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Novel Countermeasures for an Arctic Offshore Well Blowout

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Environmental Impact Control Directorate
August, 1977

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NOVEL COUNTERMEASURES FOR AN ARCTIC OFFSHORE WELL BLOWOUT

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FOREWORD

Arctec Canada Limited compiled this report under contract to the Environmental Emergency Branch of the Department of Fisheries and the Environment. Mr. W.J. Logan of this Branch supervised the work as scientific authority.

The undertaking of the Beaufort Sea Project by the Department of Fisheries and the Environment in 1974 arose from interest expressed in determining Canada's capabilities in counteracting oil spills in the Arctic environment. The findings of the Environmental Emergency Branch's portion of the Project revealed that Canada's capabilities in this field at that time were very limited.

Therefore, in an attempt to generate more thought on this subject, the Department issued a contract in 1976 to two consulting engineering firms, Arctec Canada Limited and Environmental Applications Group Limited, whose mandate called for the implementation of a means by which new ideas could be generated in the furtherance of Canadian oil spill technology, specifically applicable to the Arctic environment. An innovative "think tank" operation ensued. The two consulting engineering firms invited various representatives of various groups, such as the Federal Government, the oil industry, and private contracting and consultant firms, to a brainstorming session which met on a weekend during January, 1977. In the belief that professional persons outside the oil business could stimulate fresh outlooks, a doctor, marine biologist and architect accompanied this group by invitation as well. The result of this "think tank" session was the promulgation of approximately 150 new ideas and this report, then, is a compilation of the evaluations on various theories put forth.

ABSTRACT

The problems of cleaning up oil spilled by an offshore well blowout in the Arctic are reviewed. In-situ burning is recommended as the most promising disposal technique. Various techniques are proposed for holding the oil in a burnable layer. In calm conditions a deep-skirted boom may be suitable, but a floating cargo net is shown to be more suitable for up to 80% ice cover. For 80-100% ice coverage, it is demonstrated analytically and experimentally that oil floating amidst the ice is burnable. In the presence of large floes, techniques for breaking up the ice are proposed to allow gas to escape and oil to be burned.

RÉSUMÉ

Les problèmes de nettoyage des hydrocarbures libérés lors d'une éruption incontrôlée d'un puits sous-marin dans l'Arctique sont examinés. Le brûlage sur place est considéré comme la méthode d'élimination la plus prometteuse. Diverses techniques sont proposées pour retenir les hydrocarbures en une couche brûlable. Lorsque la mer est calme, un barrage à jupe profonde peut être approprié, mais un filet d'éligue flottant s'est révélé préférable avec jusqu'à 80% de glaces. Lorsque la couverture de glace est de 80 à 100%, l'analyse et l'expérience démontrent que les hydrocarbures flottant entre les glaces peuvent être brûlés. En présence de gros floes, le bris de la glace est proposé afin de permettre aux gaz de se dégager et aux hydrocarbures d'être brûlés.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 PRINCIPLE FINDINGS - A SUMMARY

A review of the conditions to be expected at the site of an Arctic well blowout shows that the techniques and equipment employed in cleaning up temperate region oil spills are largely inapplicable in this environment. The development of novel countermeasures specifically for Arctic conditions starts with a general survey of the problem, considering the entire range of possible disposal, storage and transportation options. Only in-situ burning survives this analysis as a feasibility based on current technology and promising some degree of applicability through the range of anticipated ice conditions.

The chemistry of burning dictates that the oil be contained in a layer thicker than its natural equilibrium slick thickness, but again, the standard techniques for retaining a thick layer are difficult to apply in the Arctic. Accordingly, two devices were devised to overcome the radial currents generated by the blowout plume and hold a calm layer of oil near the blowout source for burning. The first is a ring of fireproof booms 30 m in diameter supporting a skirt 10 m deep, which turns under the surface currents to form an eddy containing an oil-water suspension, while the oil is burned in a thin stagnation ring on the surface. This device interacts strongly with ambient winds and currents and is best suited for sheltered situations.

The second device is a floating "cargo net", made of 7-cm polypropylene rope, which is deflected by ambient currents in the same manner as the blowout plume. The mesh of the net provides calm pockets on the surface where the floating oil collects sheltered from the radial eddies of the blowout and where the oil can be burned.

In circumstances of >80% ice cover, the ice itself acts much like the net in providing sheltered leads. Laboratory tests show that the oil burns easily even in very narrow leads within thick ice. At 100% coverage, however, the key objective becomes the simple release of blowout gas to limit spreading of oil. This may be possible through bombing to break up the ice in advance of its moving over the blowout. If the movement is less than 2 km/day, the gas bubble may be able to release itself through the newly refrozen leads. In some cases it may also be possible to encourage thermal cracking, but this is less certain.

The techniques proposed show promise of disposing most of the oil produced by an Arctic well blowout in conditions from open water to almost complete coverage of large floes. Further work is required, however, to quantify the final designs and costs of the proposed devices.

1.1 Conclusions

1. In-situ burning is the most promising technique for cleaning up oil spilled by an offshore well blowout in the Arctic.

2. The oil will burn completely if it can be contained in stable pools at least 5 mm thick and at least 670 m^2 in area per m^3/min of oil flow.

3. In shallow, current-free locations, a fire-proof boom with a skirt 10 m deep can contain the oil for complete in-situ burning within 15 m of the blowout site.

4. In deeper waters where current is present, a small dome could form a bubble ring with the blowout gas, and thus contain the oil for burning.

5. A polypropylene net is an easily deployed containment device having the capability of retaining oil for complete in-situ burning in the currents, water depths, ice conditions and winds experienced in the Beaufort Sea.

6. At ice concentrations >80%, the ice itself will provide a barrier suitable for retaining oil for burning.

7. Burning of oil in small pools and channels in broken ice is feasible, although rates of flame propagation will be as low as 0.8 cm/sec. The quenching effect of the ice is insignificant.

8. In landfast ice the burning oil from a blowout can melt ice fast enough to maintain itself in the face of expected ice motion.

9. In moving pack ice, semi-continuous icebreaking will be required to release the blowout gas and allow the oil to burn in-situ. This could be accomplished through aerial delivery of penetrating masses or military bombs, although 430-kg projectiles are required for 3-m multi-year pack ice.

10. Gas could be released from beneath the polar pack by thermal cracking. The approach is theoretically well founded, but substantial uncertainty remains in the selection of a snow-removal system to produce this effect.

1.2 Recommendations for Further Study

1. Burning of crude oil results in large smoke plumes from incomplete combustion. The ultimate fate of these plumes in the Arctic environment has not been adequately documented. Accomplishing this would require computer-based modelling techniques given the region's meteorological characteristics. In addition, it is apparent that the environmental effects of the fallout or partially burned hydrocarbons have not been studied adequately. Such products would possibly alter the albedo of the area's snow cover, result in harmful effects to plant, animal and marine species or even induce detrimental health effects within humans.

2. The ice, wind and current compliance of the net and deep-skirted boom devices should be verified in model scale.

3. Deployment techniques and anchoring systems for the net and deep-skirted boom should be developed and tested.

4. The deployment, dynamics and anchoring of the net should be studied in deeper waters representative of the eastern Arctic.

5. The interaction of the oil and gas phases of a blowout plume with ambient sea currents should be analytically investigated further and in model scale so that the bottom-to-surface path of deep-water blowouts can be predicted more confidentally.

6. The burning of floating oil among broken ice should be studied more thoroughly in larger scale.

7. The icebreaking ability of the blowout plume should be quantified experimentally.

8. Oil released into the open water undergoes both physical and chemical changes. Most important of these alterations is the loss of the lighter ends resulting in residues with higher specific gravity and viscosity. Further examination of the required oil characteristics for sustained burning would be warranted. Such studies could investigate the likely physical and chemical oil properties over time in the Arctic environment and evaluate the concept of oil burning and its limitations as an oil removal method in the Arctic.

2 INTRODUCTION

Ever since the inauguration of drillship operations in the Beaufort Sea, considerable attention has been devoted to modifying temperate region oil spill cleanup technology for the Arctic situation. Special Arctic booms and skimmers have been adapted from conventional designs and are now deployed in the North. Nevertheless, these developments have been made in full realization of the fact that they provide only a modest extension of the equipment's warm, calm, open-water capability. There is no pretense that these partial solutions address the problems of winter operations, shear zone ice, or blowouts under the polar pack. Cleanup technology for these situations will require departures from temperature region approaches, that is to say, designs and techniques specific to the unique northern situation will be essential. Such has been the orientation of this study.

This report will review the conditions observed in the Beaufort Sea exploration area to develop the set of constraints applicable to a cleanup system for this environment. The various alternative cleanup strategies will then be compared in light of these constraints and a few of the most promising strategies will be isolated. Specific hardware and techniques for implementing these strategies will be examined and preliminary engineering results and cost estimates will be presented.

3 THE CLEANUP ENVIRONMENT

3.1 The Arctic Marine Environment

The Beaufort Sea, site of the current Arctic drillship exploration, includes the waters off the north coasts of Canada and Alaska, bounded on the east by Banks Island and on the west by the Chukchee Sea. The present oil-lease area in the Southern Beaufort Sea extends from the northwestern end of Banks Island to the Alaskan border. The area of immediate concern is 128°W-140°W south of 72°N.

3.1.1 Atmospheric conditions. No substantial information has been published on air temperatures offshore. However, during the summer the temperature is less than that onshore and remains about the same as temperatures onshore during the winter.

The daily mean temperatures (°C) at Tuktoyaktuk are:

January	−29	April	−18	July	+7	October	−9
February	−31	May	−7	August	+4	November	−21
March	−21	June	+2	September	−1	December	−26

The area can be referred to as a "polar desert" as precipitation over the Beaufort Sea is less than 13 cm annually. The mean number of days with measurable rainfall is less than 10 offshore. Along the coast the annual mean snowfall is about 65 cm, with the mean number of days with measurable snowfall being only 30.

Beyond the continental shelf velocities are about 60% of coastal areas. Mean hourly wind speeds (knots) at Inuvik are:

January	3.5	April	6.1	July	6.5	October	5.2
February	3.5	May	7.0	August	6.1	November	3.9
March	5.2	June	7.4	September	5.7	December	3.9

The autumn months frequently have severe storm activity. Wind direction is very important in determining ice movement with westerly winds driving ice landward. The monthly wind roses for Inuvik are presented in Figure 1.

From May to early August the area experiences daylight or twilight, but from mid-November until the end of Jaunary virtual darkenss prevails.

3.1.2 Oceanographic conditions. The main physiographic features of the coastal Beaufort Sea shown in Figure 2 are as follows:

1. Continental shelf (depths <200m) extending 110 to 150 km offshore.
2. Continental slope (depths <200m-1,000m).
3. Mackenzie (Herschel) Canyon transecting the continental shelf near 138°W in a V-shaped canyon.

Ocean currents beyond the continental shelf flow generally in a clockwise direction due to the Beaufort Gyre and their velocities usually range from 1 to 5 cm/sec, but may be considerably greater.

On the continental shelf the wind plays an important role in driving currents, as does freshwater inflow from the Mackenzie River.Surface currents are highly variable, but easterly and westerly currents of up to 60 cm/sec (1 knot) have been observed.

The tides in these waters are predominantly semi-diurnal and most offer range from 0.3 to 0.5 m. However, tides of up to 1.0 m have been reported.

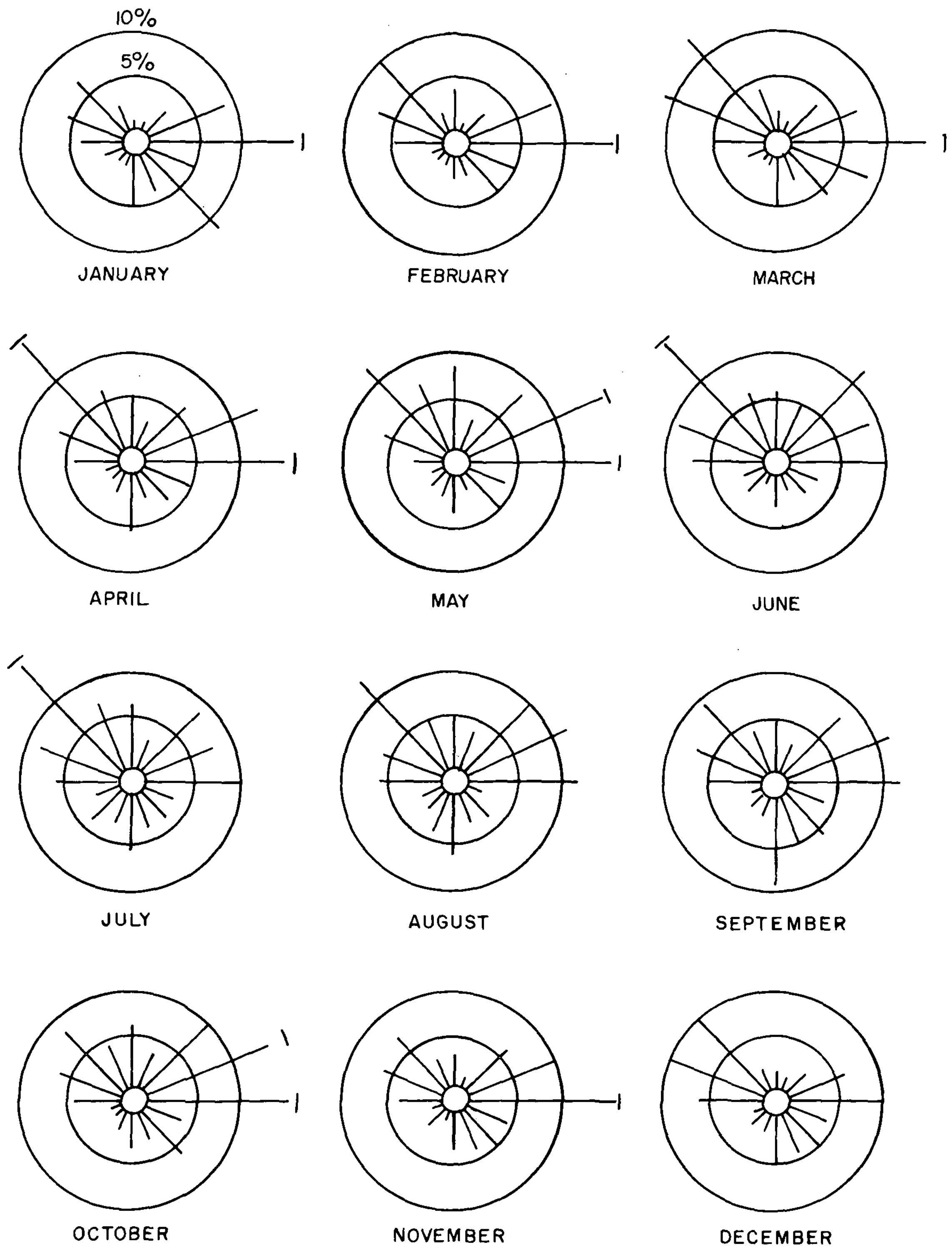


Figure I. INUVIK WIND ROSE

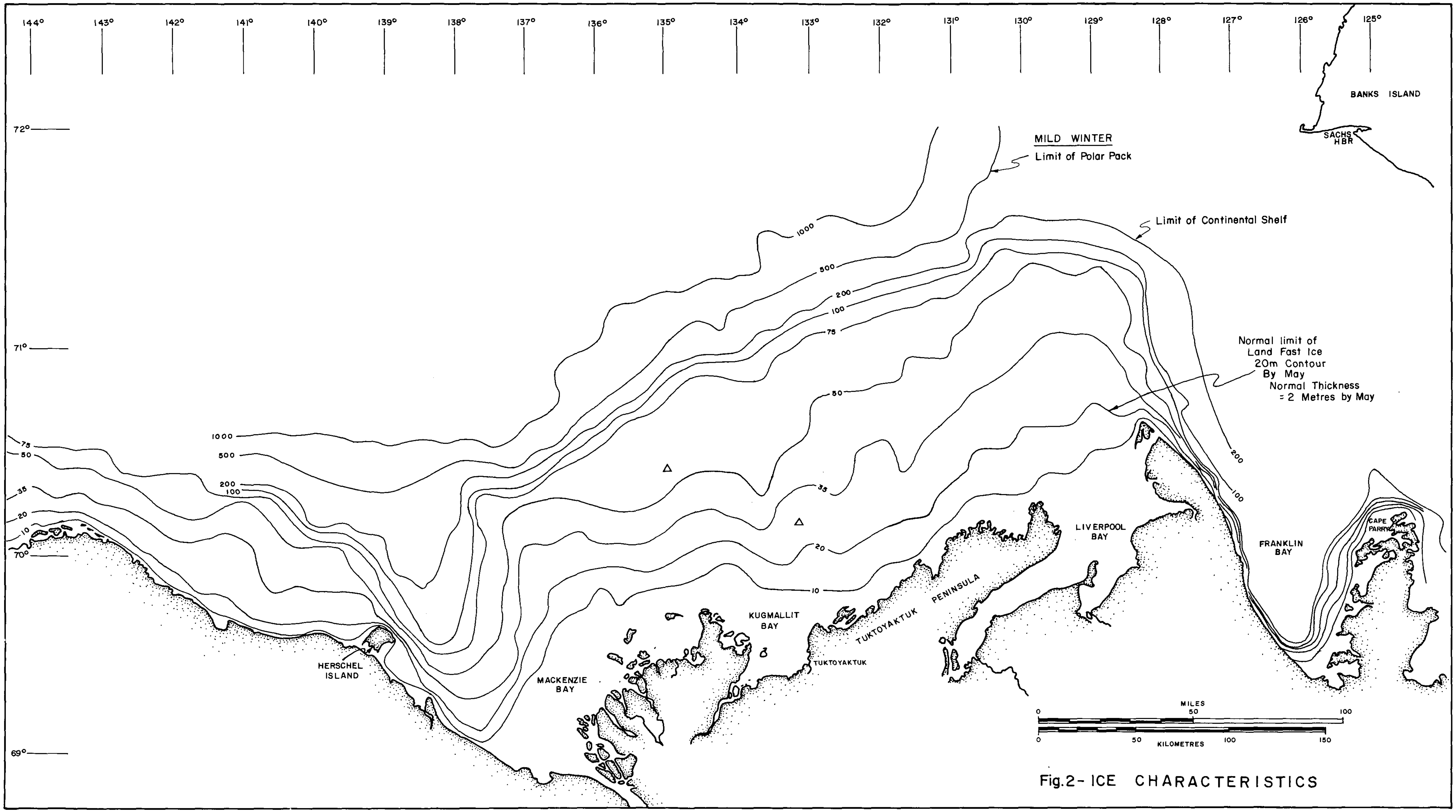


Fig.2- ICE CHARACTERISTICS

Wave heights depend on wind speed, direction, fetch and water depth, and extreme ones occur only in open-water conditions between July and October. Wave heights of up to 5 m at water depths less than 35 m, and 10 m at greater water depths, are considered extreme. More common wave heights are 2 m at water depths less than 20 m, which increase to about 3.5 m at 75-m depths where ice is present.

3.1.3 ***Ice conditions.*** The ice begins to clear north of Cape Bathurst during the second half of May and by mid-June in the southern part of Mackenzie Bay. The landfast ice has usually disappeared by July 9, and by the end of the month ice concentration is reduced to less than one-tenth within the entire area from Herschel Island to Sachs Harbour on Banks Island. Minimum ice cover exists on September 17, after which concentrations rise to four-tenths over the main areas by October 15 and seven-tenths by October 22.

Figure 3 shows a ''typical'' ice concentration cycle for an area on the continental shelf in the vicinity of the current drillholes 1 and 2. Areas north of this have greater ice infestation, while southern areas experience better ice conditions. In general the conditions remain constant in an east-west direction.

The winter ice cover consists of three zones:

The *Landfast Zone* is a continuous sheet of normally smooth ice stretching from the shore to anchoring points on grounded pressure ridges or ice island fragments. Its outer edge generally coincides with the 18-to-20-m depth contour, and its outer portions may include heavy ridging or rubble fields generated by early winter storms and subsequently ''frozen in place''.

The *Seasonal Pack,* or shear zone, is found from the seaward edge of the fast ice to roughly the edge of the continental shelf. It is a zone of rapidly deforming, heavily ridged and highly irregular ice acting as a boundary layer between the circulating ice of the Beaufort Gyre and the fast ice. First-year ice predominates within this type of region, but multi-year floes and ice island fragments are evident.

The *Polar Pack* is one which extends further into the Arctic Basin and which during winter is composed of multi-year floes with first-year ice growing and sandwiching between them. Its long-term average motion is clockwise gyral circulation, but on a time scale of days the motion is very complex and irregular as it is governed by the wind stress field.

In summary, the fast ice breaks up and disperses, and an open-water zone may extend up to 200 km from the coast, although it is always subject to closure when storms drive the polar pack shoreward.

The landfast zone begins to form early in October immediately adjacent to the shore and typically extends to about the 20-m seabed contour by spring. The sheet tends to be constrained by irregularities in the shoreline and movement is generally limited during the winter. Depending on atmospheric conditions at the time of freeze-up, isolated remnants of second and multi-year ice can be locked in the sheet.

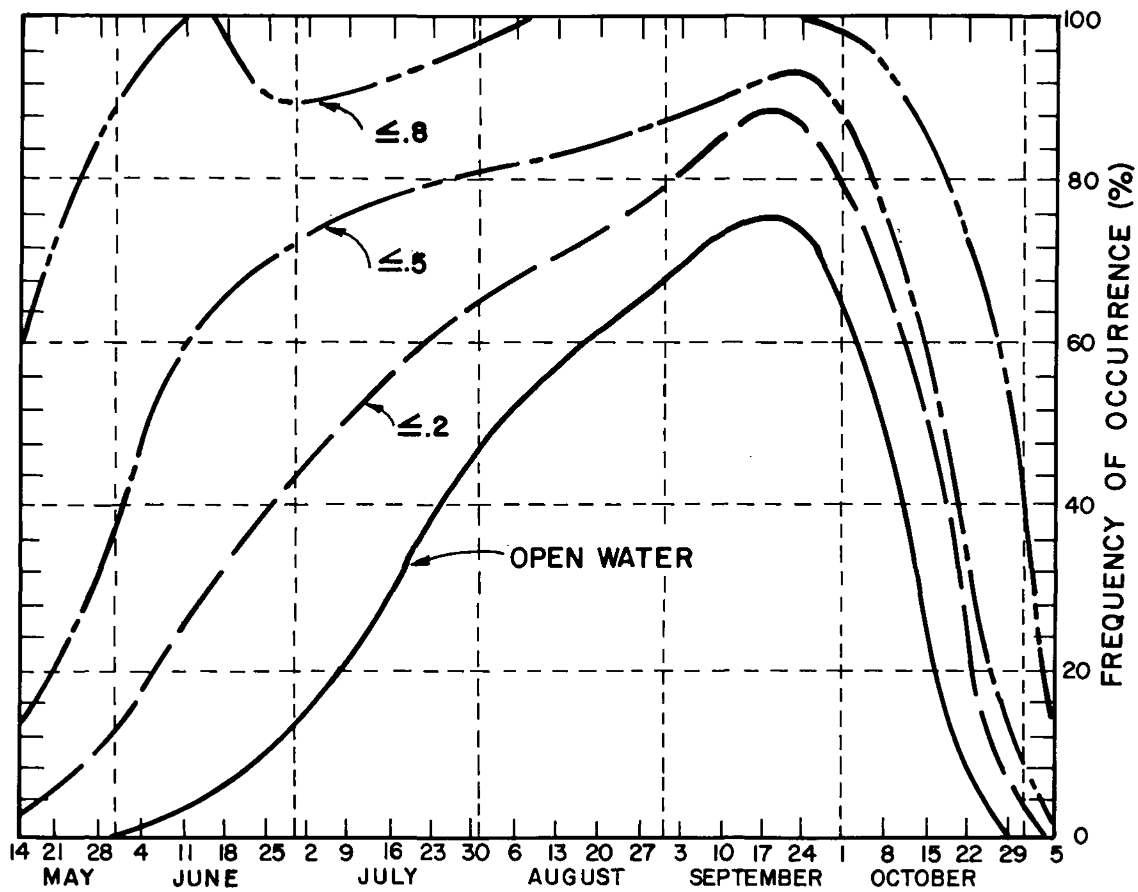


Figure 3 - TOTAL ICE CONCENTRATION

The near offshore area from Richards Island to Cape Bathurst and Cape Kellett including the approaches to Amundsen Gulf.

By late December the sheet is normally about 100 cm thick and maximum ice thickness is achieved around mid-May. Varying considerably between locations and from year to year, this ice sheet typically measures 2.0 m, although variations exceeding 0.5 m have been observed.

Due to the high level of radiation in the spring, melt pools quickly develop and signs of deterioration are normally evident by early June. Most areas are clear of ice by the middle of July.

As multi-year floes are driven into the fast ice, rafting or hummocking occurs, particularly in the fall when the sheet is thin and least resistant to deformation. The severity and duration of the pressure willdetermine the size and extent of the resulting ice features. Typically, free-floating ridges have sail heights of about 3 to 5 m, although much larger sails have been observed on grounded ridges. Leads and cracks open as the pressure is released.

The seasonal pack is essentially a transition zone between the fast ice and the polar pack. It contains both first-year and multi-year ice in various stages of consolidation, depending on the time of year and conditions. The seasonal pack moves primarily in response to motion in the polar pack. Like the polar pack, motion is predominantly in a westerly direction. The mean net long-term winter ice velocity is in the order of 2.5 to 3.0 cm/sec, or about 2.5 km/day. The width of the seasonal pack varies considerably, but can extend up to several hundred kilometres. During the summer the seasonal pack, driven by offshore winds, tends to hug the polar pack, while in the winter it is forced in against the fast ice. Periodically it will drift away from the fast ice and large recurring leads open, such as the one off Herschel Island.

The seasonal pack is the most dynamic of the three zones. In the fall loose ice is progressively compressed against the fast ice. Due to rotation of the permanent polar pack, slippage occurs in a narrow band at the boundary between the two zones. As the stress intensifies, the ice begins to shear. Shear ridges result, or if the pressure is sufficiently great, massive hummock fields form. Since the shear rate is considerably greater in the immediate vicinity of the boundary, both the size and density of ridges are higher in this area; these decrease towards the polar pack. The ridges typically measure up to 4 m high, but sails over 12 m have been reported. As a result of the continuous shear action, the new ice, which tends to be the weakest point in the matrix, is often deformed and open water is common even in the depth of winter.

