the cutting line and the corrosion control electrode. At the time of failure of the corrosion control system total darkness prevailed, preventing any further work on the iceberg.



AERIAL PLAN VIEW OF FIELD DEMONSTRATION

Figure 8

DEPTH OF PENETRATION.

To determine the depth of penetration of the cutting line into the iceberg, a simple hydrostatic pressure measuring system was installed at the electrode nearest the ship, on the lower side of the iceberg. The apparatus for making the measurement, while properly set up on the first deployment of the cutting tube on the iceberg, did not survive the cutting line burnout and subsequent replacement. Accordingly, the penetration below the waterline was not measured. The cutting tube reached the waterline, a penetration of about 3 to 4 m, approximately two hours after powerup. Cutting was then continued, at full power, below the waterline for about 2.75 hours. Using the calculated penetration rate corresponding to the 500 A current measured on the cutting line, below-water penetration of about 7 m was realized. Thus a total cutting tube penetration of about 10 to 11 m along a 30 m front was thus realized during the demonstration.

STATIONKEEPING

A stiff breeze blew from the NW throughout the demonstration. Owing to this, and the consequent seastate conditions, stationkeeping by the *Fogo Isle* of sufficient accuracy so as to inflict no damage on the feeder cable bundle would have been of dubious feasibility had it not been possible to moor the ship to an ice jigger or ice anchor on the berg.

DEMOBILIZATION.

The demobilization of the iceberg occurred on the second day after the field program, i.e. on 11 April 1985. Five persons, including the ESRF scientific advisor, were flown by helicopter to the iceberg. A two person crew with a Zodiac stood by on shore.

In preparation for the cleanup of the iceberg, the three ice penetrating elements of the iceberg jigger were removed from the the ice and the Jigger freed. All the cables were hauled onto the surface of the berg where they were coiled and lashed together. The smaller items, such as the cutting line, the tubing, and aluminum electrode were placed in a sling. The helicopter then transported this apparatus back to land, thus clearing the iceberg of all the equipment that had been used by ICE Engineering Ltd. in the field program.

An inspection of the broken cutting tube revealed, as previously deduced, that electrolytic action had dissolved the cutting tube near the positive electrode. The line had thinned almost to nothing in that portion (about 30 cm long), which was retrieved still connected to the electrode. The electrode itself showed clear corrosion damage. The negative electrode and the cutting line connected to it revealed no visible signs of corrosion.

APPENDIX 3.

Ice Jigger Operations Manual.

The ice jigger, weighing approximately 250 kg and approximately 1 m in length, width and height, can be deployed either from a helicopter or, if the target iceberg is sufficiently small and allows a safe, close approach by ship, from a boom or crane on the ship. Helicopter deployment is the more generally applicable method, and the "launching pad" may be located on a supply ship or other support vessel, on a drillrig, or indeed on land.

Fig. 9 on the following page shows the ice jigger in deployment mode and in tow mode.

1. Helicopter Deployment.

The helicopter must give good visibility of the jigger, suspended approximately 50 ft. beneath. Pilots should be trained in use of the EMPRA basket, deployment of which is closely similar, in terms of weight, size, and operational envelope to the jigger. The helicopter will be equipped with a 50 ft. cable, attached to its release point under the fuselage.

The helicopter deployment of the jigger will proceed in five phases. The phases are:

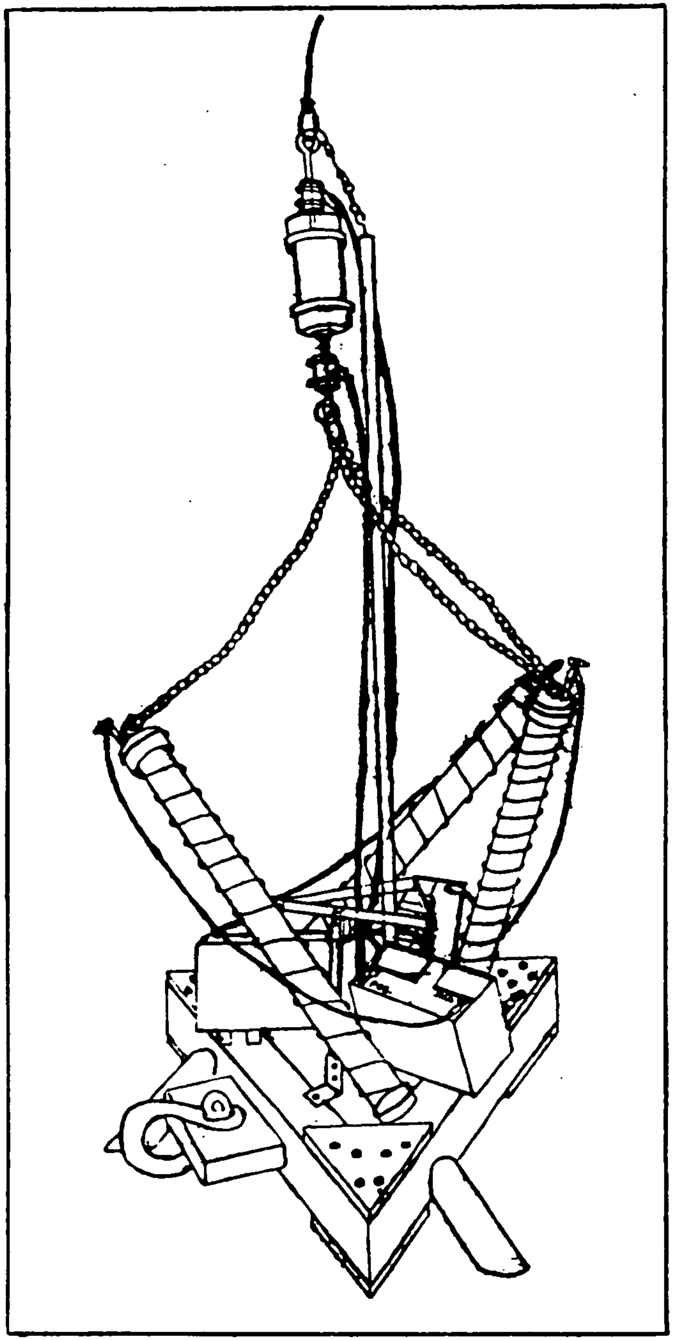
1: Arming of the jigger. The arming procedure is:
  a): The springs are connected to the bases of the penetrating elements;
  b): The tow cable is attached to the jigger and is carefully laid out over the launching pad;
  c): The safety lock on the electrical switch is removed.