The polar pack generally lies beyond the continental shelf, but can be driven towards the shore at any time by high winds. The average drift is about 2% of the wind velocity, and due to the coriolis effect, is inclined at about 30 degrees to the wind direction. During the summer the prevailing flow is to the north and the pack can reside 300 to 400 km offshore. In the winter the direction tends to be reversed and the pack moves towards the coast. The degree of penetration of the pack will depend on conditions at the time of invasion. If it occurs near freeze-up before the fast ice can develop any resistance, as was the case in 1971, the pack can approach within several kilometres of the shore. The principal restriction is generally the depth of water. Once the fast ice has thickened, it tends to hold back the advancing pack.

During the winter approximately 60% to 70% of the area of the polar pack is multi-year ice, 1% to 5% is open water and the remainder is first-year ice. There is considerable variation in ice thickness ranging from thin, first-year ice in refrozen leads to multi-year pressure ridges, which can exceed 45 m in total thickness. By the end of the winter undisturbed first-year ice is typically about 2.0 to 4.5 m thick. The salinity of multi-year ice progressively decreases with time due to leaching.

The density and size of ridges varies considerably between locations and from year to year. A typical density would be in the range of 10-20 ridges per kilometre. The average ridge height is about 3 m. The ratio of the keel-to-sail height for free floating multi-year ridges is approximately 3:1.

The drift of ice floes is related to wind pressure as well as oceanographic current. However, ice floe drift tends to be more dependent on surface current than on wind. To date, there is little consistent quantitative data available on floe speed and direction.

The size distribution of floating Arctic ice is weighted toward small floes and ice cakes, but the mix varies with the season. Figure 4 shows a "typical" floe size distribution for the same area assumed for Figure 3. No data is available concerning the median floe size of the offshore pack in May, but for argument's sake, let us assign 20 km as a size estimate. After several weeks, further deformation will have occurred. The fast ice may have begun to break up and in general, the majority of the floes will have broken at least once because of impacts with other floes or because of thermal stress, so that the median size will not be in the 10-km range. The number of floes will have doubled and the number of 20-km floes remaining will have decreased markedly. In another few weeks the median size may decrease to 1 km. Using this argument the following is stated:

- the average floe size of pack ice decreases progressively during the summer;
- the total number of floes increases in early summer as the large floes break up, but subsequent melting decreases the numbers;
- there will be a period in early summer when big floes are predominant, then their population will decrease steadily. Medium floes will predominate somewhat later than big floes; then they too will decrease in number;
- because of floe thickness and ice strength, it is likely that the variations with time of the population of first-year floes of a specific size is somewhat different than that of old floes. Their numbers should peak earlier and decrease quicker than stronger old ice. However, the old floes constitute less than 10% of the total pack in even the worst years.

Extensive scours are produced on the sea bottom of the shelf by the movements of sea ice (see Figure 5). These are produced mostly in the winter and spring by the grounding of under-ice projections such as pressure-ridge keels. Scour trenches generally do not exceed 2 m in depth, but in places are as much as 6 m deep. Scours in waters deeper than 50 m were probably formed during the end of the glacial period when the sea level was much lower than at present. Scouring is common in water depths of 15 m to 45 m with the maximum activity at 30 m within the transition zone. The deepest pressure-ridge keel so far observed in the Arctic Ocean was 49 m. Each point on the 27-m depth contour

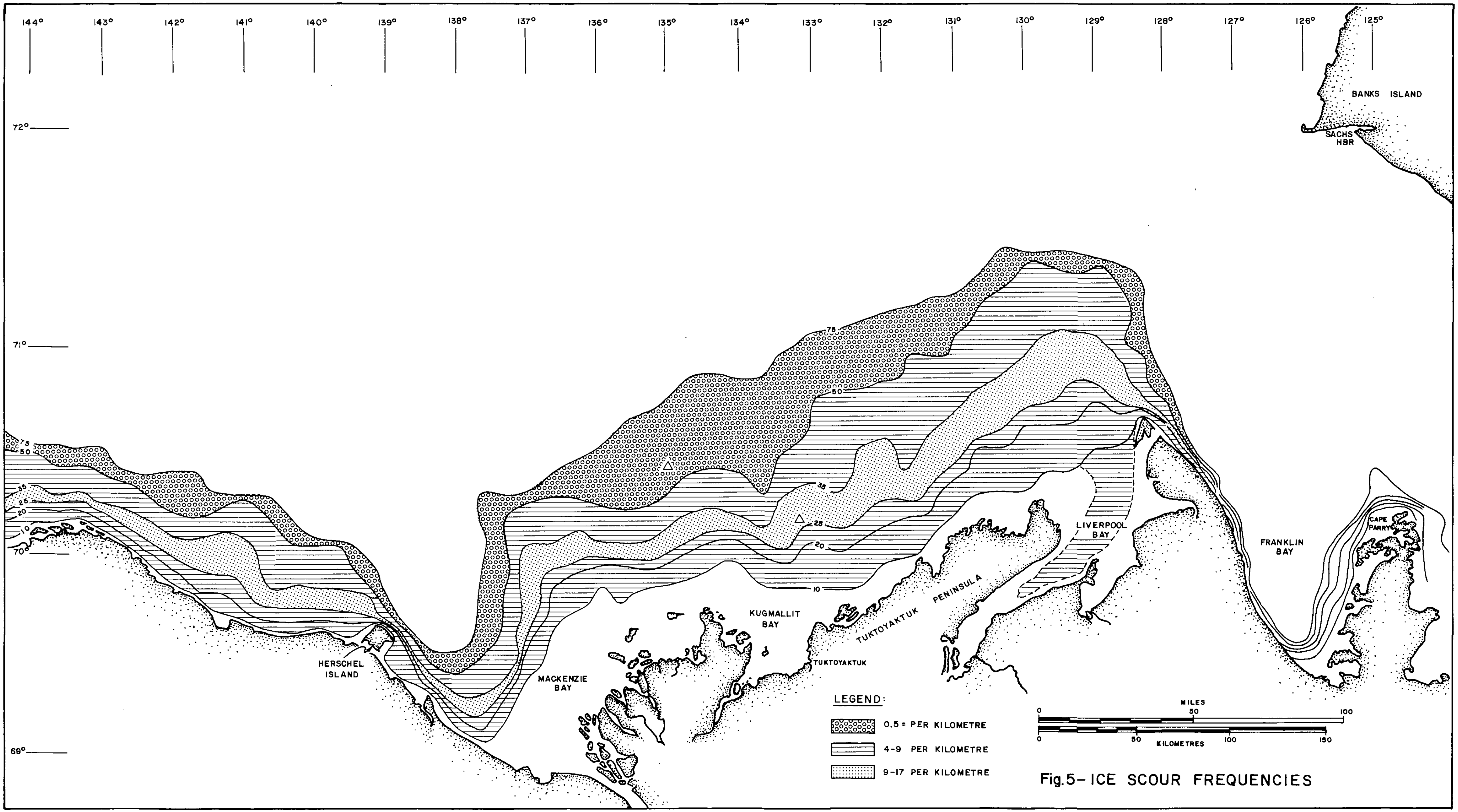


Fig. 5 - ICE SCOUR FREQUENCIES

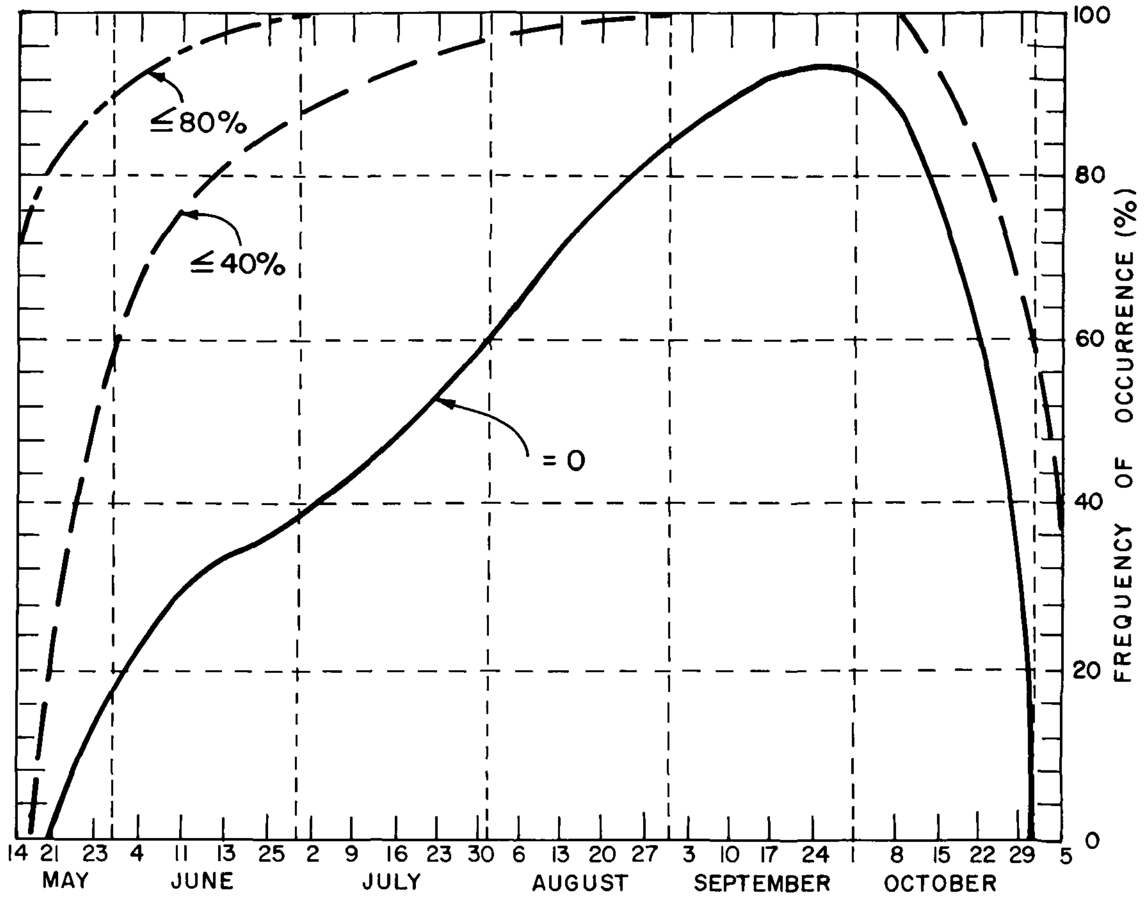


Figure 4 - FREQUENCY OF OCCURRENCE OF FLOES :
(Medium size or greater - over 100 metres)

on the continental shelf is likely to be contacted, but not necessarily scoured, once a year, unless protected by bottom topography.

3.2 A Hypothetical Blowout Scenario

An offshore blowout can take two basic forms. It can result from a) a casing, blowout preventer (BOP) or other mechanical failure, in which case the oil and/or gas is likely to be released at the wellhead, or b) the drill hole can interconnect the reservoir and faults or weak strata at a higher level, thereby providing an alternate route to the surface. It is felt that such a blowout would normally be within approximately 200 m of the wellhead.

The conditions assumed for the oil and gas flow are those of 2,500 barrels/day (398 m^3/day) reducing to 1,000 barrels/day (160 m^3/day) after one month, thereafter remaining constant. A constant gas content of 22.7 m^3/barrel when expanded to atmospheric pressure is assumed.

The general effect of such a blowout is a rising mixture of oil droplets and gas bubbles, which entrain the surrounding water to form a buoyancy-driven plume. The oil flow rate is less than 1% of the gas flow and its contribution to the total buoyancy can be considered negligible. On the other hand, the oil phase embodies most of the chemical potential of the mixture.

Topham [12.9-124] has studied the blowout phenomenon by simulating the plume in 60 m of seawater using compressed air. For water depths less than 60 m and flow rates up to 28 m^3/min of free air, he reports that the plume may be expected to have a radius of about 6 m near the surface. On breaking the surface, the flow produces a radial current outward from the plume centre. This decays outward to a diameter approximately equal to the water depth. At this point there is a reversal in surface currents and a ring of current flowing toward the centre. The converging flow pattern results in downward mixing and air bubbles have been detected to depths of 12 m while a natural entrapment zone is produced at the surface. Currents in the rising plume and at the centre of the surface flow approximate 0.5 m/sec.

To summarize this discussion on the macro and micro environment of a blowout, the Arctic is clearly a difficult environment within which to undertake the always-arduous cleanup of spilled oil. The unsuitability of standard hose-and-pitchfork techniques is apparent and the need exists for development of a system custom-designed with this environment in mind. Taking off from the techniques used in cleaning up spills in temperate regions, this report begins such a design process with a general analysis of the problem.

4 EVALUATION OF OIL CONTAINMENT AND/OR DISPOSAL CONCEPTS

Numerous quantitative and non-quantitative evaluation schemes have been created to compare and select alternatives in various disciplines. Such schemes have been used in areas as diverse as evaluating oil skimmers, selecting sites for nuclear power plants, designing optimum waste-water management systems or designing military hardware. In this study an attempt is made to avoid complex weighting or cost-effectiveness schemes. Instead, possible oil cleanup approaches using a sequential process are screened. First, the problem is defined in its most general possible terms and the most promising areas (concepts) for subsequent study are selected. These promising concepts are then studied in more detail using a different set of evaluation criteria.

The process is very similar to that frequently used to select sites for major industrial or power generating facilities. First, the entire possible area of interest is investigated using very general, broad-based criteria. From this process the most promising areas are selected for study. These areas are then investigated using the particular criteria that enable them to be compared. From this, specific sites can be chosen for very detailed study, comparison and eventual selection of the most promising.

Use of a sequential optimization process enables the study to focus on those concepts with the highest probability of yielding an adequate solution. It must be emphasized that a valid solution possibly exists in areas that are not investigated further, or even that no solution exists in the area considered most probable of yielding one.

The following evaluation is based on the premise that a blowout does occur. Hence, schemes directed at reducing the probability of occurrence such as redesigned BOP's, improving manpower training, etc., are not considered.

4.1 Evaluation of Initial Response

The immediate concern once a blowout occurs is the response at the blowout location to ensure optimum containment and/or disposal. In general terms there are three possible initial responses, as shown in Table 1.

1. *Modification:* This response involves modifying the physical or chemical properties of the hydrocarbons involved. Such modifications may include burning, altering the specific gravity, viscosity changes, creating emulsions, gelling, etc. Subsequent actions may involve transporting or storing the hydrocarbons.

2. *Storage:* This response involves storing the hydrocarbons in an unmodified form. Subsequent actions beyond this initial response may involve modifying the properties or transporting the material.

3. *Transportation:* This response involves moving the hydrocarbons away from the immediate area and is merely an interim one in that the problem of ultimate containment or disposal still remains.

The three possible responses referred to can occur in any environmental medium. These are:

a) Air - any area above the water or ice surface.
b) Surface Interface - any area at the water-air or ice-air boundary.
c) Water - any area below the water surface above the seabed.
d) Seabed - any area at the bottom of the water column.
e) Sub-sea - any area below the seabed.

TABLE 1 EVALUATION OF INITIAL RESPONSE OPTIONS

RESPONSE	RESPONSE MEDIUM				
	AIR	SURFACE INTERFACE	WATER	SEABED	SUB-SEA
Modification	D	A*	C	D	D
Storage	D	A*	A*	D	B*
Transportation	D	A*	C	B*	D

Code: A = likely to be feasible
B = possibly feasible or partially successful
C = unlikely to be feasible
D = unsuitable
E = not in study framework

* Considered worthy of further study

It is now possible to evaluate which initial responses in which media are most promising. This is done in Table 1. It should be noted that all concepts and responses are evaluated at this stage without regard to problems of ice scour, ice dynamics or seasonal variances, since these are special problems which will be included in subsequent evaluations.

Table 1 suggests the following:

1. Air - no initial response appears feasible in this medium.

2. Surface Interface - all possible initial responses are likely to be feasible to some degree in this medium.

3. Water - the only likely response in this medium is to store the oil. Modification in the water column by chemical or other means appears to be unlikely to succeed, or at least contains too many unknowns. This may be worth further study at a later date. Transporting the oil (and possibly gas) in the water column by means such as submarines, etc., also appears unlikely.

4. Seabed - no response in this medium seems very good. Transporting via pipeline, etc., could be possible, but would likely require a capture system at the blowout source and pumping systems, both of which are difficult to develop. Storage at the seabed is not feasible due to

the high volumes involved. Modification of the physical/chemical hydrocarbon properties in this area is not considered worthy of further study at present.

5. Sub-sea - no response in this medium appears likely to succeed-with the possible exception of storage which is considered possibly feasible.

From the above evaluation, six response-medium cells are considered worthy of further study.

4.2 Concept Generation

At this stage, concepts fitting into one of the previously generated six cells can be generated and evaluated. This is done in Table 2, the codes of which have the same meaning as those in Table 1. The following comments are pertinent:

1. Modification - Surface Interface: The most likely concept to succeed is burning followed by gelling or biodegradation. Both steam and gas stripping are considered unlikely, although steam stripping appears better in view of its simpler requirements. Molecular cracking is not considered worthy of further analysis.

2. Storage - Surface Interface: All surface-based storage concepts appear worthy of further study. The ones listed in Table 2 include development of ice domes and rings, as well as pumping of oil onto the surface of an ice island.

3. Storage - Water: All water storage concepts appear worthy of study, except storage within the drilling platform. This concept is ruled out at present strictly on the basis of economics. Such storage concepts are no doubt possible, but due to their very high costs would not likely be implemented strictly as an oil spill countermeasure.

4. Storage - Sub-sea: No concept here appears worthy of continued analysis. Downhole concepts involving the use of explosives, gelling agents, expandable devices, etc., are considered outside the bounds of this study. No doubt such downhole concepts could reduce the probability of a blowout, but this study is directed at a blowout resulting when all blowout prevention mechanisms, including all downhole concepts, have failed. Reinjection is considered unfeasible since it would require another well in the vicinity. Sealing by encouraging the migration of permafrost by use of freon probes etc., is unlikely due to very high cost and mechanical requirements.

5. Transportation - Surface Interface: All concepts such as barges or encapsuling the oil within the ice are considered likely to be feasible.

6. Transportation - Seabed: A pipeline to the landfast ice or to shore is not considered viable due to the high cost and unreliability of the system. No other concepts are considered.

TABLE 2 SELECTION/EVALUATION OF TYPICAL CONCEPTS

1. Modification – Surface Interface	
A	burning
B	dispersion for biodegradation
C	steam stripping
D	gas stripping
D	cracking
B	gelling
2. (a) Storage – Surface Interface	
A	ice retention (domes, rings)
A	booms
A	ice islands
2. (b) Storage – Water	
A	curtains
A	bladders
A	domes
A	tents
A	gas barriers
D	within exploration platform
2. (c) Storage – Sub-sea	
E	downhole concepts
D	reinjection
C	permafrost seal
3. (a) Transportation – Surface Interface	
A	barges
A	ice encapsulation
3. (b) Transportation – Seabed	
D	pipeline to landfast ice or shore

Note: For codes see Table 1

4.3 Concept Evaluation With Regard to Environmental Factors

To this stage in the evaluation no consideration has been given to ice conditions, including ice scour or to other elements of the physical environment. This section evaluates the concepts from Table 2 considered worthy of further study.

There are two principal areas where ice cover or movement affects a containment/disposal system. These are at the surface interface (problems of movement and cover) and at the seabed (problems of ice scour).

In Table 3, the 13 concepts from Table 2 are evaluated in terms of their ability to function adequately under various ice conditions and in an ice scour zone. As seen, no concept is considered likely to be feasible under all conditions. However, not all ice conditions are critical from a containment/disposal perspective. Clearly, containment or cleanup in the open-water situation is relatively straightforward and could utilize existing technology. Also, the table shows that each concept has a likelihood of success in the landfast ice equal to or greater than that in the moving pack or drifting floes conditions. Hence, only concepts acceptable in these two areas (with scour) are considered.

There are four concepts which appear worthy of further analysis, all of which are at least possibly feasible in ice cover conditions greater than 10% and are at least possibly feasible in ice scour zones: burning, ice retention, gas barrier and curtains. Of these, only burning is a disposal concept which promises to fundamentally attack the problem. The other alternatives are containment techniques which promise to assist in applying burning as the ultimate disposal technique.

5 BURNING FLOATING OIL

Combustion of any fuel is a vapour phase phenomenon. Accordingly, the combustion reaction itself is preceded by a 2-step process in which the fuel is vapourized and the vapours are heated to a temperature at which they will react when mixed with oxygen from the air. Figure 6 portrays in cross-section one flame of an established fire of floating liquid fuel. The combustion reaction, with the release of heat, is taking place at the flame front. Air is convecting inward from the periphery, while back-radiation from the flame vapourizes additional fuel to maintain the process. Points A and B are at the boiling point of the liquid fuel, while point C is in an atmosphere of pure fuel vapour at a temperature between the boiling point and the flame temperature. Temperatures in the water layer (point D) will be between the bulk water temperature (normally about 0°C in Arctic seawater) and the boiling point of water. This will depend on the temperature at A (thus on the type of fuel) and on the thickness of the fuel layer.

The water body forms an infinite heat sink conducting heat away from the fuel layer. A finite pool of fuel will diminish in thickness as it burns, until this heat sink effect becomes comparable to the heat back-radiated from the flame. At this point the rate of vapourization slows and the rate burning and height of the flame moderate in consequence. There is a temperature at which vapourization is no longer sufficient to maintain the flame in competition with heat losses to the water substrate. This is the fire point (T_f), and when, during the thinning process, the temperature at point A in Figure 6 reaches T_f, the fire goes out.

TABLE 3 EVALUATION OF CONCEPTS FOR VARIOUS ICE CONDITIONS

	Ice Condtions				
	Surface Problems				Seabed Problems
	Landfast (100% coverage)	Moving pack (80%-100% coverage)	Drifting floes 10%-80% coverage)	Open water (<10% coverage)	Ice scour zone
Modification					
Burning	A	B	A	A	A
Gelling	C	D	C	B	A
Biodegradation	C	D	C	B	A
Storage					
Ice retention	A	B	B	D	A
Booms	C	D	C	A	A
Ice island	A	B	C	D	A
Curtains	A	B	B	A	B
Bladders	A	B	B	A	D
Gas barriers	A	B	B	A	B
Domes	A	B	B	A	C
Tents	A	B	B	A	D
Transportation					
Barges	A	D	D	A	A
Ice encapsulation	A	B	C	D	A

NOTE: For codes see Table 1

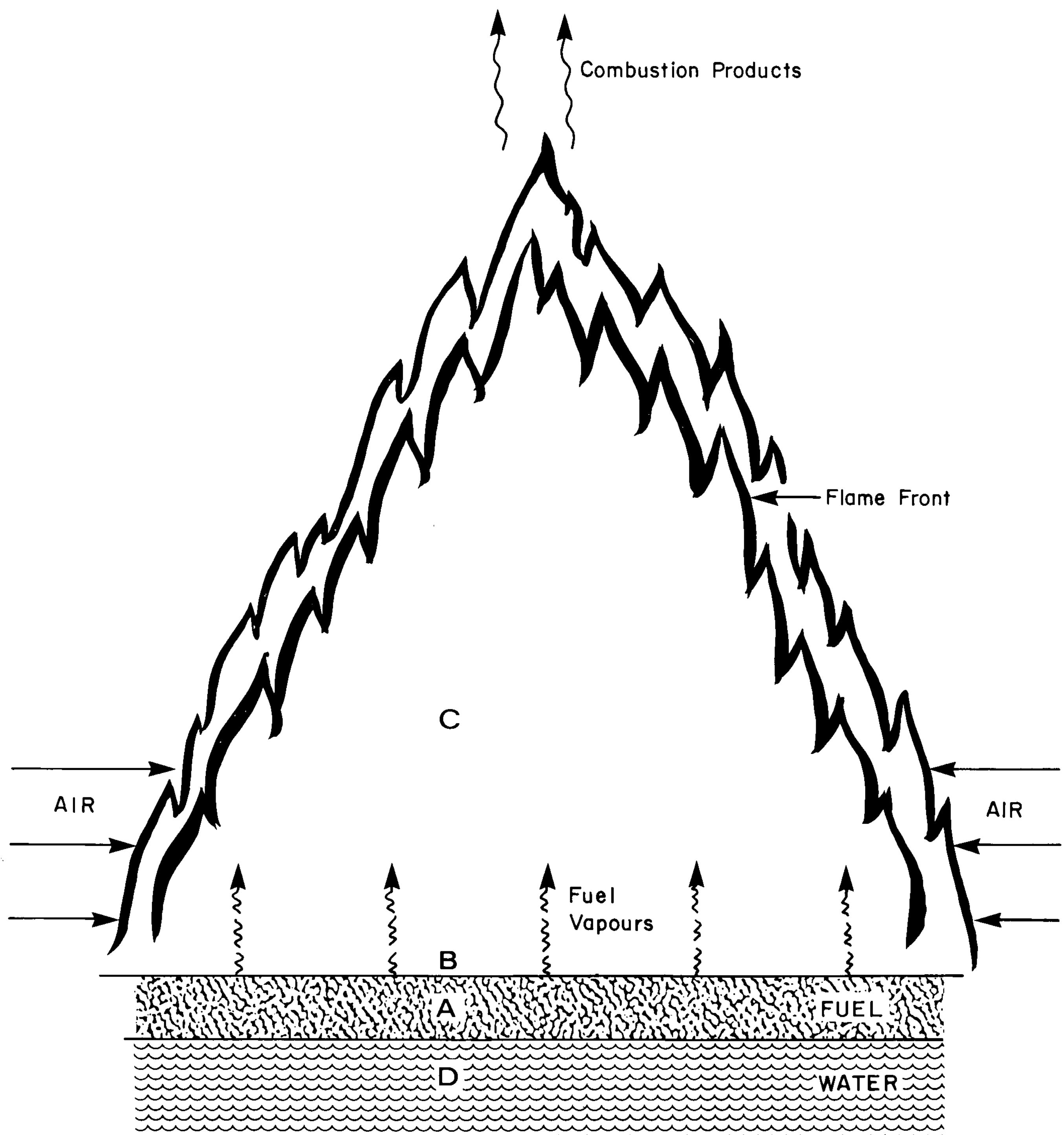


Fig. 6 Cross-section of a Flamelette above floating liquid fuel.

T_f is a chemical and thermodynamic characteristic of the fuel material. For some light hydrocarbons it is below 100°C, so in principle these materials will burn away completely. However, with crude oil as the fuel it has been observed that the boiling point and fire point of the residual material at the end of combustion is in excess of 100°C and that various crude oils burn out when the layer thickness falls to about 0.5 cm [12.9-47].

At the start of burning these same considerations apply, except that the crude will contain "light ends" which vapourize easily and give it a lower fire point. The initial fire point of most crudes is below 50°C, but this rises as the material weathers, and it rises during burning as the lighter materials are preferentially vapourized. As a design criterion, any system for promoting in-situ combustion of the pollution from a sub-sea blowout must form an oil layer substantially in excess of 0.5 cm deep.

A second consideration is the area required to burn the oil from a blowout as fast as it is being evolved. From the foregoing discussion, the rate of burning is likely to be a complicated function of the fuel volatility, the heat released in combustion and the rate of air convection. There have been extensive experimental studies on this point and Figure 7 presents a correlation of this experimental data in which the curve labelled "petroleum" represents a Russian crude oil. Data from burning oil spills [12.9-47] have been added for comparison. The figure predicts that the large-area fires typical of spilled oil will burn at 1.5 mm/min of surface recession. Put another way, a device to facilitate burning of the oil from a blowout must be designed to provide 670 m^2 of burning surface for each cubic metre/minute of oil flowing from the blowout. In the balance of this report techniques for attaining these areas and thickness standards for effective burning are discussed. In particular, the case of oil burning amidst pieces of brash ice deserves additional discussion, as the individual burning leads may not fall in the turbulent range of Figure 7.

The consideration of burning as a disposal technique supposes that the combustion process converts an obnoxious floating oil layer to harmless carbon dioxide and water vapour which are quickly dissipated in the atmosphere. For an open fire this is a reasonable approximation, except for the plume of smoke that would be generated. Various observers [12.9-106, 12.9-112] have remarked on the smoke plume and observed that it leaves no trace on the surrounding snow. Coupal [12.8-13] measured the smoke from large and lengthy crude oil fires and demonstrated that no observable smoke deposition should be expected.

6 RETAINING OIL FOR BURNING

The oil from a well blowout arrives at the surface as a thin film surrounding the bubbles of natural gas that drive the plume. This film breaks as the gas escapes and the oil film is carried outward on the surface by the radial current. On the 38-m circumference of the plume itself, the 0.5 m/sec average current would spread a 1,000 barrel/day flow (1.85 x $10^{-3} m^3$/sec) in a slick .009 cm thick. As the current decellerates, surface tension forces will gather this thin film into a smaller slick at the equilibrium floating slick thickness.

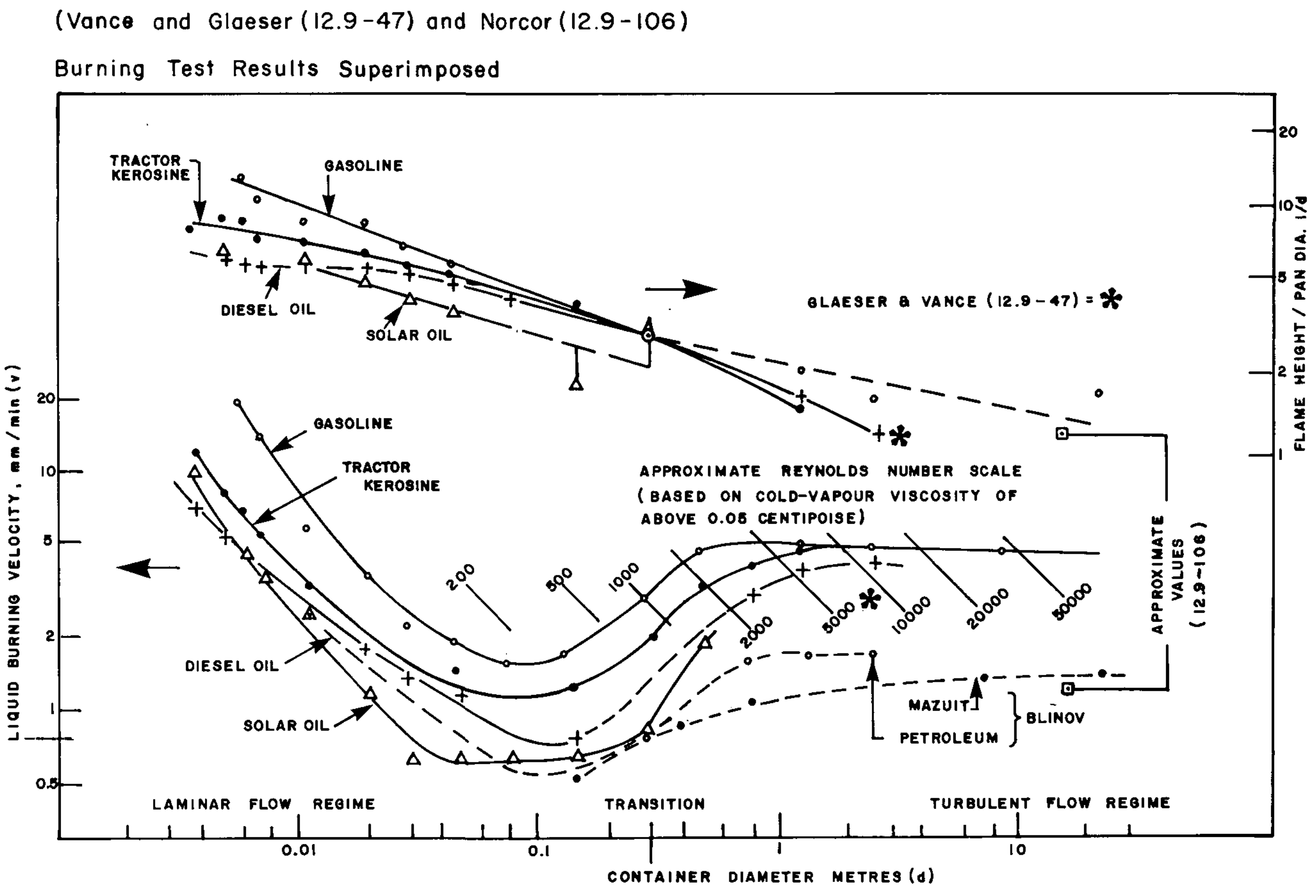


Fig. 7 - Hottel's analysis of various sources of pool burning data (from 12.8-11)
Liquid burning velocity and flame height to pan diameter data
vs
Pan diameter

The equilibrium thickness that will be assumed by a given oil is determined by its density and a ''spreading coefficient'' computed from its interfacial tension with seawater at mutual saturation. Rosenegger [12.9-115] has estimated the equilibrium film thickness at 0°C for typical Canadian crude oils and predicts that freshly spilled crude will form a slick approximately 0.25 cm thick. Thus, the equilibrium still-water distribution of oil from a blowout should be impossible to ignite in-situ. Some form of thickening process will be required.

The conventional approaches to gathering a layer of floating oil are skimmers and ''burning agents''. Skimmers attempt to separate the oil layer from the underlying water and collect it in a sump for pumped transfer. The variety of mechanisms and designs proposed for this function is enormous, but these will not be reviewed in detail in this report for the following reasons. No skimmer design provides for completely automatic operation. All call for on-site operators who would be exposed to the hazards of the explosive and possibly toxic natural gas blown out with the oil. Further, all skimmers call for a certain amount of hardware with attendant support vessels, pumps and power systems. Deployment and manipulation of such systems in the presence of floating ice poses formidable logistic and ice engineering problems. Finally, various skimmer principles have been tested for their ice-hardiness [12.1-74] and only two have demonstrated capability of picking up an oil layer in the presence of floating ice. Lockheed has delivered a unit for service in the Beaufort Sea, but its effectiveness has not been demonstrated in a spill emergency in this environment.

An approach which comes closer to the goal of in-situ burning is to apply ''burning agents''. A burning agent is a granular or fiberous material which, distributed on the oil layer, wicks up the oil to allow burning away from the heat sink effect of the water. Figure 8 (adapted from [12.8-15]) schematically depicts the thick insulating layer which allows the temperature at A to remain above the fire point as the fuel layer is depleted and flows into and through the wick. Numerous materials have been proposed as wicking agents including charcoal, sintered minerals, asbestos, straw, wood chips, peat moss and various industrial wastes. A few patented preparations are marketed including glass beads and agglomerated silicate particles. Freiberger and Byers [12.8-5] tested a range of these preparations and reported enhanced combustion under some conditions. On the other hand, their results highlight two important limitations in the use of burning agents. First, they must be applied at a level such that the volume of wick is comparable to the volume of oil to be burned. Second, the mode of application can be critical to successful burning. In sea trials, Freiberger and Byers found that broadcasting or blowing burning agents onto the oil was ineffective. Eventually, only hand spreading over the side of a ship gave effective coverage. In an ongoing spill from a blowout, this again implies massive logistical problems, as careful, continuous application of the burning agent would have to be maintained throughout the life of the emergency.

So neither mechanical skimming nor the application of burning agents recommends itself as a promising technique for promoting in-situ combustion of the oil from a blowout. Nevertheless, Arctic tests [12.9-47] have shown that when a thick layer of unweathered fuel is available, burning is easily accomplished and is an effective means for reducing the volume of the spill about 90%.

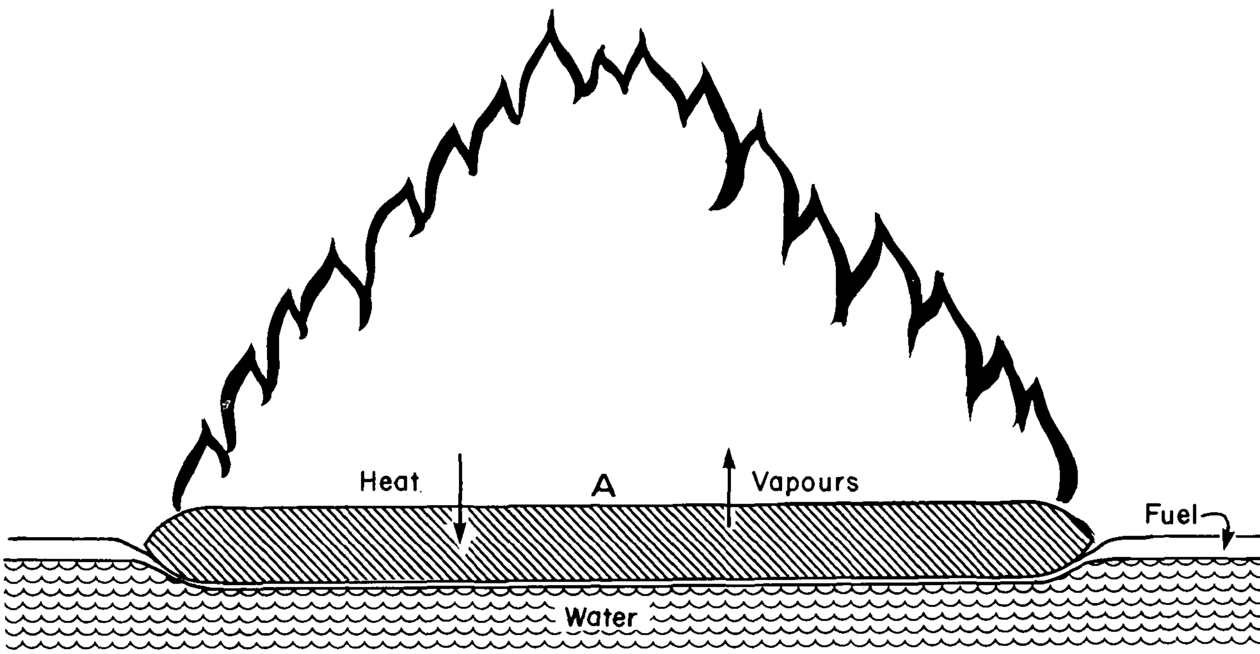


Fig. 8 Burning Agent thickening and insulating a thin fuel layer.

It is well known that when a boom is deployed in a current in the path of a floating oil slick, the current builds up a thick oil layer in the stagnant region upstream of the boom. One feature of the well blowout situation is the radial current pattern that will reliably develop, and this leads naturally to the suggestion that a boom deployed around the plume would trap the out-flowing oil in a layer thick enough for burning.

The geometry of the soil layer formed by a boom in a current has been studied by many authors [12.2-86, 108, 113]. It has been demonstrated that the layer assumes the form sketched in Figure 9 (adapted from [12.9-9]), and that its geometry can be described by a Froude number based on the water or layer depth and the current speed. When this Froude number reaches a critical value, the head wave portion of the oil layer begins to shed droplets of oil which are swept under the barrier and lost downstream. As a rule of thumb, these investigations concur that 30 cm/sec is the maximum current for retaining a stable oil layer upstream of a surface boom. Much of the work in this area has been devoted to increasing the length and depth of the retained layer, but the approaches devised have involved adding gelling chemicals [12.7-100] or complicating the boom into a current-powered wier skimmer [12.2-108]. The first approach is incompatible with burning the retained slick, while the latter adds a costly device highly susceptible to damage by passing ice. Nevertheless, that a conventional boom can be expected to retain a slick adequately thick for burning has been shown in experiments by Jones [12.2-87]. He held oil layers against a solid wall using currents developed by a bubbler system and correlated a densiometric Froude number for the slick with a densiometric Reynolds number for the flow, both based on the slick thickness. His result predicts:

$$h = \frac{0.47V^{1.34}}{(1-v)} \qquad (1)$$

where h = maximum thickness obtainable (in inches)
V = current velocity at the headwave (in ft/sec)
v = specific gravity of the oil

In his experiments, Jones retained 12 cm thick layers of 0.92 specific gravity oil in a 26.5 cm/sec current.

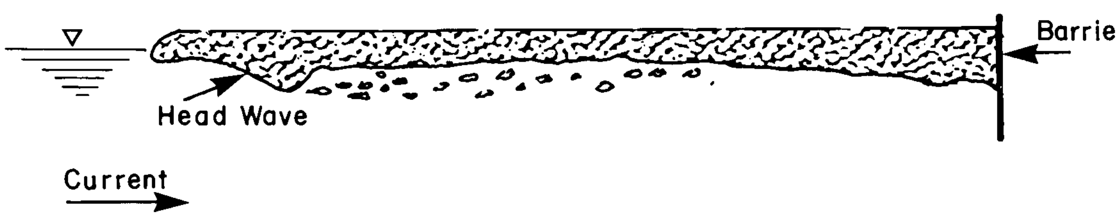


Fig.9 Oil layer retained by a barrier against a current.

Koberger and Getman [12.2-2] tested various boom designs under Arctic field conditions and counsel that a reliable boom for service in ice is not currently available. They found that booms with integral tensioning systems tended to ride up onto impinging ice floes, while booms with external tensioning attempted to resist the ice. Either behaviour would destroy a boom deployed around an Arctic sub-sea well blowout. What is required is a design which will be strong and deep enough to retain a thick oil layer against the radial current, yet compliant enough to submerge under impinging ice floes and re-emerge to resume retaining oil.

7 A DEEP-SKIRTED BOOM

7.1 The Concept

The 30 cm/sec guideline for the maximum current in equilibrium with a slick was developed under two significant assumptions: the currents extended to the bottom of the channel and the currents remained at a steady speed. These assumptions can be re-examined in the case of a blowout. Specifically, a very deep-skirted boom surrounding the plume could divert the thin surface current downward and force it to recirculate. The resulting flow would have little tendency to carry entrained droplets out under the boom skirt and the volume inside the boom ring would gradually fill to a significant depth with an oil-water mixture resembling salad dressing. The vorticity of the flow would maintain the oil in suspension. The surface oil layer retained by the barrier would build up to the critical Froude number, then additional oil flowing into the slick along the surface would simply cause a corresponding amount to be entrained from the head wave.

Figure 10 shows Tophams observations [12.9-124] of surface currents around a simulated blowout. A barrier for this velocity field must retain an oil layer with its inner radius larger than the radius of 0.3 m/sec current, and with an outer radius large enough that the burning rate over the resulting area will equal the rate of new oil flow. Assuming that the average burning rate is 1.5 mm/min, the minimum surface area under the flame may be calculated. The calculations are based on equating the oil flow rate to the total burning rate and the results are represented in Figure 11. Therefore, for an average oil well blowout of 1,000 bbl/day (159 m^3/day) and 60 m deep, the minimum boom diameter required to provide an adequate burning surface is 30 m.

The depth of the skirt must be sufficient to divert the surface and subsurface currents downwards and initiate recirculation. Topham, in open-water experiments, observed that the circulation at the wave ring radius is 10 m deep. Therefore, it may be assumed that in order to maintain a similar circulation with a boom at a 15-m radius, the skirt depth may be chosen as 10 m. The presence of the boom will certainly change the velocity profiles at any depth, but it is likely that a smaller size circulating cell will develop. The 10-m depth of the skirt assures that only a small quantity of oil mixed down to this depth will escape the retention boom. Therefore, for a standard blowout the barrier (or rather the chimney) takes the shape of a flexible cylindrical wall 30 m in diameter and 10 m deep. Three major components may be isolated, as shown in Figure 12.

1. Top-fire-resistant boom.
2. Float and anchoring section.
3. Bottom-oil-resistant rubber skirt.

There are currently aluminum (Reynolds) and steel (Gamlen) booms on the market, so the entire idea is an extension of existing technology. Because of its flexibility, the rubber skirt could be rolled up and stored on a barge. If a blowout occurs at the drill site, the boom would be deployed to the site and anchored by cables to the seabed. The boom would be centered over the hole and burning of the oil could commence as soon as a sufficient oil ring width is formed. If burning cannot commence immediately, or if the fire is extinguished by ice floes, an oil-water "salad dressing" would collect in the chimney for several days before spilling out under the barrier. The chimney must be designed to

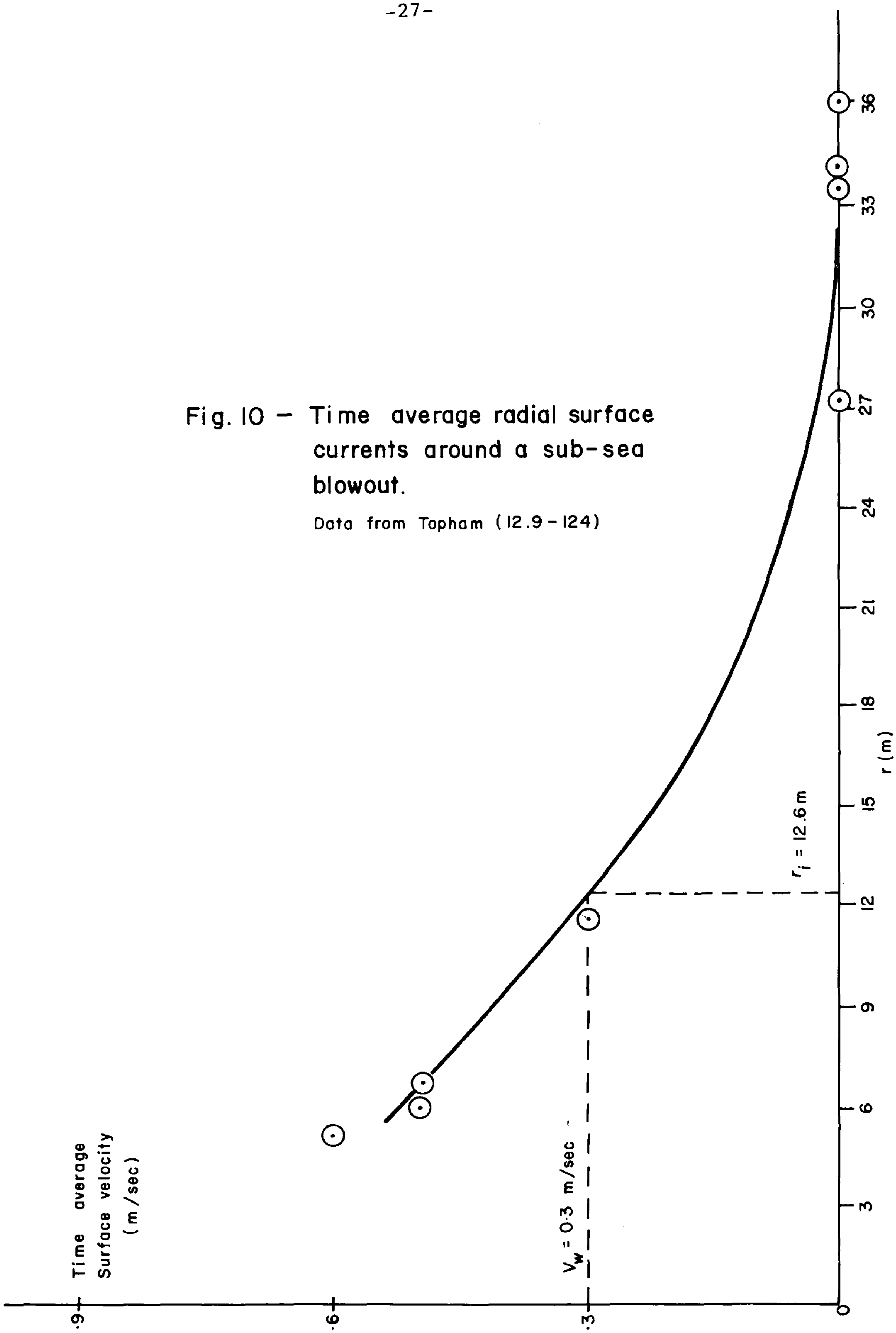


Fig. 10 — Time average radial surface currents around a sub-sea blowout.

Data from Topham (12.9 - 124)

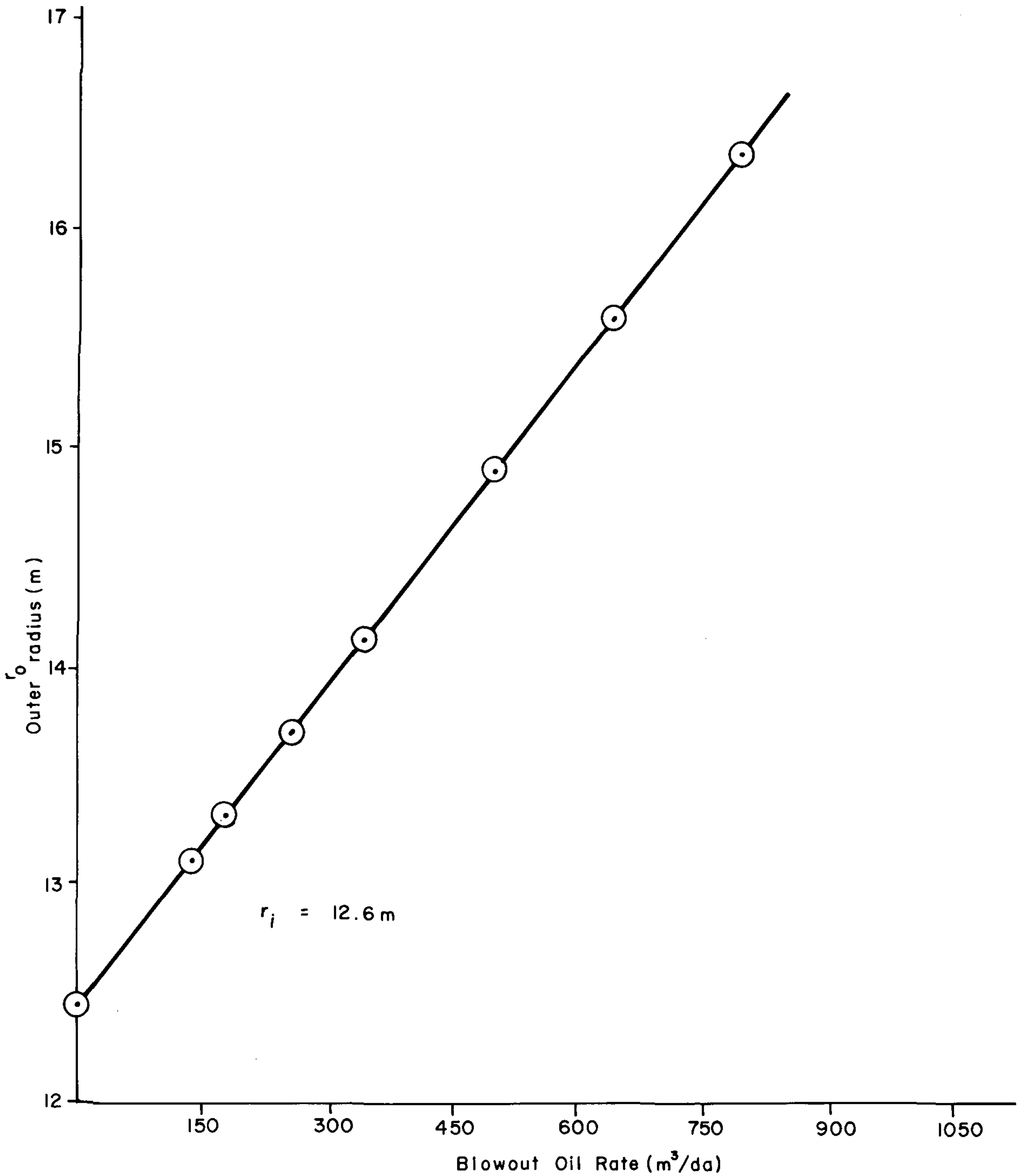


Fig. 11 – Barrier radius required to burn oil flows

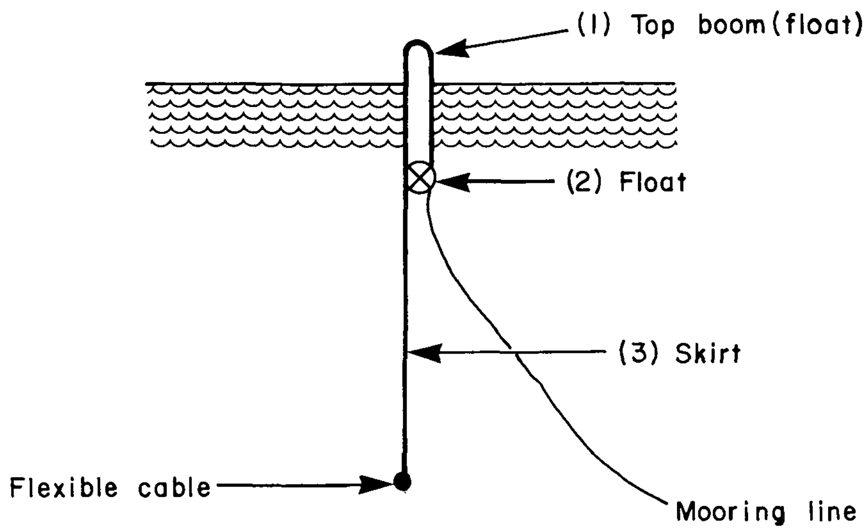


Fig. 12 Schematic cross-section of a deep-skirted boom

submerge under the ice so that when ice floes pass, the chimney can resurface undamaged and oil can again collect and be ignited.