The arming procedure is to be carried out only by a qualified technician.

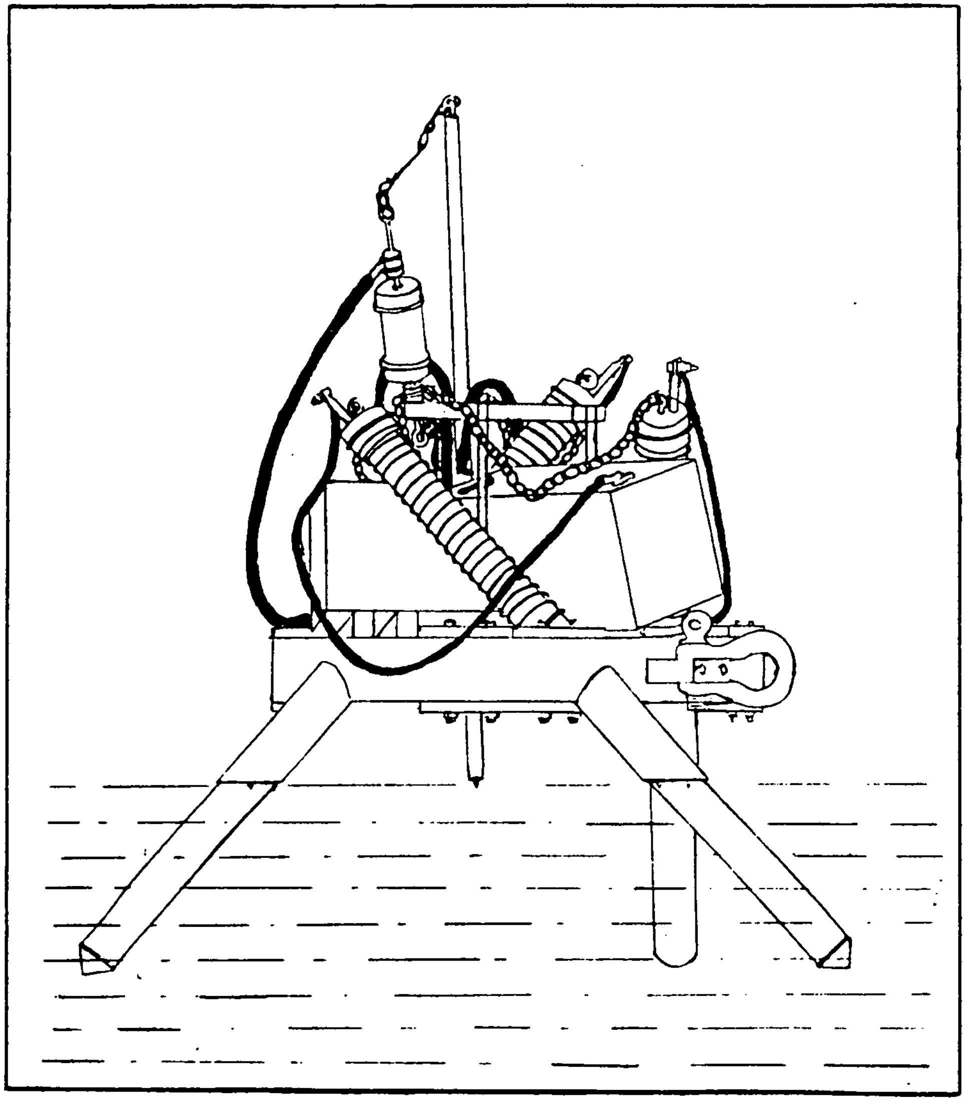
2: Connection to the helicopter. The lift cable from the jigger is connected to the sling attachment beneath the helicopter.