7.2 Effect of Ambient Current and Wind

Due to its large projected area, the boom will be vulnerable to water currents. A current with average velocity, v, will exert a total force on the boom, F_d, which may be determined from the standard formula for drag on a cylinder:

$$F_d = C_d A \cdot \frac{pv^2}{2} \qquad (2)$$

where C_d = form coefficient = 1 for a cylinder
A = projected underwater area = 300m^2
p = fluid density = 1/9.8 ton sec^2/m^4 (1/8889 kg sec^{-2}/m^4)
v = ambient current

Assuming an average current velocity of 1 knot (0.5 m/sec) the total drag force will be approximately 4 tons (3,629 kg). This load is within the capacity of a conventional mooring system from which a line could be run to balance the drag. However, a flexible rubber wall will definitely deform under pressure and this requires further consideration.

Consider the rubber wall to be subjected to a uniform pressure which will tend to deform the skirt upwards, deform the circular section into an oval shape and shift the centre of the boom from the centre of the blowout.

The deformation of the skirt is particularly favourable. Since the currents will shift the whole boom away from the centre of the blowout, the tensions in the upstream mooring line will increase. This increases the horizontal force balancing the water drag, as well as the downward tension which tends to sink the whole assembly. Fortunately the skirt deformation, as shown in Figure 13, will create a resolved drag component which tends to uplift the walls and will partially counteract the line tension vertical component, thus reducing the buoyancy required to keep it afloat. The hydrodynamic forces exerted by the circulating flow inside the boom will slightly affect the extent of deformation until a pressure balance on both sides of the rubber wall is achieved, otherwise the rubber skirt will continue to deform and surface. As the skirt deforms, the projected area decreases, resulting in a subsequent drop in the drag force. Meanwhile, the radial deformations of the boom results in an oval-shaped form which tends to increase the drag. Overall, it is reasonable to assume that the drag force will remain approximately as estimated.

In the detailed design of such a containment device, four factors deserve special consideration:

1. The skirt may be stiffened by flexible cable around the bottom which will prevent excessive deformation, as well as act as a ballasting weight.

2. The uplift force due to skirt deformation may be directly correlated to the current velocity. If the horizontal and vertical components of water drag are known, the mooring system stiffness and tension angle at zero current may be determined.

3. The centre shift of the boom is a desirable feature. Since ambient currents will deflect the rising plume away from the centre of the blowout, the centre shift can be adjusted with the current velocity and water depth such that the boom will follow the plume. This determines an additional requirement for the mooring system. Consider, for instance, 60 m of deep water and a uniform-water current of 0.5 m/sec. The steady speed of the rising plume is approximately 0.7 m/sec. Therefore, at a water depth of 10 m the centre shift of the plume would be approximately 35 m. If the diameter of the plume is 12 m, this would require a centre shift of the boom of at least 26 m in order to contain the products of the blowout as they surface. Such a centre shift can only be obtained from long mooring lines with low stiffness. This requirement will vary with the water depth. However, it should be mentioned that a loose mooring line may not provide enough line tension to restore the original location as the currents die out. Therefore, a compromise design must be obtained by which the centre shift of the boom can follow the plume to a certain extent beyond which the effectiveness of the device drops. In fast currents it will be rendered ineffective.

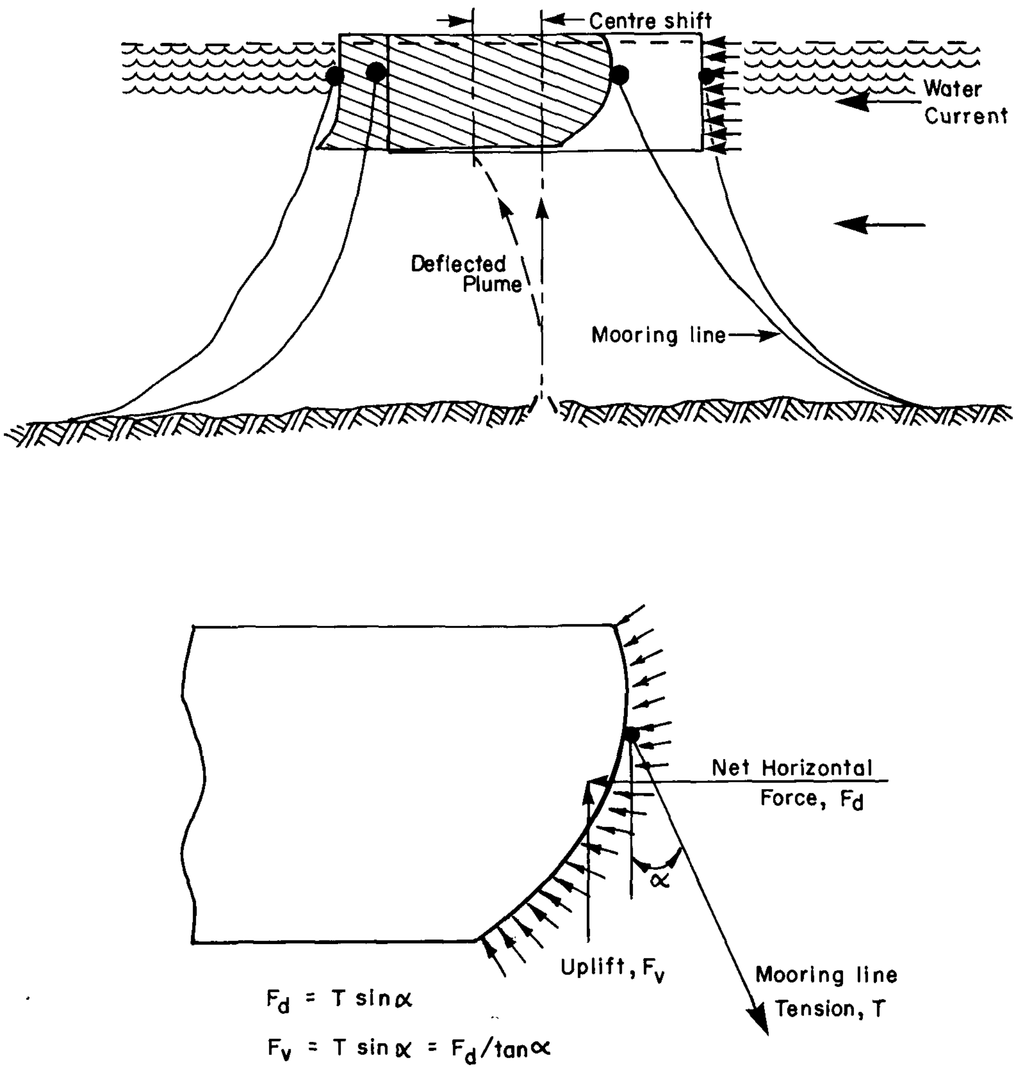


Fig. 13 - Effect of ambient currents on a ring of deep-skirted boom

4. Effect of wind on the boom may be determined from:

$$F_w = 0.33\ A_w v^2_w \qquad (3)$$

where

F_w = wind drag, kgs
A_w = exposed projected area, m^2
v_w = wind velocity, m/sec

The wind speed v_w may be estimated from:

$$v_w = 0.5 \times (\text{average velocity}) + 0.4\ (\text{maximum gust velocity}) \qquad (4)$$

For instance, if the average wind velocity is 40 km/hr gusting to 70 km/hr, the wind drag on all surfaces will approximate 2 tons (1,815 kg). This wind force has to be considered as an additional requirement for the mooring system. This force will centre shift the boom, but may not affect the plume centre. Therefore, a relatively stiff mooring system would be desirable. It is apparent that this requirement will reduce the mobility of the boom.

To sum up, it seems that a deep-rubber ''chimney'' can retain the crude oil resulting from an oil well blowout under certain conditions considered in its design. These conditions include still water and can tolerate low or medium-velocity water currents and blowing winds. The mooring system may be designed to permit off-centre shift of the boom to cope with the deflection of the rising column of blowout products due to water currents.

But, what will happen to this device if impacted by a large ice floe?

7.3 Ice Floes and the Retention Boom

A rigid metallic boom may be capable of deflecting small ice floes as long as its surface is smooth [12.2-2], but a flexible rubber boom may not be capable of doing so due to its high flexibility. Therefore, two approaches might be followed to overcome this difficulty. The first is to increase the capability of deflecting ice floes by reinforcing the top boom. This approach is suited for small ice floes. For large ice floes the boom must submerge and allow the ice to pass over. Afterward, it must be capable of surfacing and returning to its original station.

As an ice floe approaches and pushes a boom, it will deflect locally and totally move off-centre. As the boom moves off-centre, it must submerge to permit the passage of the ice floe. In this case, the uplift due to water currents will be absent and the line tension will exceed the buoyancy forces, resulting in gradually submerging the system as the ice floe advances. This permits the safe passage of an ice floe over the boom and centre of the blowout. As ice moves away, the chimney will resurface and resume collecting the oil.

In summary, it may be possible to design skirted containment booms with some applicability in shallow water where limited currents could be expected. As a general solution to the problem, the deep-skirted boom is not applicable to a wide enough range of locations and conditions.

7.4 A Bubble Barrier

Another approach to the problem is embodied in the concept of a gas barrier under development by Canadian Marine Drilling. It evolves from the bubble barriers used to retain oil spills in harbours (see, for example [12.2-95]) and from the observation that the substantial volume of gas released at the seabed could power the device. Atlas Copco has patented a similar idea. The principle patented by Canadian Marine Drilling is presented schematically in Figure 14, in which a cylindrical dome is shown intercepting the blowout plume in the water column. The gas decants from the oil within the dome with the gas escaping through peripherial holes to form a bubble ring at the surface. The oil spills upward through the standpipe to emerge within the bubble ring. The dome is of reasonable size and will not interact with surface ice. The gas rising from the bubble ring could be ignited to burn off the contained oil pool.

If the blowout is to be contained by a deep-skirted barrier, the bubble barrier seems to be a preferred approach. The effect of wind and currents is nullified, the anchoring system is simple and the hardware is unaffected by floating ice. In this study no attempt has been made to duplicate the design and costing effort underway on this concept.

8 A FLOATING NET

In discussing the potential for a deep-skirted boom, it was proposed to retain the oil near the blowout plume by diverting the thin surface current into premature recirculation. The same end could be served by forming, instead, a thin zone at the surface sheltered from the current and wind. This is the effect of a high concentration of floating ice pieces and this case will be discussed in a later section. Artificially, such a layer could be created by floating a rope mesh on the surface in the nature of a polypropylene cargo net. The individual strands of the mesh would each act as a miniature boom creating a small sheltered region. The many strands in series could combine to provide the area and depth required for in-situ burning. Such a floating net could provide a particularly practical solution since it could survive in ice-infested waters without damage. The net could be designed to submerge when encountering an ice floe, and thus not obstruct the movement of ice as it traverses the blowout region. As the ice passes, the net will resurface and float without being damaged.

Figure 15 shows an impression of the net around the blowout in case of high-water currents and oil collecting eccentrically. The net has an annular shape minimizing the total cost. The material proposed for fabricating the net is polypropylene rope. The device is anchored to the seabed by six cables at equi-angular separation.

Several parameters must be considered in the design of this containment device: water depth, water current speed and direction, wind speed and direction, crude oil properties such as viscosity and density, and ice effect.

A net could be designed to cover a wide variation in parameters, but at greater expense. Therefore, the approach to the problem is to specify the various parameters and their variation based on

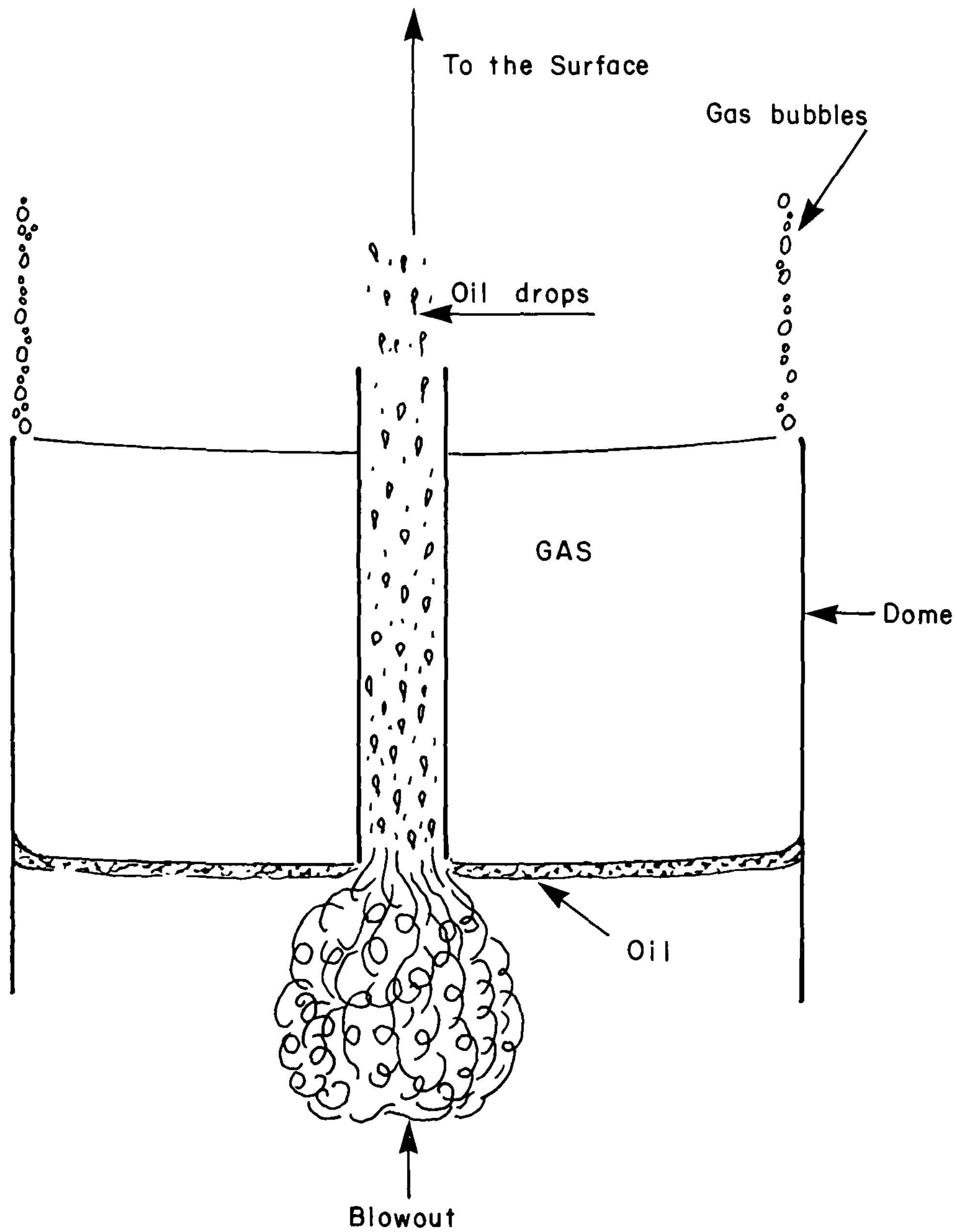


Fig.14 Schematic presentation of a gas curtain device

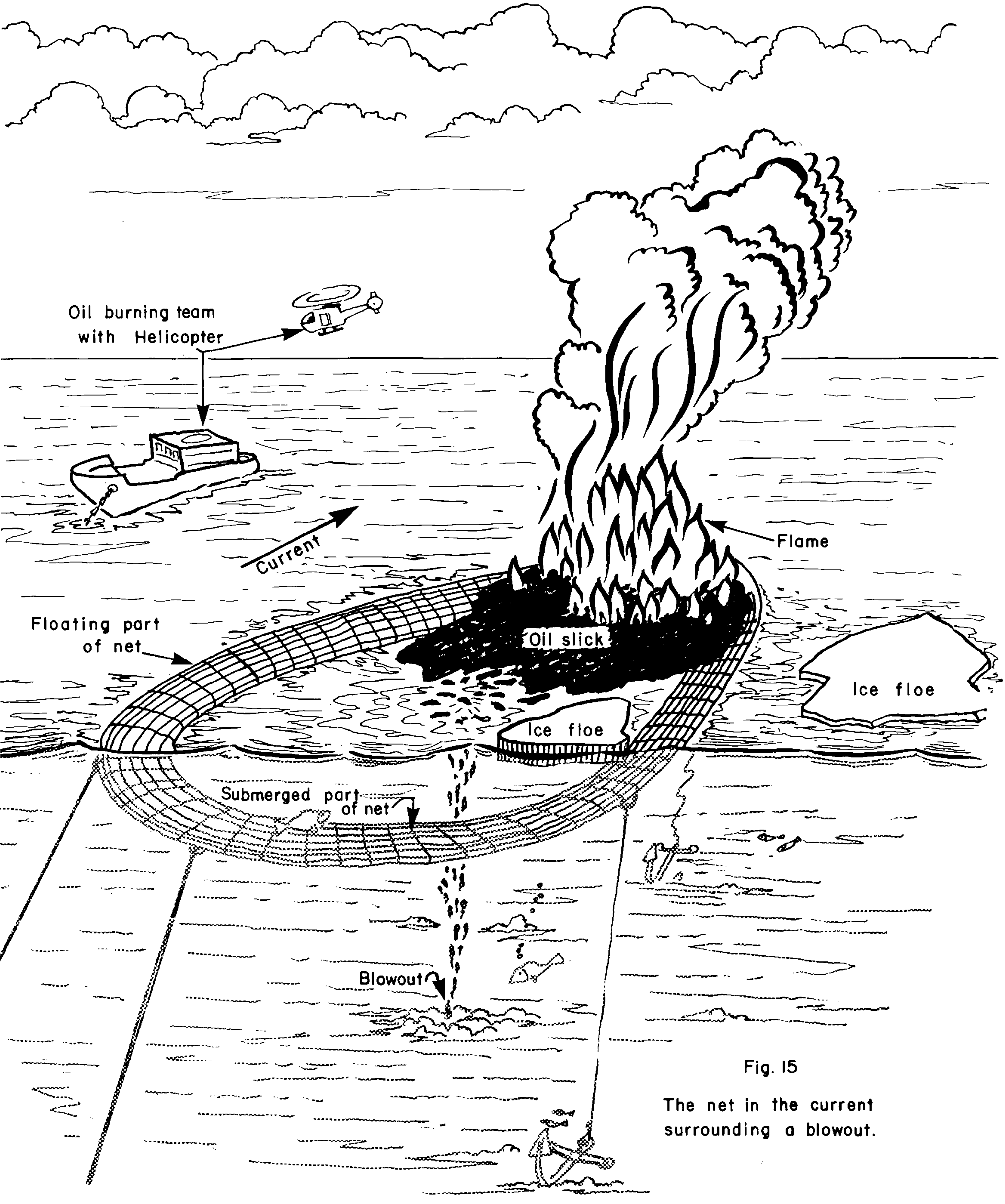


Fig. 15

The net in the current surrounding a blowout.

probabilistic estimates of speed, depth, etc., and use these data in a preliminary design which tolerates some variation in the parameters and which can be made at a reasonable cost.

The following aspects will be considered:

1. Dimensions of the net.
2. Spacing of the net mesh.
3. Total rope length requirement.

8.1 Dimensions of the Net

The dimensions of the net are calculated such that the centre of the plume emerging at the surface will always be inside the net. The rising plume will rise vertically only in still water. In the presence of ambient currents, the direction of rise will be a vector sum of the buoyant current and the ambient current. Thus, the outside diameter of the net may be determined from:

$$D_D = h_D [1 + (v_c/v_o)] \qquad (5)$$

where

D_D = "design" outer diameter of the net
h_D = "design" water depth at the drilling site
v_c = "design" water current velocity which is the maximum estimated velocity at the drilling location
V_o = vertical velocity of uprising plume which is the estimated "steady" speed of rising of the blowout products, m/sec.

For still water the current velocity is zero and the outer net diameter will equal the water depth. Practically, the net size should be more than this minimum value.

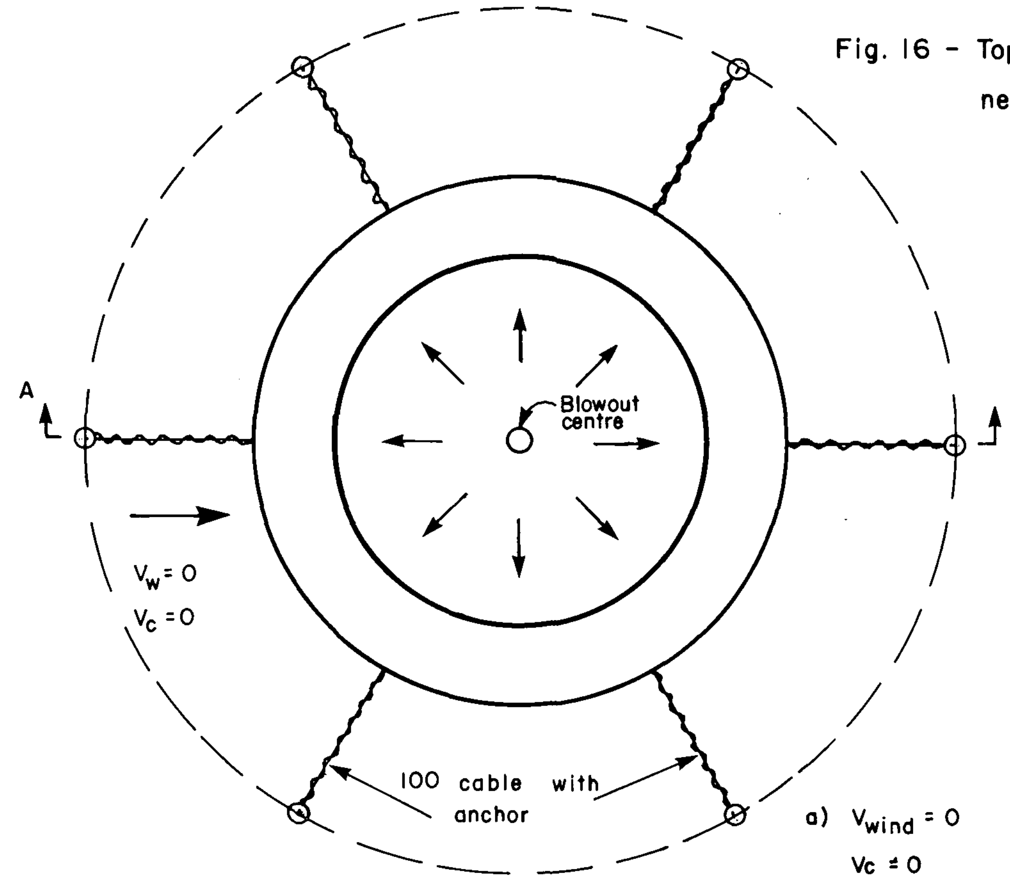
The net must form an annular ring with an inside diameter which permits enough width to achieve complete oil retention. Analysis to be presented below indicates that the width of the net should be at least 20 m, i.e. the inner diameter.

$$d_D = D_D - 40 \qquad (6)$$

In practice, economics dictate that if d_D is less than 20 m, a full circular net is preferred over the annular net. That is, if the outer diameter is less than 60 m, the inner diameter is set equal to zero. The choice of the annular shape will cut the cost of the net particularly for deep waters and fast-current designs. For smaller diameters the cost of a sloping end (which is discussed later on) may exceed the cost of the circular net itself.

As the water currents increase, the net deforms, as illustrated in Figure 16, and the oil collects at one side of the net. The oil storage capacity of the net will be reduced by fast flowing currents and it is recommended that burning be started as soon as possible.

Fig. 16 - Top views of the floating net and moorings
Scale (1:2,000)

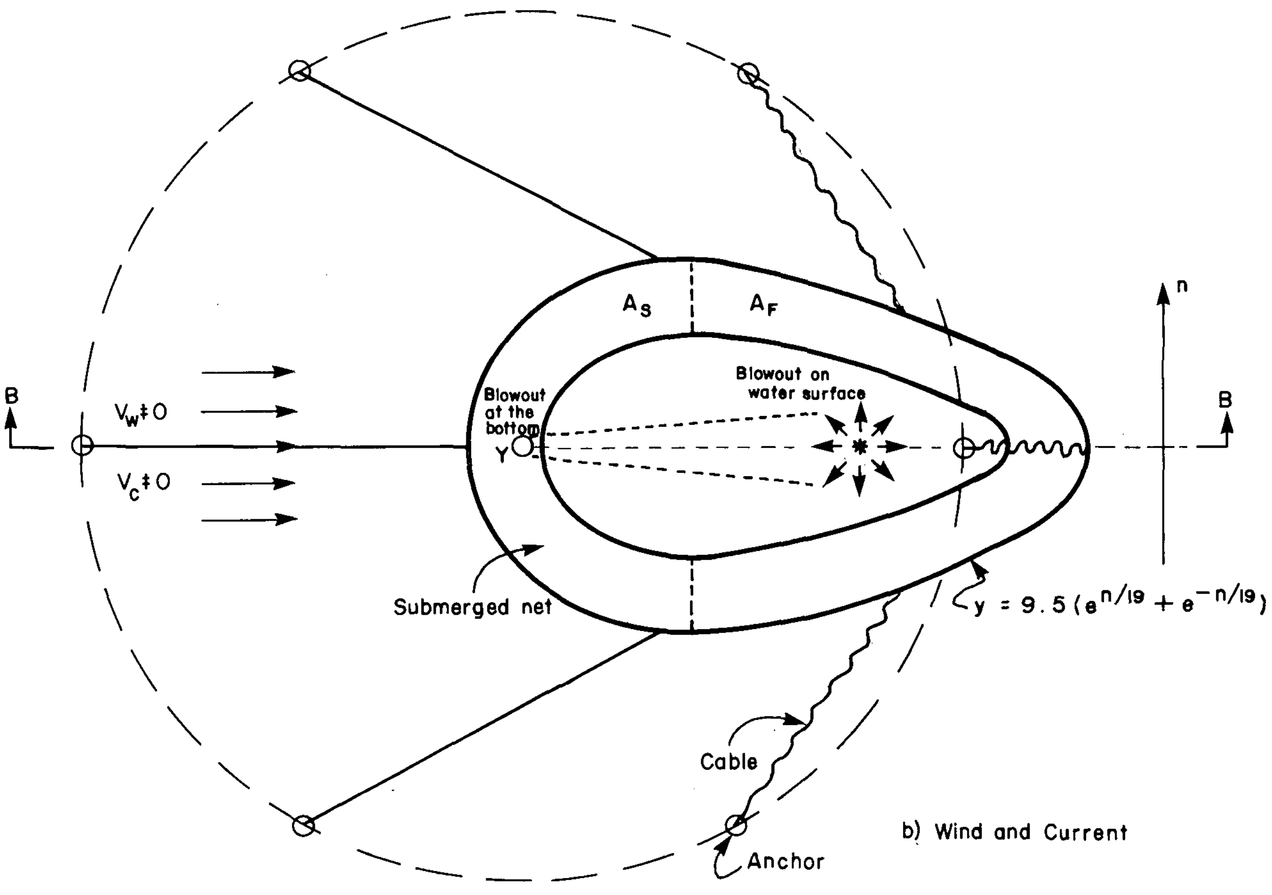


Design Values:

h_D = 60 metres

Vc = 0.57 m/sec (1 knot)

V_0 = 0.46 m/sec



8.2 Spacing of the Net Mesh

The main function of the net deployed around the centre of the blowout is to provide a storage capacity in which oil collects in thick films to facilitate burning. It also provides a delay time, which is the time necessary to fill the mesh with oil before it exceeds the net boundaries.

The mesh size of spacing of the rope sections is designed to provide an adequate storage space for oil. Meanwhile, the net should be able to withstand and overcome the forces that may be exerted by small ice floes intruding on the mesh.

8.2.1 Mesh size and storage capacity. The storage capacity for a given size mesh is affected by the current speed beneath the mesh. As the current speed exceeds a limit, which will be referred to as the critical velocity, the stored volume will decrease and the flow will carry away the excess oil. This critical velocity is a function of the spacing between rope sections.

An investigation was reported by L.A. Hale et al [12.9-9] which describes the oil slick retaining capacity of a boom for different velocities. The results, obtained on a wide variety of oils in the viscosity range from 3.9 to 1867 centipoise, indicate a constant critical velocity of 0.34 ± 0.04 m/sec. The loss of oil was also determined. For instance, for the lowest viscosity oil (Diesel No. 2: 3.9 cp) the oil loss per minute was less than 1% of the total volume of the oil slick retained behind the boom (which was 10 m long and 9 cm thick). This oil loss was observed for a current velocity of 1 knot (0.5 m/sec). When the velocity increased to 1.24 knots (0.63 m/sec), the oil loss increased to 2%. It is interesting to note that the oil loss seems to increase in linear proportion to the current velocity.

Based on these experimental observations, it appears that the oil will initially be retained inside the net annulus. As water currents develop, they will tend to move the oil slick across the net down the stream. This tendency is sketched in Figure 16b and represents the worst case of operation. The capacity of the net must be designed for this case to provide sufficient area for burning without losing a significant amount of oil outside the net.

For a blowout discharge Q_B m^3/hr and a burning rate of V_B m/hr, the surface requirement S will be:

$$S = Q_B/V_B \tag{7}$$

where for crude oil the burning rate ranges from 0.06 to 0.12 m/hr. For a standard blowout of 2,500 bbl/day (16 m^3/hr) the required surface area will be approximately 140 m^2 which can easily be satisfied inside the annulus and the inner part of the mesh.

Figure 17 shows the oil travel across the ropes from one loop to the next. As the oil accumulates inside and fills pocket A, it moves to the next loop, B, filling it, and continues to spread outwards. If the spaces of the net are all filled, the oil will leak out. This provides a time delay during which proper measures can be taken to burn the oil in-situ and limit the contamination to the immediate blowout location. For known blowout discharge, water current speed and burning rate, a state of equilibrium may be determined for which the spreading of the oil slick will be nullified.

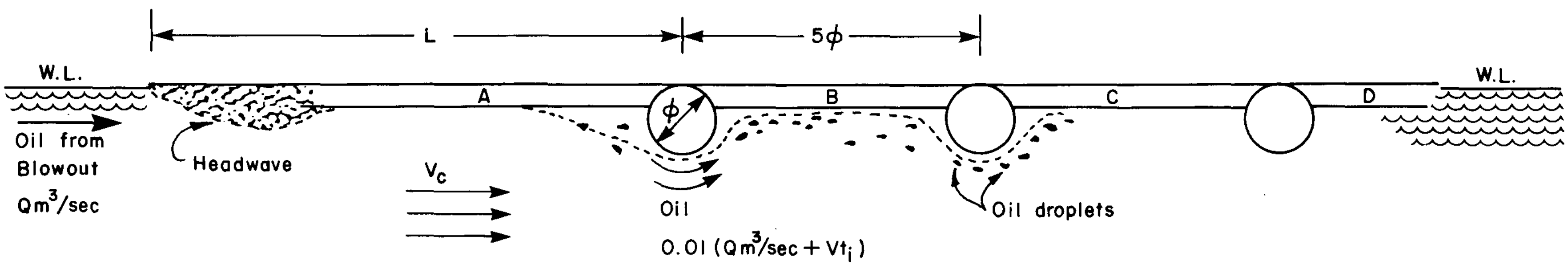


Fig. 17 - Propagation of the oil in the net

8.2.2 Interaction with ice floes. The second critical design consideration is the possibility of damage by travelling ice floes which must be eliminated or at least minimized. For this purpose the spacing between ropes should be close enough to prevent an ice floe from wedging onto the loops and destroying the net. Our preliminary calculations indicate that for reasons of protection from ice floes, as well as permitting a sufficiently large storage volume, the ratio of centre distance spacing, L_D, to the rope size, ϕ_D, may be taken as 5. The spacing of radial ropes is $5\phi_D$ at the net mean circle diameter of (D_o-20).

The outer circumference of the net will be sloped down and anchored to the mooring line. Similar sloping in the inside would also be necessary in case of annular net to guard against the possibility of small ice floes pulling against the inner boundary and resulting in destruction or drifting of the net. For this purpose an additional sloping boundary may be created, probably by using aluminum tubing. For a slope 1:2, the additional width should be 2.23 times the maximum ice thickness in the region of operation. Therefore, it appears that for ice 2-3 m thick, an additional net width of 4-6 m will be required with necessary sinking weights. Based on this and the estimated cost of the sloping part of the net, it is recommended that if d_D is less than 20 m, a complete circular net be used.

8.3 Total Rope Length Requirement

The circumferential length of the ropes, L_c, is:

$$L_c = \pi \left(\frac{D_D + d_D}{2}\right) \cdot \left(\frac{D_D - d_D}{2L_D}\right)$$

$$= \frac{1}{L_D} \quad \frac{\pi}{4} (D^2_D - d^2_D)$$

$$L_c = A_N/L_D \tag{8}$$

where

A_N = area of the net.

The radial length of the ropes, L_R, is:

$$L_R = \frac{\pi}{L_D} \left(\frac{D_D + d_D}{2}\right) \left(\frac{D_D - d_D}{2}\right)$$

$$L_R = A_N/L_D = L_c \tag{9}$$

Therefore, the total length of rope required for the net, L_T, is:

$$L_T = L_c + L_R$$

$$= 2\ A_N/L_D$$

$$= 0.4\ A_N/\phi_D \tag{10}$$

8.4 Stability of the Net in a Tidal Region

In order to evaluate the mooring system required for the net, the calculation of the drag forces resulting from the wind and the water currents is required.

8.4.1 Wind force on the net. When the floating part of the net is subject to wind drag, the force can be calculated by using the same formula as for the drag force on a rough surface. The frictional force, τ_w, between the air and the net is given by:

$$\tau_w = C \rho v^2_w \tag{11}$$

where

C = constant (25×10^{-4})
ρ = air density $(1.3 \times 10^{-3} gr/cm^3)$
v_w = wind speed measurement at 7 m above water level (net surface), (cm/sec)
τ_w = frictional force (dynes/cm^2)

Therefore:

$$\tau_w = 32.5 \times 10^{-7} v^2_w, \text{ dyne/cm}^2$$

or,

$$\tau_w = 3.32 \times 10^{-7} v^2_w, \text{ tons/m}^2$$

where in the last equation v_w is given in m/sec.

Therefore, the total wind force, F_w, may be calculated if the exposed area of the net, A_f, is known:

$$F_w = 3.32 \times 10^{-7} A_f v^2_w \tag{12}$$

where

F_w = wind force on the net, tons
A_f = exposed or floating area of the net, m^2
v_w = wind speed, m/sec

It should be noted that the wind forces on the net are considered equal to the frictional drag on the water surface. This assumption is justified by the large surface area of the net and the relatively small spacing of the ropes.

8.4.2 Current force on the net. The total force on the net caused by water currents may be given by:

$$F_t = F_f + F_s \tag{13}$$

where

F_t = total current force
F_f = drag force on the floating part of the net
F_s = drag force on the submerged part of the net

8.4.2.1 Drag force on the floating part of the net. The geometrical roughness of the net is a significant factor in estimating the drag on the floating net which is determined from:

$$\tau_f = C_D \; A_p \; \gamma_w \frac{v^2_c}{g} \qquad (14)$$

where

τ_f = drag on the net, ton/m²

C_D = drag coefficient – 1.00 for a cylinder

A_p = roughness coefficient, which is evaluated by the projected area of the rope in 1 m² and ranges between 0.1 and 0.2 m²/m² (for $L_D = 5\phi_D$) depending on the buoyancy of ropes and thickness of retained oil

v_c = current velocity, m/sec

γ_w = weight density of water = 1 ton/m³

g = gravitational constant = 9.8 m/sec²

Therefore, the drag force, F_f, is:

$$F_f = \tau_f \; . \; A_f \; \simeq \; 0.1 \; A_p \; . \; A_f \; . \; v^2_c \qquad (15)$$

8.4.2.2 Drag force on the submerged part of the net. The drag force on the submerged part of the net depends on the buoyancy and the mooring cable length. A 2-dimensional calculation was done to define the required angle between the cable and the bottom side of the net. (The drag force on the cable is not considered in this preliminary analysis.) In order to maintain effectiveness of the net, it must be designed such that N% of its total area ($N \simeq 50$) is afloat. The load includes:

a) drag force on cords parallel to the flow which changes with the projected area perpendicular to the flow;

b) drag force on cords perpendicular to the flow which is a constant component.

Therefore, the total drag on the submerged part may be expressed in the form:

$$\tau_s = \tau \; (1 + \sin \alpha) \qquad (16)$$

where

τ_s = drag on the submerged part of the net

τ = drag on the cords perpendicular to the floe

α = angle between the anchor cable and the bottom, as shown in Figure 18.

The constant component is given by:

$$\tau = C_D \; A_p \; \frac{\sigma^{v^2_c}}{2g} \tag{17}$$

where all parameters are previously defined and C_D = drag coefficient = 1.5 for submerged cylindrical shape.

The value of τ_s becomes:

$$\tau_s \simeq (1 + \sin \alpha) \; 0.075 \; A_p \; v^2_c \tag{18}$$

and the total drag force on the submerged part will be:

$$F_s = \tau_s \; A_s = (1 + \sin \alpha) \; 0.075 \; A_s \; A_f \; v^2_c \tag{19}$$

where A_s = area of the rope area of the submerged part of the net.

The resultant force from the water current is:

$$F_t = F_f + F_s = [0.100 \; A_f \; °0.075 \; A_s \; (1 \; +\; \sin \alpha)]A_p \; v^2_c \tag{20}$$

For A_p = 0.2,

$$F_t = [.020 \; A_f + 0.015 \; A_s \; (1 + \sin \alpha)] \; v^2_c \tag{21}$$

8.4.3 ***The buoyancy force on the submerged part of the net.*** The buoyancy force depends on the weight density of the rope. The buoyancy force is therefore:

$$F_b = A_s \times \frac{\pi \phi}{10} \times (\delta_w - \delta_r) \tag{22}$$

where

A_s = submerged area of the net, m^2
ϕ = rope diameter, m
δ_w = water density, ton/m^3
δ_r = rope density, ton/m^3

8.4.4 ***Ice/net friction forces.*** As the net is submerged by ice floes, the moving ice exerts frictional force on the ropes which directly relate to the buoyancy force by:

$$F_i = [A_f \; \frac{\pi \phi}{10} \; (\delta_w - \delta_r)] \; [\mu] \tag{23}$$

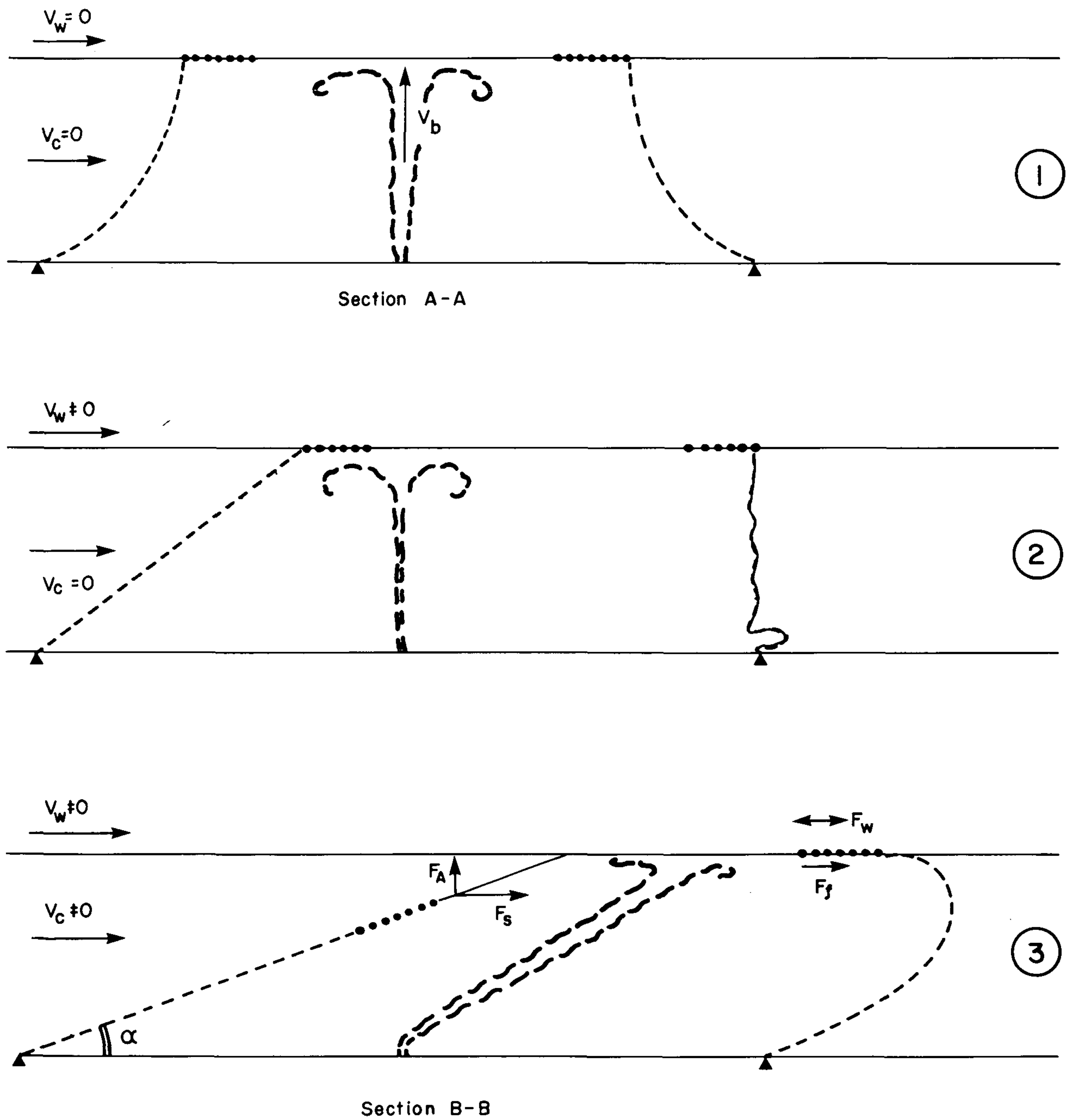


Fig. 18 - Sectional elevation from Fig. 16 showing the effect of winds and currents

where

F_i = ice frictional force, tons

A_f = area of floating part of the net, m^2

ϕ = rope diameter, m

δ_w = water density, ton/m^3

δ_r = rope material density, ton/m^3

μ = friction factor

Finally, these wind and drag forces have to be sustained by the mooring system. Therefore, at equilibrium the angle α is determined from:

$$tg\ \alpha = \frac{F_b}{F_s + (F_w + F_p)} = \frac{F_b}{F_t + F_w} \tag{24}$$

Substituting for F_b, F_t and F_w obtain:

$$tg\ \alpha = \frac{0.1\ \pi\ \phi\ A_s\ (\delta_w - \delta_r)}{[0.020\ A_f + 0.015\ A_s\ (1 + \sin\alpha)]\ v^2_c + 3.32 \times 10^{-7}\ A_f\ v^2_w} \tag{25}$$

A solution to this is only obtainable by trial and error methods.

Figure 19 shows an overall breakdown of the factors that affect the operation of the net; namely, wind and water current and their combinations.

8.5 Design of the Mooring System

The mooring system should be designed to permit the free movement of the net in all directions under combinations of water currents and wind speed (as detailed in Figure 19).

A symmetric 6-line mooring pattern may be used to maintain the net around the blowout location where the oil spill will be trapped and burned. The lines of the mooring systems are assumed to be made of a lightweight material (such as propylene ropes) with a steel cable in the core. This provides a reasonably strong mooring line which has a weight density close to that of water, i.e. the buoyancy forces on the mooring cable will be zero. This allows us to consider that the mooring line is straight and justifies the analysis which will follow. The disadvantage of these straight mooring lines in the high stiffness which is, in fact, not a pressing requirement for this design. The net will therefore sink to compensate for the lack of flexibility of the system. The sinking will be partial and will not interfere with the function of the net since the oil will always be dragged to the opposite side.

Generally, two parameters of the mooring line will be required. These are the cable length and angle and the anchor force.

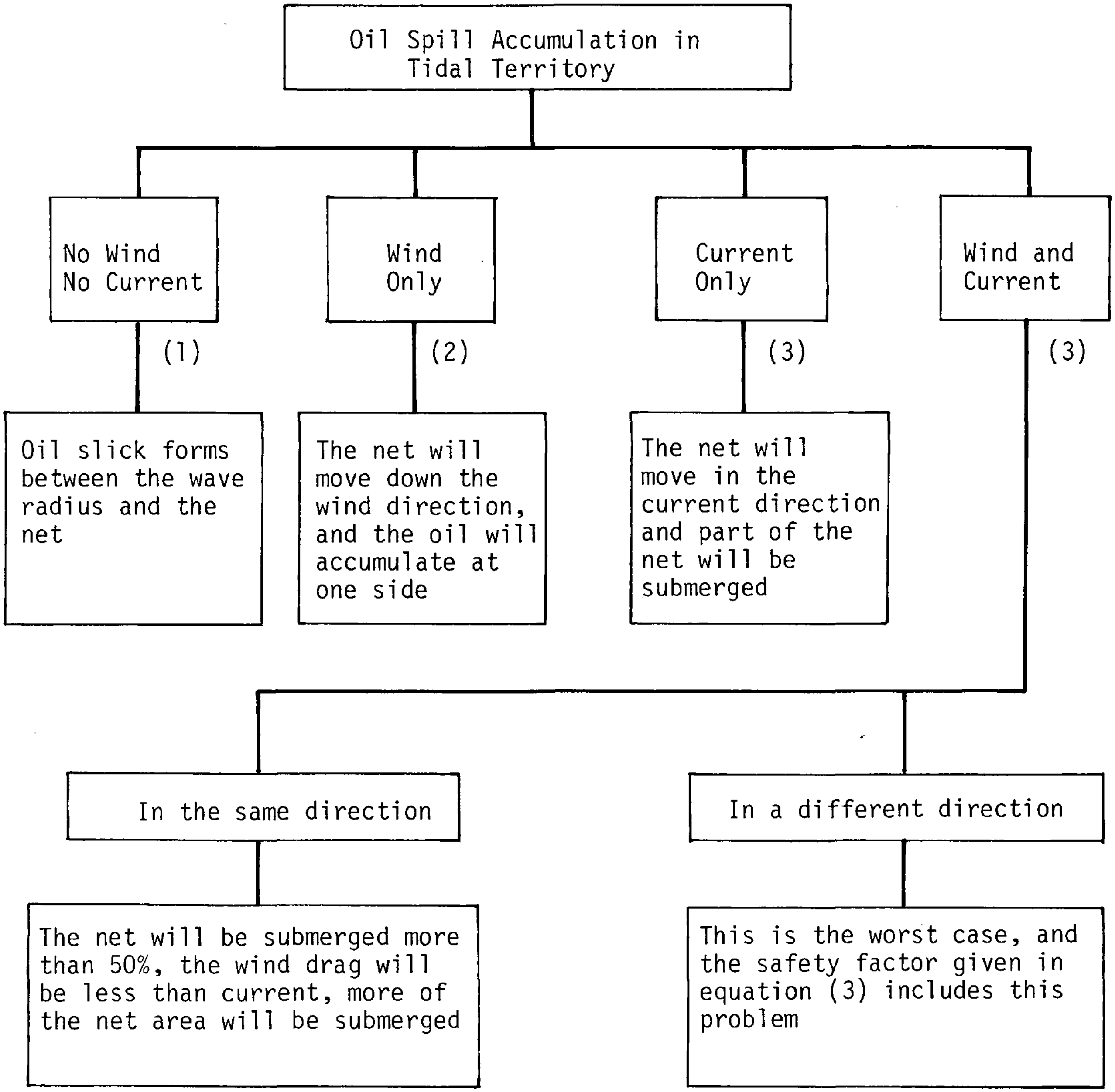


FIG. 19 ENVIRONMENTAL RESPONSE OF A FLOATING NET

Note: Numbers in parentheses refer to Figure 18.

8.5.1 ***Cable length and angle.*** The angle α between the seabed and the mooring cable at maximum water current may be determined from:

$$\sin \alpha = h_D/(0.5\ D_D + l_r) \tag{26}$$

where

h_D = design water depth
D_D = outside diameter of the net
l_r = length of the cable

Therefore,

$$l_r = \frac{h_D}{\sin \alpha} - \frac{D_D}{2} \tag{27}$$

In calm water the angle β is determined from:

$$\sin \beta = \frac{h_D}{l_r} \tag{28}$$

8.5.2 ***Anchor load.*** The maximum force on the anchor can be calculated from: drag force due to water currents, F_t, buoyancy forces, F_b, and ice frictional force, F_i, ignoring the wind drag. The resultant force on the mooring line, R, will be:

$$R = \sqrt{(F_t + F_i)^2 + F^2_b} \tag{29}$$

The resultant force will be shored either by two or three cables. If we consider two cables displaced by 60° the cable tension, R_a, will be:

$$R_a = R/2 \cos 30° \tag{30}$$

$$\simeq 0.58\ R$$

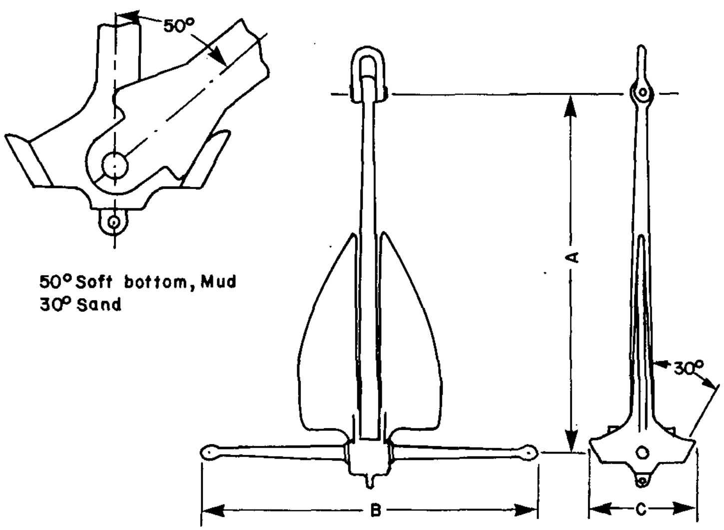
Fig. 20 gives the anchor weight and dimensions which are required for different tension loads and angles. The lightweight cable will have a tensile strength of approximately 300 kg/cm² (4,500 psi).

8.6 Illustrative Example

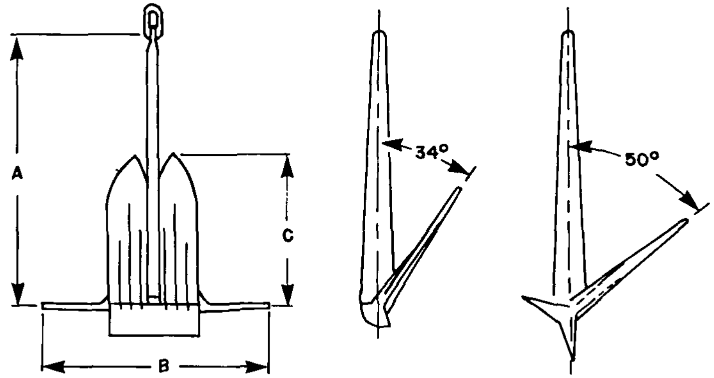
Given the following values for the parameters involved in an oil well blowout, an attempt at making a preliminary design and cost estimate for a floating net device will be made.

Given

design water depth, h_D	= 60 m
steady speed of rising plume, V_o	= 0.46 m/sec
maximum water current speed, V_c	= 0.57 m/sec
maximum wind velocity, V_w	= 40 m/sec (144 km/hr)
density of polypropylenic rope, δ_r	= 0.7 ton/m³ (635 kg/m³)
density of water, δ_w	= 10. ton/m³ (9,701 kg/m³)



ANCHOR WEIGHT	A	B	C	SHACKLE SIZE	PROOF TEST LBS
3,000	103 1/2	104	66	3	45,000
6,000	124	118	114	4	81,500
10,000	144	137	88	4	125,000
15,000	157	149	96	4	170,000
20,000	173	164	106	4	220,000
25,000	186	206	114	5	249,000



ANCHOR WEIGHT	A	B	C	SHACKLE SIZE	PROOF TEST LBS
3,000	129	109	72	1¾	90,000
6,000	144	143	92	2¼	180,000
9,000	160	170	100	2¾	270,000
12,000	186	197	113	3	315,000
15,000	204	224	126	3½	360,000
20,000	210	230	129	3¾	435,000
25,000	226	246	137	4	490,000

FIGURE 20

ANCHOR DIMENSIONS

rope size, ϕ = 0.0762 m (3' diam)
friction coefficient between
polypropylene and ice, μ = 0.3

Assume

Floating area of the net = submerged area = 50% A_n

Calculate

1. Outer diameter of the net from equation (5) = 135 m

2. Inner diameter of the net from equation (6) = 95 m

3. Area of the net from equation (7) = 7226 m^2

   floating area = 3613 m^2
   submerged area = 3613 m^2

4. The angle α is calculated from equation (25) by trial and error. Substituting proper values gives:

   F_w = 1.92 tons (1,742 kg)
   F_b = 25.95 tons (23,541 kg)
   F_t = 49.07 tons (44,516 kg)

   and by iteration

   α = 27°

5. Mooring line length from equation (27) = 65 m
   required length of mooring line = 390 m

6. Angle β from equation (28) = 67°

7. The ice frictional force from equation (23) = 7.78 tons (7,058 kg)

8. The resultant force from equation (29) = 62.5 tons (56,699 kg)

9. The anchor load from equation (30) = 36.3 tons (32,931 kg)

8.7 Cost Estimate

The cost of the net may be determined for various rope sizes. Table 4 provides the summary of calculations made for various cable sizes and densities of commercially available polypropylenic material.