3: Liftoff. The helicopter will lift the jigger from the launching pad. The lift must be quick and smooth, and as nearly vertical as possible. Asymmetrical, dragging forces must be avoided.

4: Visual check. The helicopter will orbit or hover close to an observation point, such as a ship's bridge if that is chosen as the deployment platform. A qualified technician will check that the jigger has been lifted off correctly with the electrical switch engaged and with no premature activation of the penetrating elements. If the observer sees that the jigger is correctly set up he will signal the helicopter to proceed to the iceberg. Otherwise he will signal for the jigger to be returned to the launching pad for rearming. Radio communication is preferred, although predetermined hand signals could be used if necessary.



Deployment Mode



Tow Mode

THE ICEBERG JIGGER

Figure 9

5: Jigger emplacement. The emplacement of the jigger on the iceberg must be quick, smooth and sure, and as nearly vertical as possible. Asymmetric dragging forces must be avoided. Once emplaced, the helicopter must release the jigger promptly without lifting it off again. In the event that the emplacement does not proceed smoothly, either according to the knowledge or the opinion of the helicopter pilot, or as determined by observers on the deployment vessel, the jigger shall **promptly** be lifted off and returned to the launching pad on the deployment vessel.

2. Boom deployment.

The steps in a boom deployment are essentially the same as for helicopter deployment, but telescoped.

1: Arming of the jigger and attachment to the boom.

- a): The springs are connected to the bases of the penetrating elements;
- b): The tow cable is attached to the jigger and is carefully laid out over the launching pad;
- c): The jigger is attached to the boom cable, and all slack is carefully taken up on the cable without displacing the jigger.
- d): The safety lock on the electrical switch is removed.

Arming is to be carried out only by a qualified technician.

2: Liftoff and inspection. When informed that arming is complete, the boom operator will lift the jigger off the deck quickly and cleanly, and will hold it several feet above the deck for visual inspection. Following the inspection, the jigger technician will signal the boom operator either to return the jigger to the deck for rearming or to proceed with emplacement.

3: Emplacement. The boom operator will carefully swing the jigger over the side of the ship, being careful to avoid any contact between the ship and the jigger. The jigger shall be set down on the iceberg quickly and surely, but without roughness. In the event of a poor or uncertain emplacement, the jigger shall **promptly** be lifted off from the iceberg and returned to the ship. The decision to do so will be made by the jigger technician.

APPENDIX 4.

Archived Audiovisual Materials.

This appendix contains a catalogue of audiovisual materials produced in the course of this iceberg fracturing study. The materials are available for inspection at the:

Ocean Engineering Information Centre,
Memorial University of Newfoundland,
St. John's, Newfoundland,
A1B 3X5,
Telephone (709) 737-8377.

VIDEO:

One colour VHS - format video tape of approximately ten minutes duration summarizing the field program. The tape has a sound track but no commentary. It was edited from approximately six hours of videotapes made during the field program.

PHOTOGRAPHS:

All photographs were made by J.C. Lewis using a Nikon F3 35mm camera.

A. Pond test.

1. General arrangement showing pond, equipment, and truck with generator and welding machine.
2. Shows penetration of the cutting line into the ice.

B. Preliminary Reconnaissance.

3. Iceberg and Gull Island.
4. View of iceberg showing circle to guide pilot in jigger placement.

C. Field Program.

5. Preparing the ice jigger.
6. Attaching the jigger to the helicopter.
7. Liftoff of jigger.
8. Jigger and uncoiling tow hawser.
9. Helicopter, jigger, and tow hawser at altitude.
10. Jigger on iceberg with the *M.V. Fogo Isle* in the background.
11. *Fogo Isle* connected to the jigger.
12. Slinging equipment to the berg.
13. Ice jigger under tension.
14. Electrical return cable, cutting tube, and electrode connection immediately prior to deployment.
15. Deployment of the anticorrosion electrode.
16. Final assembly with the *Fogo Isle* in the background.
17. The cutting line and the jigger, after deployment but before powerup.
18. Removal of excess equipment before powerup.
19. The generator on the *Fogo Isle*.
20. The welding machine at low power.
21. The jigger and feeder cable bundle spool as seen from the *Fogo Isle*.

D. Demobilization.

22. Iceberg with jigger and feeder cable bundle spool.
23. Jigger, spool, and electrical return cable; the tow hawser can be seen in the water. The electrode connecting the electrical return cable to the cutting tube was not visible, and hence was obviously well below the surface.
24. Closeup of above.
25. Preparing a slingload of equipment for removal.
26. Removal of the ice jigger from the iceberg.
27. Witless Bay. The jigger in a half-ton truck, with bystanders, as seen from the helicopter on return from the iceberg.

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