TABLE 4 SAMPLE COST ESTIMATE FOR A FLOATING NET

Rope Specifications								
ϕ		Density	Ultimate Load	Total Length[2]	Total Weight	Estimated Price[3] in Thousands of Dollars	Oil Retaining Capacity	Solid Volume of Net
in	cm	δ_r, gr/cm^3	(ton)[1]	(km)	(ton)		m^3	m^3
3	7.62	0.70	18.24	37.9	121.2	288	148	551
2	5.08	0.57	8.11	56.9	66.2	158	77	367
3	7.62	0.55	18.24	37.9	95.0	226	116	551
4	10.16	0.53	32.43	28.4	122.3	291	155	734
5	12.70	0.52	50.67	22.8	150.0	357	194	918

1 Strength = 400 kg/cm^2

2 From equation

3 Based on $2.38 per kg

8.8 Summary

Based on the foregoing analysis, it appears that the concept of the floating net as a device for containing crude oil after an oil well blowout is feasible. A net must be designed for a range of variables or for a particular drilling area with known environmental conditions. The aforementioned guidelines and considerations may be used to determine a preliminary estimate of the design parameters and expected performance of the net. However, a more detailed study is needed to establish a concrete design procedure and reduce the design requirements and subsequently the cost.

Two questions might be raised concerning the feasibility of the net. The first is whether the net will burn as a result of burning oil collected within the mesh, particularly when a polypropylenic rope is used in the manufacturing of the net. This question was raised during the progress of this work and led to the performance of a simple experiment to obtain a direct and realistic answer.

A 19-mm diameter, 1.5-m long polypropylene rope was placed in a water-filled channel cut in solid ice, and on which channel a thick crude oil film floated. The rope was set up such that some portions of its length were completely submerged and other portions had a floating height of up to 6mm on top of the oil surface. The oil was ignited; the flame propagated and covered the rope length. The burning continued for five minutes, after which the rope was examined for fire damage. The rope was completly covered by thick oil residues and after thorough cleaning, slight damage was observed on the floating parts due to localized melting of the most exposed surfaces. The melting point of the rope material is approximately 130°C.

Although this simple test does not depict serious fire damage to the net, it indicates that the choice of rope material is critical. Two particular parameters must be carefully chosen. These are the weight density of the rope material to minimize the freeboard, and the melting point of the surface to eliminate distortion of the net.

The second question is the possibility of the net freezing in ice and the subsequent problems which may arise from this. Certainly, if the net is allowed to freeze into moving pack ice, it will be carried away. However, as long as the burning of the blowout products continues, the ice will not be permitted to form in the surrounding area. Techniques for maintaining broken ice around the blowout will be discussed further. Additional study is required to examine this situation.

9 BURNING AN OIL LAYER CONFINED BY ICE FLOES

The systems proposed thus far--the bubble barrier, the deep-skirted boom and the net--are designed to function in ice coverage from zero to 80%. Above this level the surface flows can no longer be relied upon to maintain open water over the plume and the oil is retained less by the devices than by edges of floating ice pieces.

This situation would normally apply to ice-infested conditions which may exist in the spring and fall periods, and may also be encountered during winter, particularly in the shear zone along the edge of the landfast ice. It includes all transitory conditions in which broken ice floes ranging in size from 2-m brash ice to up to 2-km long floes.

On the other hand, burning oil amid ice pieces can be an important situation at all times of the year, since a blowout at seabed will induce surface currents outside the outer wave ring which are directed towards the centre of the plume [12.9-126]. These currents will tend to drag brash ice, in light degrees of packing and small pieces, into the entrapment zone at the wave ring radius. In the central area, with the violent turbulence induced by the plume, even larger first-year ice floes intruding this region are likely to be broken into smaller pieces and carried to the wave ring. Therefore, conditions are likely to create a natural boom composed of broken ice floes at the wave ring zone and the central area will be kept clear. Meanwhile, oil will be collecting at the same radius, and thus filling the narrow channels which exist between the ice pieces. The ice will reduce wind drag on the oil, and hence reduce the disruption of the wave ring configuration. Generally, much thicker oil films are likely to be produced in the channels and oil thicknesses of several centimetres may be expected [12.1-87].

However, it should be noted that the channel system created at the wave ring will greatly reduce the volume of oil that can be accommodated in the wave ring region in comparison with the action of a smooth boom at that radius. This means that some oil will have to collect inside the wave ring until a balance with hydrodynamic forces is reached. If not ignited, the oil will then begin to find its way outwards through the channels. The danger of widespread contamination would prompt the need for immediate burning of the oil and keeping the burning rate at its maximum to limit the flow in the channels, therefore containing the oil in a limited area centered about the blowout.

The following cases will be examined to assess the feasibility of burning oil in ice-infested conditions: the burning of oil in pools surrounded from all slides by ice floes, and the burning of oil in channels running between ice floes.

Generally, burning of oil on water while confined by ice is influenced by a complex interplay of:

1. Wind velocity and shielding of the flame.
2. Ice thickness and minimum pool size requirements.
3. Flame propagation in channels.
4. Surface temperature of the oil.
5. Quenching effect of the ice floes.

Each of these effects will be discussed separately.

9.1 Effect of Wind

When the surface of burning liquid fuel is flush with its surroundings, the flame is "blown off" when the air flow reaches a critical speed. Hirst and Sutton [12.8-18] report a series of experiments with small pans of kerosene and isodecane in which they measured the wind speed required to blow out an established fire. At all fuel temperatures the limiting speed for both fuels was 4.5 m/sec (16 km/hr) for a directly exposed fuel. However, with even a narrow obstruction at the upstream edge, the flame is stable to much higher flow rates and the burning rate will increase. Hirst and Sutton found that a 3.2-mm windbreak raised the limiting velocity to 25 m/sec (90 km/hr). They observed that the flame burned in the wake of the obstruction after it had been extinguished over the rest of the fuel surface, so the obstruction performed like the flame holder in a ramjet engine.

Accordingly, it appears that burning oil in small deep pools amidst ice floes would be possible as the ice will shield the flame, even under very high wind gusts. In channels, due to the irregularities in shape and orientations, it does not seem unreasonable to assume that ice floes will provide the necessary upwind obstruction and protect the flame from extinction. However, the flame may not be capable of spreading in channels parallel to the wind direction and this, in turn, will affect the oil supply distribution in the channel system. As a result, if high winds persist for extended periods of time, burning may be limited to channels transverse to the wind direction. Flame spreading in channels under various wind conditions needs to be thoroughly investigated before a concrete conclusion can be established.

9.2 Effect of Ice Thickness

Consider the oil collecting in a pool surrounded on all sides by ice. Assume the pool to be of an approximately circular shape and of diameter d, and let the rim of ice walls have height h_r, above the oil level. Hall [12.8-19] has compiled an extensive review of the fundamentals of pool burning. From these fundamentals it develops that as h_r becomes comparable to d, the burning mechanism becomes increasingly complicated, and the effects of thermal conductance and access of oxygen become significant. The burning rate decreases with an increase in h_r and the flame becomes extinguished at some critical value h_{cr}.

Artemenko and Blinov [12.8-20] determined a relation between h_{cr} and d based on the rate of supply of oxygen according to a modification of Fick's law:

$$h_{cr} = 0.0055\ d^{1.7} \qquad (31)$$

where d and h_{cr} are in millimetres.

This relation was supported by experiments on petroleum distillates and applies for diameters of greater than 50 mm. Therefore, for continuous burning, this condition must be satisfied:

$$h_r \leq h_{cr} \qquad (32)$$

but, the height h_r for a floating ice floe of thickness h is determined from:

$$h_r = (1-\gamma_i)h \qquad (33)$$

where γ_i is the specific gravity of ice = 0.9. Therefore, using equations (31), (32) and (33):

$$0.1h \leq 0.0055\ d^{1.7}$$

or

$$d \geq 5.5\ h^{0.59} \qquad (34)$$

Equation (34) determines the minimum pool diameter to secure enough air supply as a function of the ice floe thickness. Figure 21 is a plot of this relation. For instance, for ice floes 1.6 m thick, the minimum required pool diameter is 0.43 m, while for 3-m thick ice, d would be 0.61 m. It should be mentioned that fire may be sustained in smaller size pools as the spacing between ice floes will provide an additional air supply to the flame. As these spacings increase, the size calculated from equation (34) or determined from Figure 21, tends to be a conservative estimate.

For burning of crude oil in pools Blinov [12.8-19] determined a rate of burning of 0.8 mm/min in pools as small as 300 mm in diameter. In his experiments the rate increased with increasing the pool size until it reached a maximum of 1.6 mm/min at a 1-m diameter and remained constant thereafter.

In channels, the air supply will be continuous from the ends and equation (34) or Figure 21 will yield very conservative estimates of the minimum channel width. A similar curve for channels is expected to be much lower than the present one. However, as can be determined to date, experiments have not been performed on fuels burning in long, narrow channels with high side walls.

9.3 Flame Spreading in Channels

Although no literature is available on burning of oil in long, narrow channels with high side walls, a relevant study was reported by Mackinven, Hansel and Glassman [12.8-21] on the flame spread in trays with relatively low rim height-to-width ratios. They investigated the effects of variation of the tray dimensions on the flame spreading velocity. They used pure fuels with various tray wall materials: aluminum, glass-lined aluminum and Pyrex. Their findings, though not strictly applicable to crude oils, may serve as a guide to what trends might be expected in field situations.

The following parameters will be examined in view of their effect on flame spreading in channels:

1. Height of the tray rim above the fuel surface.
2. Tray width.
3. Tray length.
4. Oil thickness.

9.3.1 ***Effect of rim height.*** The results shown in Figure 22 indicate that the flame propagation velocity is reduced by increasing the rim height and it approaches a constant rate at approximately a 7-mm rim height. It should be noted that the channel width was at least six times the conservative estimate determined from equation (34). An interesting comparison at approximately the 13-mm freeboard may be made between the various points obtained by the investigators.

Point A in Figure 22 was obtained for an aluminum tray lined with plate-glass inside the entire long wall, thus minimizing heat loss through the walls. Point B was determined for an unlined aluminum tray. The decrease in flame spreading rate was therefore caused by heat losses through the

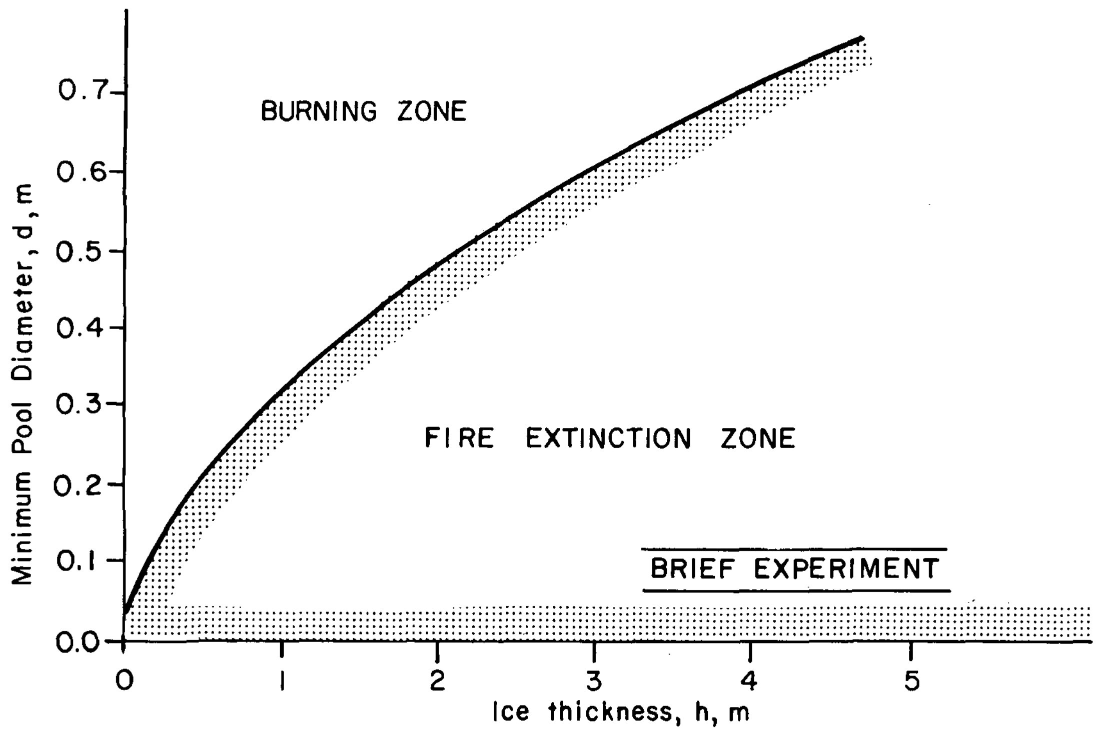


Fig. 21 – Minimum pool size for various ice thicknesses.

*A brief experiment was conduct in Arctec Canada's experimental facility to examine the validity of equation (4) derived from Russian results. A deep hole 0.17 m in diameter and 0.40 m deep was drilled in solid freshwater ice. The hole was partially filled with water and a 10-mm crude oil layer such that the rim height was adjusted to 0.27 cm, which is equivalent to 2.75 m of ice thickness. The ambient temperature was 2°C. The oil was easily ignited by a candle flame. It was observed that the fire was not extinguished, but the flame was very weak and very turbulent. The flame only covered a part of the surface area of the pool to permit air supply. The burning rate was slow and the flame height did not exceed the rim height. Ice erosion was less than what was observed in chemical burning. This single result does not negate the logic of equation (4), but demonstrates the need for data on burning crude oil under simulated field conditions.

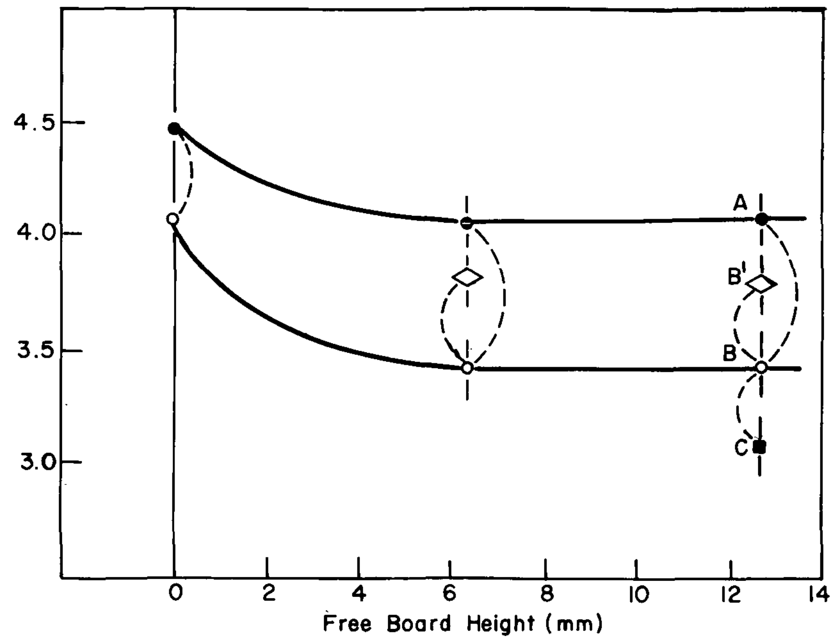


Fig. 22 - Flame spreading velocity of Dipentene as a function of the height of the tray rim above the liquid level — The Free Board Height. (from Mackinven, Hansel & Glassman 12.8-21)

Conditions: 4mm depth of dipentene floated on 14.8 mm of water in trays 120 cm long by 15 cm wide; o aluminum tray, ● aluminum tray lined with 19-mm wide plate-glass inside the entire long wall, ◇ aluminum tray lined and with 19-mm wide plate-glass inside the central 45 cm of the length, ■ aluminum tray lined with 13-mm wide plate-glass inside the entire length such that the glass obscures the freeboard.

walls. A partial lining would decrease the heat loss and increase the rate to the level B[1]. When the aluminum tray was lined with plate-glass such that the glass obscured only the aluminum wall above the fuel surface, an additional fall to point C was observed. This fall could be attributed to the fact that insulating the freeboard caused a loss in the heat conduction to the fluid through the wall. Meanwhile, the fuel being in contact with the wall in the latter case loses some of its heat to the surroundings as well.

In view of these results, it is not unreasonable to assume that if the sides of the channel were made of ice, the rate of flame spreading will fall below C. Furthermore, a much lower rate would be expected for crude oil. At the present it is predicted that the rate of flame spreading in narrow channels would probably be of the order of 1 cm/sec. A realistic figure, however, will have to be determined by experiment.

9.3.2 ***Effect of width.*** The width effect is shown in Figure 23 from which some interesting points are made:

1. As the tray width narrows down to less than 60 cm, the effect of heat losses through the walls becomes significant for a rim height of 6 mm. This confirms that the heat losses from the liquid fuel to the walls becomes less important as the width exceeds 0.6 m. For narrower channels the quenching effect of ice walls will become increasingly significant and may be found to control the burning process. Quenching will be discussed later.
2. As the heat losses increase with decrease of tray width, the flame spreading diminishes rapidly. However, the diminution, in this case, is attributed largely to the viscous flow effects which become apparent at smaller widths. This changes the heat convection process and results in a series of small flamelets which are basically independent of one another in the 25-mm wide tray.

9.3.3 ***Effect of length.*** The results shown in Figure 24 indicate that for tray lengths above 1.8m the flame spreading velocity is insensitive to increases in length. However, the spreading velocity decreases slightly as the length shortens. The decrease amounts to approximately 8% for a 0.9-m long tray. This loss is attributed to the perturbation of the flow characteristics of the convective motion in short trays.

9.3.4 ***Effect of film thickness.*** The effect of fuel film thickness with n-decane is illustrated in Figure 25. Minimum thickness requirements will be dicussed further.

9.4 Surface Temperature of the Oil

A necessary condition for continuous combustion is equilibrium between the rates of vapourization and fuel burning. This requires that the surface temperature of the oil be maintained at the fire point or higher.

It has been found [12.8-19] that the temperature distribution in a fuel pool floating on water will approximate that for the fuel alone. Generally the temperature gradient is shallow and steep.

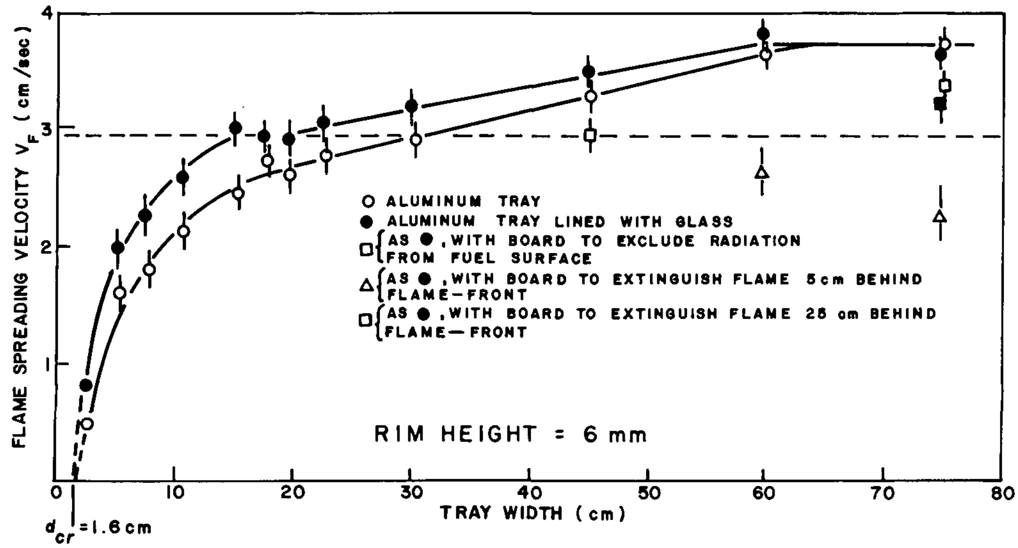


Fig. 23 — Flame spreading velocity of *n* - Decane as a function of tray width (from Mackinven, Hansel and Glassman: 12.8 -21)

Conditions: 4 mm depth of *n-decane* floated on 14.8 mm depth of water in trays 120 cm long by 2.5 cm deep; initial temperature 23.0 ± 0.1°C.

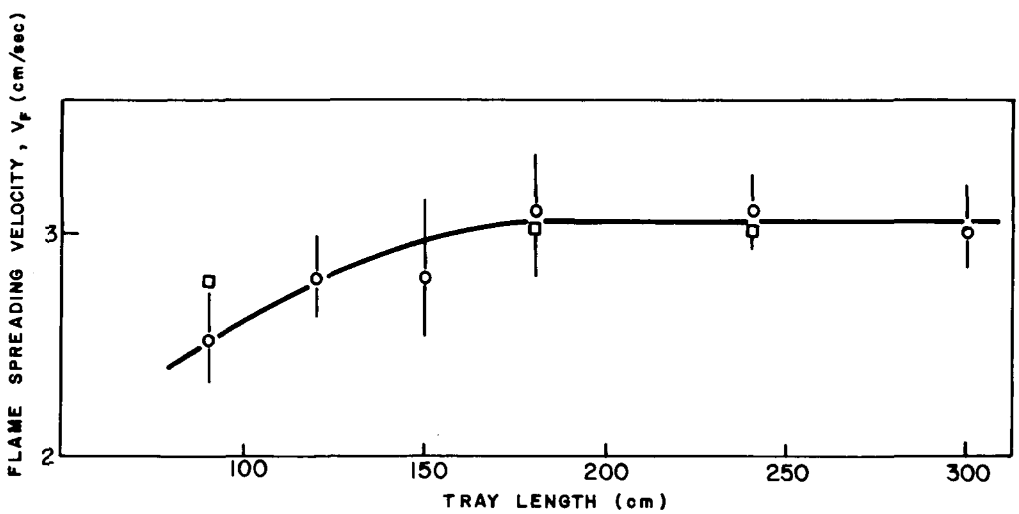


Fig. 24 – Flame spreading velocity of *n*-Decane as a function of tray length (from Mackinven, Hansel and Glassman: 12.8-21)

Conditions: 4-mm depth of *n-decane* floated on 14.8 mm depth of water in trays 19.5 cm wide by 2.5 cm deep lined with glass inside the long wall; initial temperature of fuel is 23.0 ± 0.1°C; □ indicates cinematographic runs.

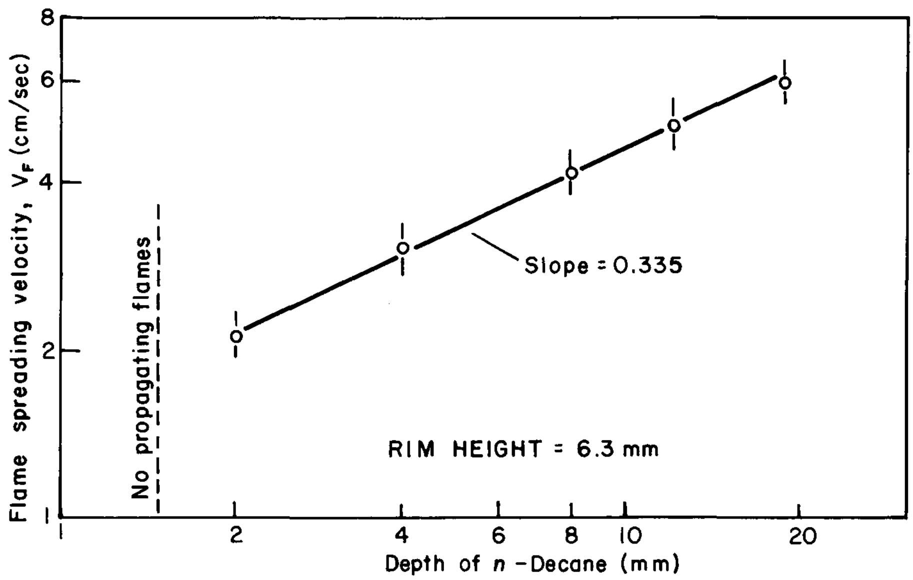


Fig. 25 - Flame spreading velocity of *n* - Decane as a function of fuel depth.

(from Mackinven, Hansel and Glassman (12.8-21)

Conditions: *n-decane* floated on water such that the total depth of liquid is 18.8 mm; tray 180 x 19.5 x 2.5 cm lined with glass inside the long wall; initial temperature of fuel is 23.0 ± 0.1°C.

The penetration of heat below the surface is on the order of a few centimetres depending on the fuel type and water temperature. However, a minimum thickness is necessary to reduce the temperature at the fuel-water interface. This is essential to minimize the heat loss in evaporating water and the inerting action of its vapour which may lead to non-propagation of the fire or even to its extinction.

The critical thickness for combustion of fuel on water is defined as the thickness at which the heat conducted through the film into the water is equal to that radiated from the flame to the fuel. For a typical oil this is estimated to be 1.3 mm. As the thickness decreases, the percentage of liquid residues will increase. In laboratory experiments to determine the minimum depth of crude oil which will burn floating on water, it was found that oil layers with initial depths of 1.35, 0.7 and 0.35 mm burned to leave liquid residues of 0.35, 0.4 and 0.27 mm, respectively. The liquid residue remains as a sludge which contains an amount of water proportional to the degree of water vapourization [12.8-19].

It should be indicated that thinner oil slicks will be more difficult to ignite, particularly under weathering conditions. Weathering affects the loss of light fractions by exposure. It has been stated that a 3-mm layer of Kuwait crude oil lost approximately 24% by weight after exposure for 24 hours. This oil could not be ignited by the application of a gasoline/air flame, except when primed with more volatile fuel.

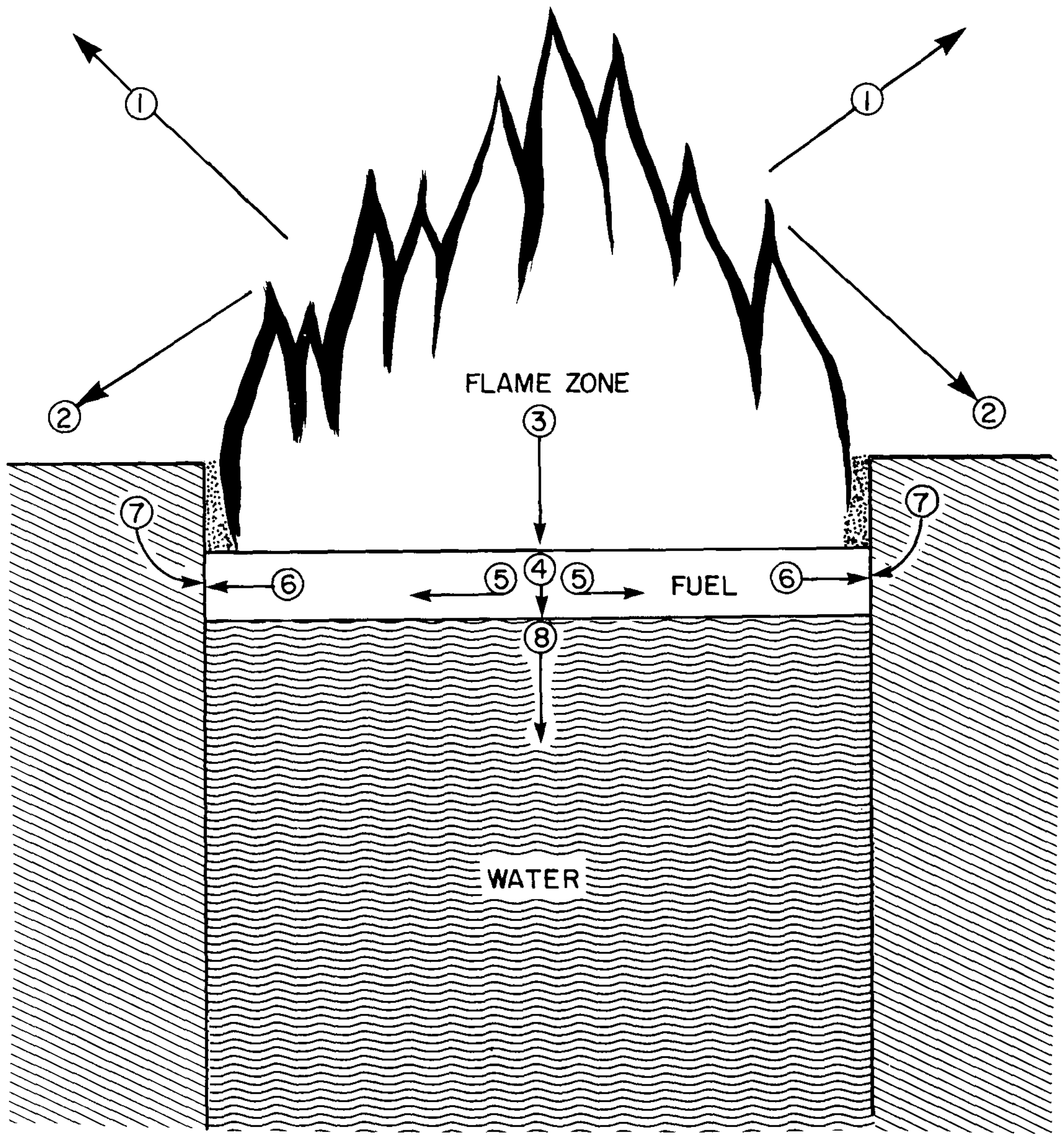
9.5 Quenching Effect of Ice Floes

It has been observed by Russian investigators that the burning rate varied markedly with both the thickness and the thermal conductivity of the wall for liquids in containers with diameters of up to 20 mm. Generally, it should be expected that the smaller the pool size, the more significant the losses through the walls will be. The effect of walls may be visualized by examining Figure 26, which is a schematic representation of the process of heat transfer during burning.

The situation of burning oil confined by side walls of ice is rather unique. Ice is different from metal or glass in that it forms almost a constant temperature wall. As the surface temperature of ice rises to its melting point, the heat input will be consumed in fusion of thin surface layers of ice. This may result in large heat losses through the fuel-ice interface and subsequently, may reduce the surface temperature of fuel in the flame zone. This, in turn, may reduce and stop the evaporation process from destroying the balance between burning and evaporation, possibly resulting in the flame being quenched.

In the ice wall rim above the fuel level, it is likely that, due to high intensity of radiation, a thin layer of water vapour will form and act as an insulating layer. The amount of vapour may not be sufficient to have inerting and disturbing effects on the burning process, but will greatly reduce the heat loss through the rim walls. Furthermore, the component #7, as indicated in Figure 26, might be neglected. As a consequence, hot zones may not form under these conditions and the loss of heat at the oil-ice interface will be significant.

A simple laboratory experiment was conducted to demonstrate the burning of oil in deep channels and to obtain a first-hand knowledge on the effect of quenching. Crude oil was used rather than other light fuels. A wedge-shaped channel was dug in solid freshwater ice in a large frozen pool. The channel was 3.3 m long and had a 360-mm base width. Width measurements were taken every 30 cm



① Heat radiation from flame to atmosphere
② Heat transfer from flame to ice walls
③ Heat transfer from flame to fuel surface
④ Heat transfer from fuel surface to fuel-water interface
⑤ Convection from heating centre outwards
⑥ Heat loss from fuel layer to wall
⑦ Heat transfer from ice walls to fuel
⑧ Heat transfer from fuel to water

Fig. 26 QUENCHING EFFECT OF ICE FLOES

from the wedge point and these locations were marked with steel markers laid on the channel side. These markers served as a scale in the photographs and were also used for width measurements after burning the crude oil. The channel was filled with water up to a rim height of 150 mm, which is equivalent to 1.5 m ice thickness. Then a 10-mm thick crude oil layer was created on the water. The average water depth below the surface was 120 mm.

The oil was ignited at the base of the channel, and the buildup and propagation of the flame was observed. Photograph facsimiles, Figure 27, illustrate the progress of burning. The average rate of flame propagation was 0.8 cm/sec and this agrees with earlier predictions.

After the fire died out, the channel dimensions were measured. It was observed that the wall had eroded all along the channel rims above the oil level. The amount of erosion varied with the width. Generally as the width decreased, the erosion decreased.

Substantial erosion was observed at the oil layer level. This erosion took the form of a 17-to-10-mm-wide groove, deep enough that one could easily insert his fingers in the groove. The surface of the groove was reasonably smooth with minor irregularities in shape. Its depth varied from a minimum of 20 mm measured around the wedge point up to 50 mm at its base. The numerical values of both wall and groove erosion are tabulated for different widths in Table 5.

The walls at the wedge point were observed to melt, forming a rather rounded shape. The groove continued to exist at the wedge point. Figure 28 compares the shape of walls before and after burning.

When the erosion is plotted versus the channel width, as shown in Figure 29, it is possible to determine best fitting, straight lines. The fitting indicates that wall erosion, E_w, is linearly proportional to the channel width and the proportionality constant is equal to 6.7%. Since this erosion is directly influenced by the amount of radiation from the flame, and since it is generally understood that the flame height is a function of the pool size, it is not unreasonable to expect this direct proportionality. However, as the channel width increases to more than 600 mm, the burning rate of crude oil stabilizes [12.8-19] and the flame spreading velocity virtually tends to be constant (Figure 23). The erosion will therefore tend to a maximum value regardless of the distance between floes.

To express this wall erosion in terms of oil quantity, an approximate erosion rate of 0.007 per mm of crude oil may be calculated. From the experiment the burning rate of oil is approximately 2 mm/min, which is slightly higher than Blinov's figure of 1.67 mm/min determined for pools. Thus, for continuously burning channels the rate of wall erosion, E_w, may be determined from:

$$E_w \text{ (mm/min)} \simeq 0.007 \times d \text{ (mm)} \times v \text{ (mm/min)} \qquad (35)$$

$$\simeq 0.014\, d$$

As the channel width exceeds 600 mm, the erosion approaches a constant rate of approximately 8 mm/min. Therefore, brash ice floes of 2 to 3 m in diameter are expected to disappear within a few hours if surrounded by fire.

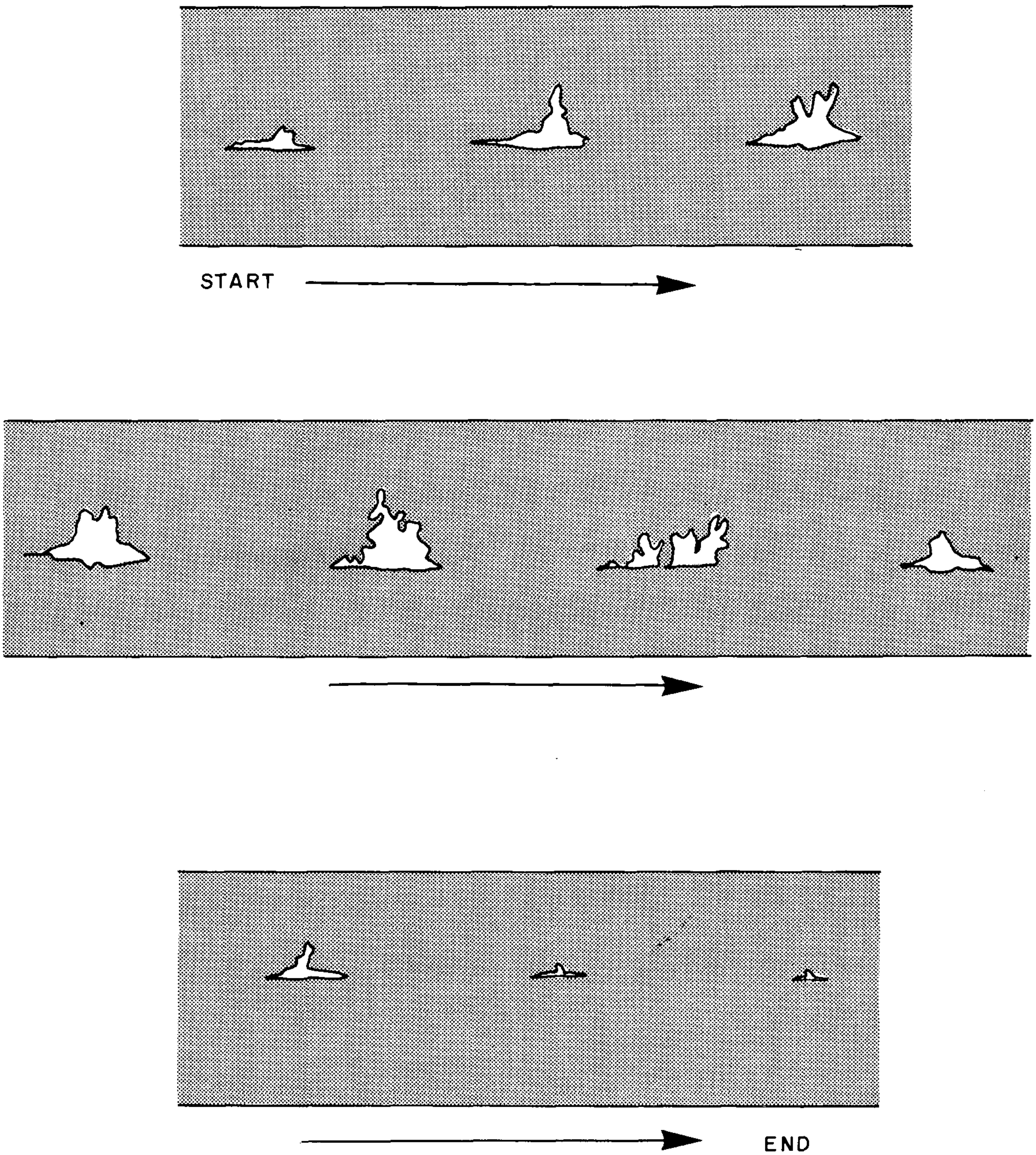


Fig.27 Burning oil in a wedge of ice

TABLE 5 NUMERICAL VALUES OF WALL AND GROOVE EROSION

DISTANCE FROM APEX OF WEDGE (mm)	WIDTH d (mm)	WALL EROSION (mm)	TOTAL GROOVE DEPTH (mm)	PERCENTAGE WALL EROSION %	PERCENTAGE GROOVE DEPTH %
305	95	7	27	7	28
610	152	10	35	7	23
915	183	12	44	7	24
1220	216	14	58	6	27
1525	292	16	67	5	23
1830	318	25	76	8	24
2135	356	25	76	7	21

NOTE:

$$\text{Percent wall erosion} = \frac{\text{Wall erosion}}{\text{Channel width}} \times 100\%$$

$$\text{Percent groove depth} = \frac{\text{Total groove depth}}{\text{Channel width}} \times 100\%$$

Wall erosion = 0.5 x increase in channel width

Finally, it should be noted that these figures strictly apply to the 1.5-m thick ice. Generalization is subject to experimental evidence.

Groove erosion, E_g, may be determined from the following exponential relation:

$$E_g = 0.52\ d^{0.854} \tag{36}$$

where d = the channel width in mm

This is subject to the same condition of maximum channel width. It should be noted that the rate of groove erosion is three to four times the wall erosion. This fact emphasizes that the effect of convective heat loss (component #6 in Figure 26) is far greater than the radiation component from the flame to the ice walls. By analysis similar to that of wall erosion described earlier, the rate of erosion in the groove is expected to reach a maximum value of approximately 30 mm/min.

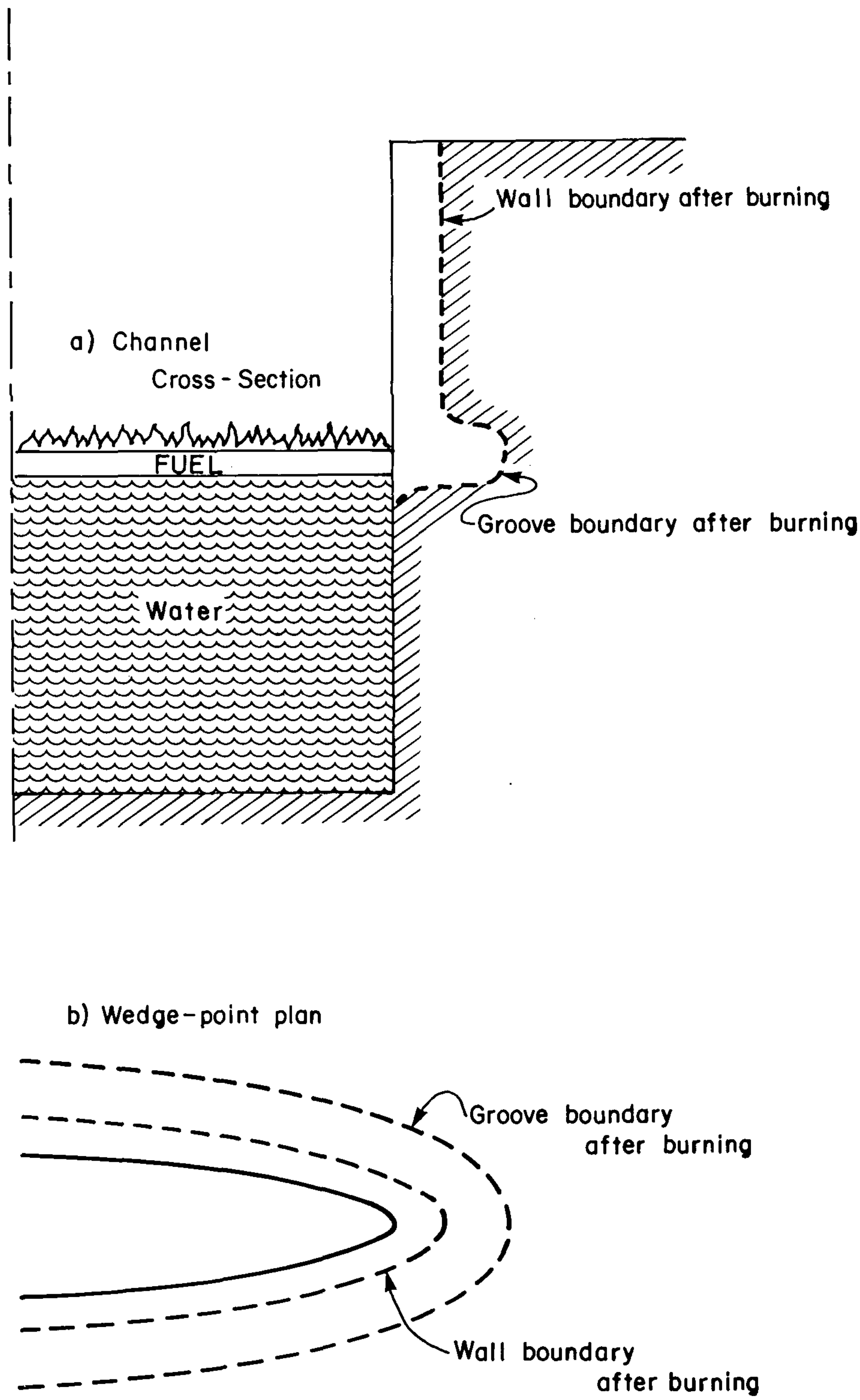


Fig. 28 - Erosion of ice boundaries due to burning

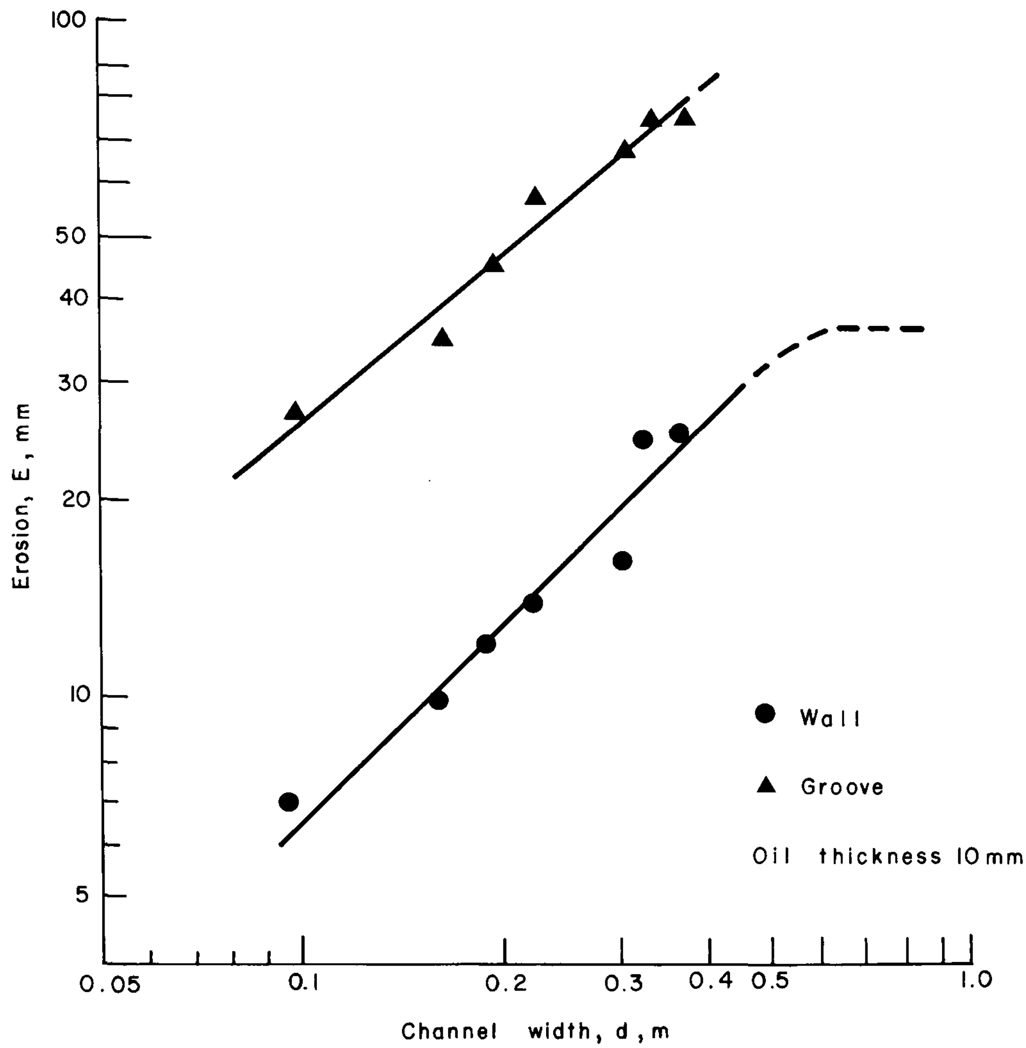


Fig.29 - Erosion in a burning channel

The mechanism of thermal erosion of the ice walls during crude oil burning becomes more complicated by the fact that the ice floe is continuously moved upwards by the buoyancy forces at a speed proportional to the erosion rate.

Now in considering moving ice floes, examine the possibility of flame survival and assume that the maximum erosion rate of the walls is achieved. This means that the fire will erode the wall of an advancing ice floe at a rate of 0.5 m/hr or 12 m/day. If the ice floe is large in diameter and moves at a higher speed, the fire will not be able to withstand its advance and might become extinguished. There is not enough heat available in the standard 1,000 barrel/day (159 m^3/day) blowout to entirely melt any substantial volumetric rate of ice intrusion. However, if the ice floe is broken into small brash ice floes possibly by bombing the front of the advancing floe at intervals, it should be possible to maintain the burning process in open areas between the moving ice pieces.

If it is possible to break the ice cover into small ice floes, an additional supply of oil will be made available as the ice melts. This is the oil contained in depressions and pools under the ice.

In the landfast ice zone where ice is relatively immobile, it is likely that the erosion rates will suffice to melt the front of the limited ice movements and maintain the burning of oil. In ice-infested regions, burning is expected to continue as long as there is sufficient supply of oil in the channels and pools. In continuous and moving ice zones, area bombing seems to be the only solution to create the conditions necessary for flame survival.

10 BREAKING ICE FOR BURNING

10.1 Impact Methods

There are four apparent impact methods for breaking the ice to create a crater for burning:

1. Placing a charge under ice.
2. Using an ice penetrometer.
3. Placing shaped charges on the ice.
4. Bombing.

10.1.1 Placing a charge under ice. Several studies have been undertaken to assess the efficiency of creating ice craters with explosives placed under ice sheets. (Livingston, 1960, Michel, 1971, Frankenstein and Smith, 1970). Such tests have shown that for maximum efficiency the explosive charge should be placed 2-3 m under the ice sheet. Frankenstein and Smith, 1970, report that for optimum fracture the charge depth below ice (h) should be such that:

$$h = 0.79\ W^{1/3} \qquad (37)$$

where

h = placement depth below ice sheet (metres)
W = charge weight (kg)

Various types of explosives have been tested for efficiency in removing ice jams and it has been found that ANFO (ammonium nitrate fuel oil), TNT (trinitrotoluene) and dynamite all yield approximately the same crater size to explosive weight ratio. Thermite, which is a mixture of aluminium power and iron oxide, was not found to be very efficient.

For underwater placement, TNT may be preferred to ANFO since it is unaffected by water. ANFO must be packaged in waterproof packages since it will not detonate if wet. Dynamite is susceptible to cold temperatures which cause the nitroglycerine to bleed out, resulting in an unstable mixture. It is also possible that liquid oxygen could be used as an explosive and the released oxygen could assist burning.

Frankenstein and Smith, 1970, report the following relationship for the diameter of the crater when charges are placed at the optimum depth as previously discussed:

$$d = 8.02\ W^{1/3} - 9.54 \qquad (38)$$

where

d = crater hole diameter (metres)
W = as before

Hence, creating a crater 6 m in diameter in ice 2 m thick requires $W = 7.3$ kg, with depth of charge placement below the ice being $h = 1.5$ metres.

One method of placing the charge below the ice is shown in Figure 30.

Nikolaev, 1971, reports on an icebreaking method used in the Soviet Union using directional explosives consisting of two charges; a preliminary auxiliary charge which is detonated just before a main blast. The weight of the main charge can be determined from:

$$C_2 = Kh^3 \qquad (39)$$

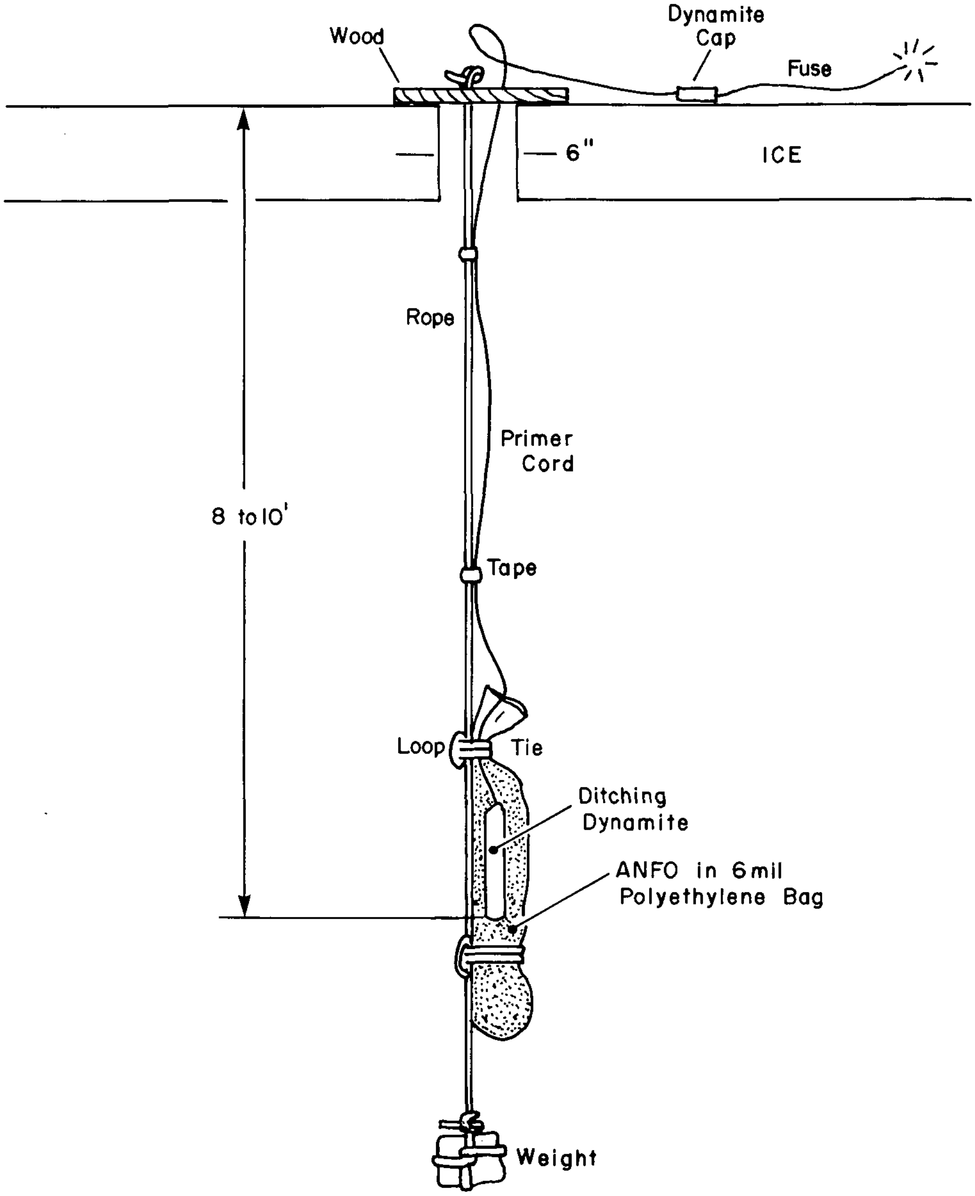
where

C_2 = weight of main charge (kg)
h = ice thickness (metres)
K = ice coefficient (See Figure 31)

The auxiliary charge C_1 should have a weight such that:

$$C_1 = \frac{C_2}{6} \qquad (40)$$

Based upon these formulae, for ice 2 metres thick, $C_2 = 80$ kg and $C_1 = 13$ kg. These are considerably greater than the charges determined in the method of Frankenstein and Smith, 1971. One possible explanation for the larger charge estimates may be that the directional blasting method yields larger-sized craters. Nikolaev reports that the breakage zone of ice fracture is elliptical when directional blasting is used rather than circular, which would be the case for concentrated point or



Location of explosive charge dependent on water depth and charge weight. Weight size dependent on current.

Fig. 30 - Optimum placement of explosive charge.
(From [12.9-145])

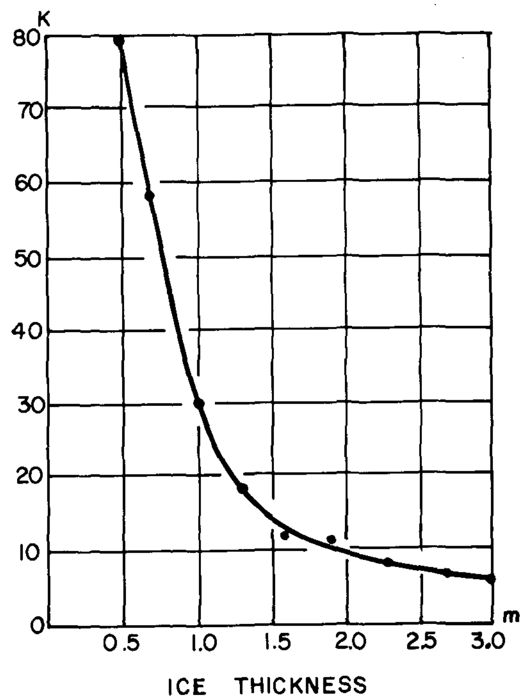


Fig. 31 – Coefficient K as a function of ice thickness, for S from 3 to 7%, ice from –5 to –10, and TNT used as explosive.

suppressed charges. It is reported that the use of directional blasting produces breakage zones, which for given ice thicknesses are 45 to 70% larger than that resulting from the same charge weight when concentrated blasting methods are used.

The size of crater resulting from blasting would depend upon the compressive stresses within the ice sheet. For inner landfast ice which is not highly stressed, it is expected that craters would remain open until refrozen. However, for outer landfast ice and ice within the shear zone, it is possible that the crater sides would flow inward as the ice creeps under compressive stresses.

10.1.2 Ice penetrometer. Ice penetrating projectiles have been developed for measuring ice thickness. One such system has been developed by the Sandia Laboratory (Young and Keck, 1971, McIntosh, Young and Welsh, 1973) which consists of a long projectile with a shaped nose and is guided by tail fins, as shown in Figure 32. The penetrometer has sucessfully measured sea ice thicknesses of over 3 metres. Young & Keck report the following relationship:

$$D = 0.0117\ SN\ \frac{W}{A}\ V - 30.5 \quad \text{for } V \text{ greater than or equal to } 61 \text{ m/sec} \qquad (41)$$

where

D = ice penetration (m)
S = index of penetrability
N = nose performance coefficient

W = weight of penetrometer (kgs)
A = cross sectional area (cm^2)
V = impact velocity (m/sec)

The value of "S" depends upon the ice characteristics and is lower for more resistant materials such as multi-year ice. Typical values for S are:

1.9 multi-year ice
2.8 first-year ice
3.7 – 6.8 refozen leads

The nose performance N varies with the physical properties of the projectile tip. Experimental results show a typical N = 0.7. The impact velocity V varies with the shape of the projectile, its weight and the height above the ice surface of its release; however, a typical value is V = 150 m/sec. Based upon these approximations, the following relationship could readily be determined:

$$\frac{W}{\phi^2} = 0.35 \frac{D^2}{S^2} \qquad (42)$$

where ϕ is the diameter of the projectile in cm. This equation has been plotted in Figure 33 for various values of S.

As seen from equation (42), to penetrate 2 metres of landfast ice (first-year ice) requires a value $\frac{W}{\phi^2} = 0.18$. Hence, a 6-cm diameter penetrometer must weigh 6.5 kg.

When dropped from a fixed wing aircraft, the penetrometer has a horizontal velocity component and may not strike the ice surface at a sufficiently steep angle to penetrate. Ideally a rotary wing aircraft would be used or a fixed wing aircraft with a special chute to initiate the proper trajectory. Tests have shown that the impact angle should be at least 40° above the horizontal plane for penetration. However, at these shallow angles considerable penetration energy is lost.

The penetrometers developed by the Sandia Laboratory deployed a trailing line system with a transmission line and transmitter to relay deceleration information. Based upon the deceleration information relayed back, the ice thickness for penetrometers penetrating sea ice could be determined by:

$$T = \sin\theta \left[D_1 - \frac{L}{3} - D_2\right] \qquad (43)$$

where

T = ice thickness (cm)
θ = trajectory angle at impact measured above the horizontal
D_1 = penetration of nose when deceleration decreases to the 80g level

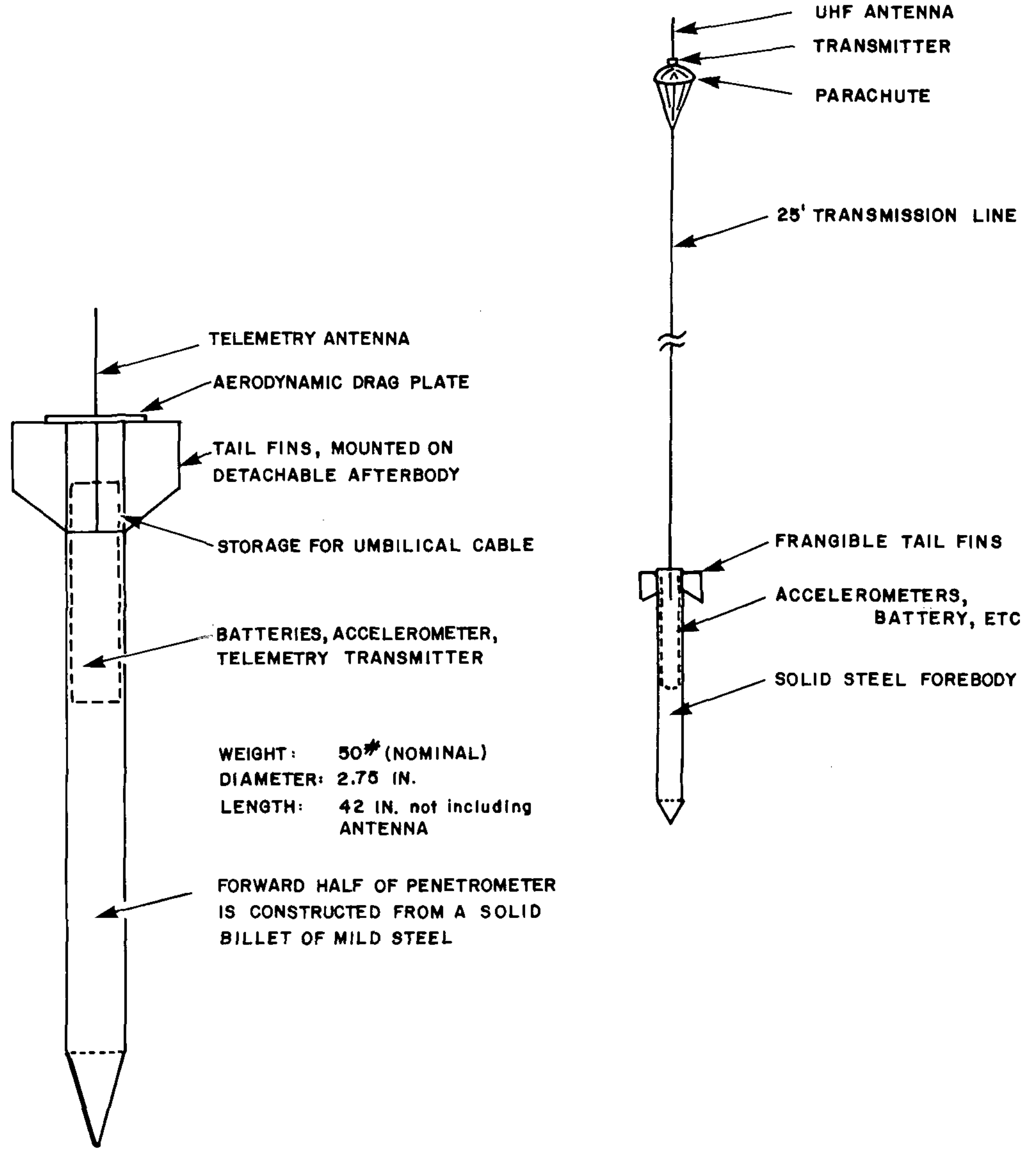


Fig. 32 - Penetrometer arrangement developmental test series

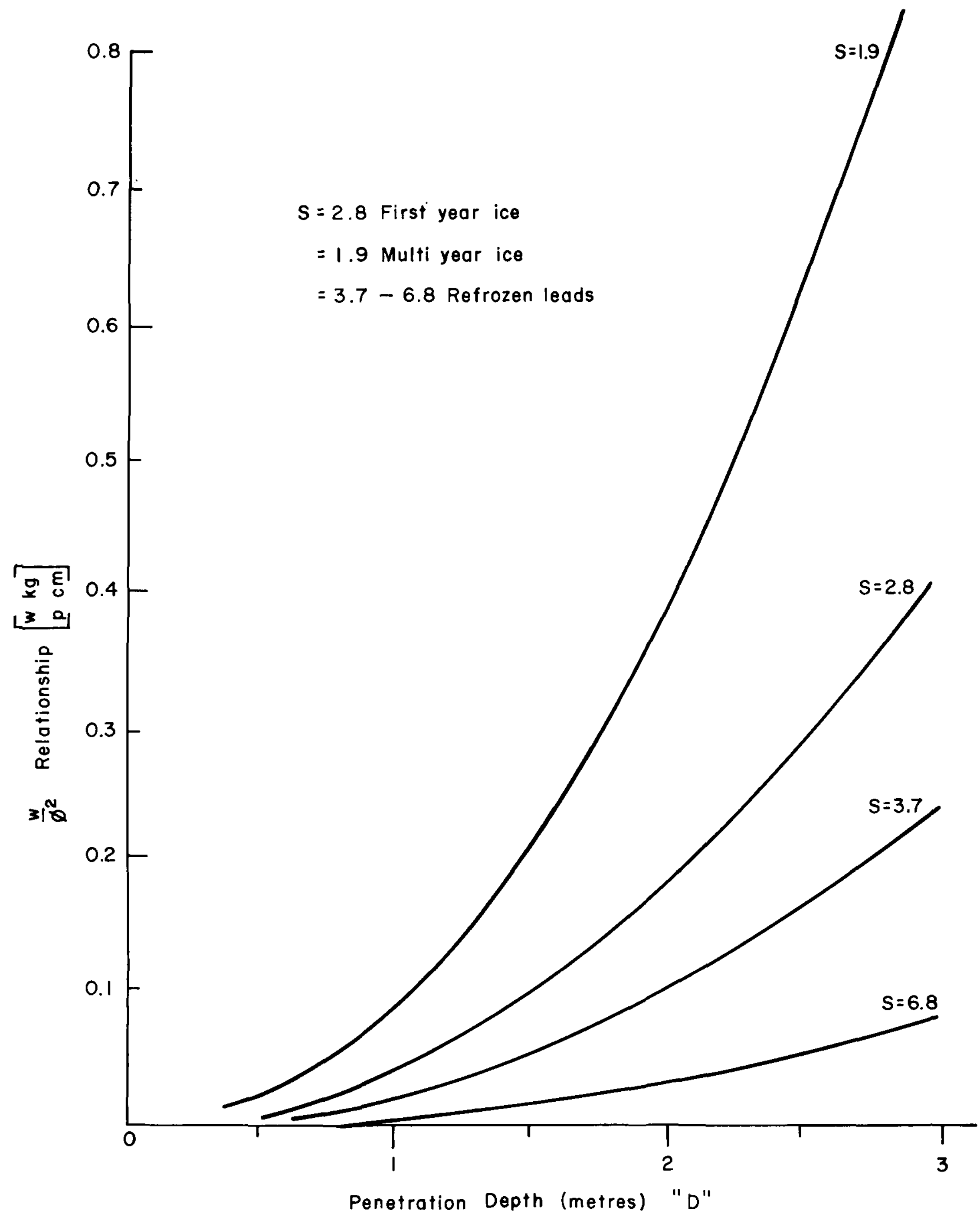


Fig.33 Plot of $\frac{w}{\phi}2 = 0.35\left[\frac{D}{S}\right]^2$ for various values of S.

L = length of penetrometer nose
D_2 = distance travelled through snow (cm)

The distance travelled through snow is:

$$T_2 = \sin \theta \; D_2 \qquad (44)$$

where T_2 = snow thickness

The value of D_1 is important because it was empirically determined that when the deceleration decreased to a value of 80 g, one-third of the length of the nose had departed from the bottom of the ice and therefore protruded into the sea.

Penetrometers, as described above, could be used for several purposes in combatting oil spills in the Beaufort Sea. Due to their relatively low cost for small models (about $100 each in 1973) they could be readily deployed to find major pools of oil underneath ice surfaces. If dropped on an oil and gas pool, it is likely that some oil would become visible on the ice surface which might not otherwise be detectable.

While penetrometer holes would normally be relatively small in diameter, larger projectiles could be developed so that the resulting hole would be large enough to support combustion. As discussed in Section 6, for combustion to be successful the hole diameter (ϕ) must be such that:

ϕ is greater than or equal to $0.55\ h^{0.59}$ (Refer to equation 34)

where

d = hole diameter (centimetres)
h = ice thickness (millimetres)

Based on equations (32) and (34), the proper dimensions and weight of a penetrometer to place a hole capable of supporting burning can be determined. For example, in first-year ice $S = 2.8$ and $\frac{W}{\phi^2} = 0.18$ and hence $\phi = 2.36$ W. Hence, 2.36 W is greater or equal to 0.55 h, where h = ice thickness in millimetres. Thus, for ice which is 2 m (2,000 mm), the weight W is greater than or equal to 430 kg, and hence $\phi = 49$ cm. Such a projectile should penetrate the ice with a diameter sufficiently large to support combustion.

If the penetrometer is smaller than that required for combustion, the holes created could be used to lower an explosive charge through the ice, or the penetrometer could be a bomb set to detonate when the charge has penetrated a sufficient distance through the ice.

10.1.3 Shaped Charges. Shaped charges are explosive devices so shaped that the energy of the explosive is concentrated in a small area and creates a tubular-shaped hole in the object against which it is placed. Such a device can be made of three distinct components (1) container (2) cone liner and (3) explosive charge. The container is the outer covering of the shaped charge, while the cone liner is usually a hollow cone forming the cavity at the bottom of the charge producing the directional effect. The charge may be any of several types of suitable explosives. Figure 34 shows a typical shaped-charge arrangement.

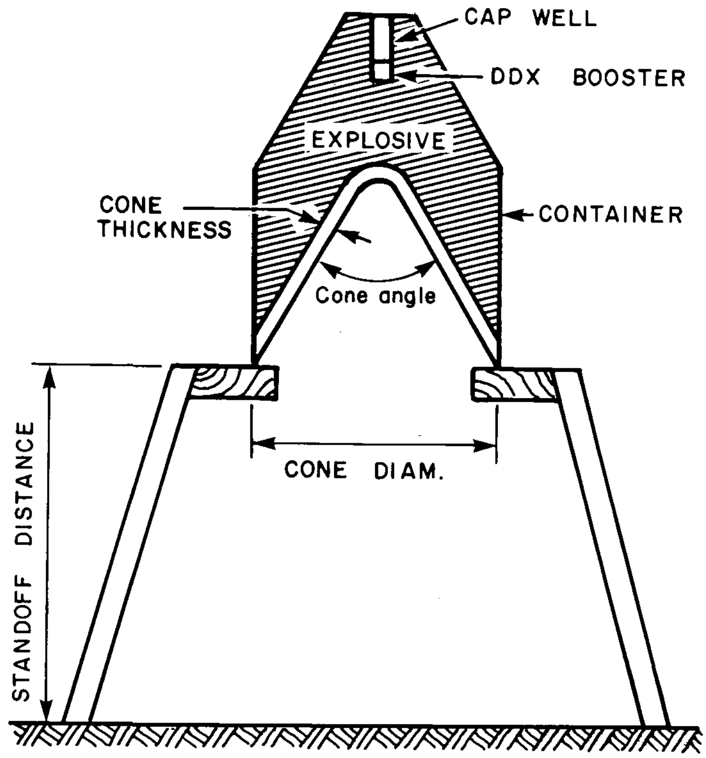


Fig.34 Shaped charge in firing position

While shaped charges have been used for rapid placement of foxholes in frozen terrain, they could likely be used to create craters in sea ice. Such devices could be lowered onto the sea ice surface by helicopter and detonated. One of the major advantages of such a system is that dud munitions could be handled relatively simply since there would not be a requirement for sub-sea salvage activities.

10.1.4 ***Bombing.*** Apparently there is little available information on the feasibility of bombing ice to create craters. Such operations are no doubt feasible; however, they would be military operations. The Canadian Department of National Defence has reported that a 500-lb (227-kg) bomb can blast a hole 2 m in diameter in ice 2 to 4 m thick, and that a 1,000-lb (454-kg) bomb would only increase the crater diameter to 3 m. Bombs in the order of 500 lbs (227 kg) are relatively common and should be readily available. It is likely that the accuracy of bombing would be only within a range of 100 m.

10.1.5 ***Delivery System and Logistics.*** As discussed in Section 1.1, all aerial operations will be difficult if not impossible during much of the winter. For much of the time flying with VFR will not be possible. While airports at both Tuktoyaktuk and Inuvik can be used when flying conditions deteriorate below VFR standards, only Inuvik has an instrument landing system. At Tuktoyaktuk charts are available for VFR landings.

The runway of Tuktoyaktuk has a heading of 126°-306° and is only 1,074 m long. The runway at Inuvik has a heading of 40°-220° and is 1,830 m long. For helicopter operations, Tuktoyaktuk would likely be the preferred airport due to the greatly reduced range of these craft with high payloads. Fixed wing aircraft that are normally operated in the MacKenzie Delta can use the Tuktoyaktuk airport. However, larger craft such as the C-130 Hercules would have to use the facilities at Inuvik.

Virtually all fixed wing aircraft commonly used in the MacKenzie Delta are capable of carrying at least a 450-kg payload. For heavier systems such as a large ice penetrometer or bomb, larger aircraft would be required and in certain cases would require an involvement by the military.

There are several types of rotary wing aircraft commonly operated in the area which have payload capabilities of at least 450 kg. However, these craft frequently have small ranges.

Under normal conditions a rotary wing aircraft would be better than a fixed wing for each of the four icebreaking methods considered. Both the placement of a charge under the ice surface and the utilization of a shaped charge placed on the surface require a helicopter. A fixed wing aircraft could not safely be landed on the ice surface during the winter, particularly in the polar pack or shear zones. A fixed wing aircraft could be used to deploy the penetrometer if a special chute is used, likely from an aft loading aircraft such as the DeHavilland DHC-5D Buffalo or the Lockheed C-130 Hercules. However, due to the horizontal velocity imparted by these craft, a helicopter would probably give better penetration results. Bombing, which might have to be a military operation, could be accomplished from either a fixed or rotary wing aircraft. However, if undertaken from a fixed wing, the accuracy would normally only be within 100 m.

One of the major concerns influencing the practicality of aerial-based methods to penetrate ice is the frequency of the aerial missions to ensure the capture of reasonable volumes of oil. In the stationary landfast zone the frequency of such missions would likely be very low. The burning oil could melt most ice shifts and icebreaking assistance might only be required once during the season. However, in the polar pack zone, due to the gyral motion, the mission frequency required would be determined by the variable velocity of ice motion.

If the ice motion were pure translation or a pure random walk, developing a statistically sound bombing pattern would be more straightforward. Instead, the observed ice motion in the polar pack zone is a combination of the two and forecasting techniques must be applied, perhaps to each individual mission, to ensure efficient coverage.

The objective would be to break up an area large enough on each mission so that the blowout source would still be within the broken area at the time of the succeeding mission, despite anticipated ice motion in the interim. Strictly on the basis of refreezing rates in the anticipated conditions, this would seem an impossible requirement, but recently published work by Topham [12.9-147] has shown that the blowout plume itself probably has considerable icebreaking capacity. While the results are not definitive, Topham has shown that under a rough ice surface the bubble formed by gas from the blowout quickly develops enough pressure to break monolithic ice 1-3 m thick. The rubble field from a bombing or blasting sortie would be a very rough surface laced with thinly refrozen leads. Thus, daily or three-times-weekly missions could well provide enough weakening of the pack to enable the blowout plume to keep itself open during the interim. This is an area deserving further definition through model scale experiments and field trials.

In summary, all of the methods of creating craters in the ice cover considered in this report appear feasible. However, further information on the sizes of explosive devices and the resulting ice crater characteristics is needed to select the best method. Aerial methods to create craters for burning oil and gas appear feasible, but might have limited use during the winter months unless wide areas are to be broken up, as flying conditions will be difficult during this period.

10.2 Thermal Cracking

A second approach to releasing the gas and allowing the oil to surface for burning would be to fracture the ice through thermal shock. The smallest crack would serve to release the gas and, as previously discussed, gas pressure would tend to keep such a crack open once formed. Oil burning, on the other hand, requires an adequate area for the oil to burn at its rate of arrival. In 3-m ice, the freeboard is sufficient such that only oil entrained in the gas flow would emerge on the surface. To allow burning of the oil the initial crack would have to widen under the influence of stresses in the pack. This would not be considered a very promising possibility except for reports that when snow is removed from landfast Arctic ice to form roads, cracks often form down the road centre, and this is usually followed by flooding. On this basis the phenomenon merits further evaluation.

10.2.1 Ice Mechanics. Consider an infinite, uniform floating ice sheet of thickness h_i covered by snow of thickness h_s. For $h_s = 0$, the temperature at the upper ice surface (T_{it}) will equal the air temperature (T_a), while the lower surface will be at -2°C. L.W. Gold of the National Research Council of Canada has shocked ice in this configuration by changing the air temperature. He has found that shocks as small as 6°C form 1-cm deep surface cracks in four to five seconds.

Snow has a thermal conductivity of an order of magnitude lower than ice, so in deep snow the ice layer is very nearly isothermal at -1°C. If the snow is suddenly removed over a width D, a crack of width

$$\delta_t = D \, \Delta T \, \epsilon \qquad (45)$$

will be formed, where

δ_t = crack width on the upper surface
D = width of chilled region
ϵ = thermal expansion coefficient (5×10^{-5} at 0°C)

provided that the temperature difference exceeds 4-6°C depending on the strength of the ice.

The crack will propagate through the entire sheet, but will, theoretically, have zero thickness at the under-surface.

The cracked sheet is sketched in Figure 35, which emphasizes the zone load created by the snow and gas pressure under the ice. Therefore, the formation of surface cracks is certain upon removal of the snow cover as long as the temperature of the air is -5° to -7°C or colder. However, these cracks will only propagate to a certain depth depending on the severity of the thermal shock and the width of the track.

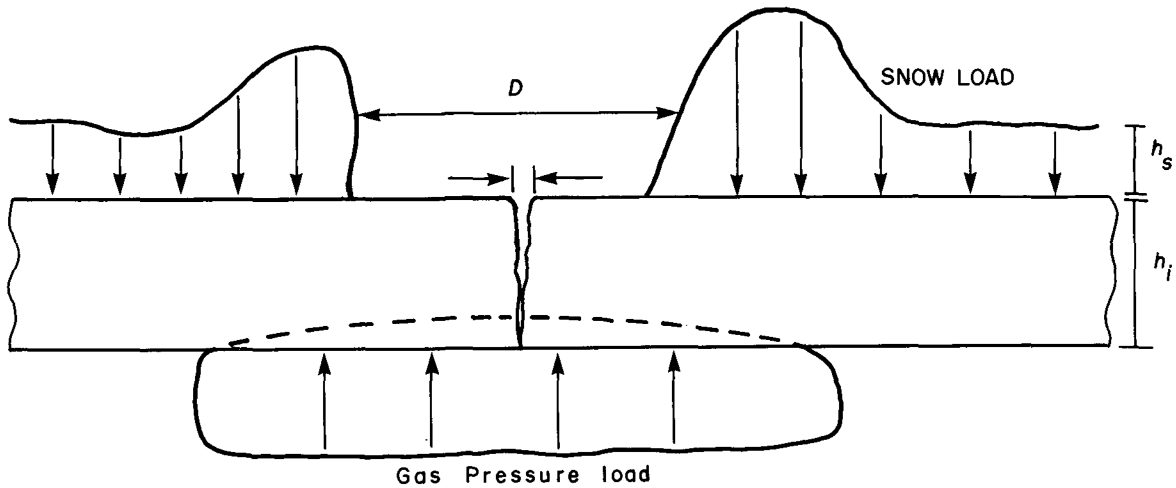


Fig.35 Forces on a floating ice sheet after cracking

The propagation of the crack is affected by the buoyancy forces which tend to deflect the ice cover, as shown by the dotted lines in Figure 35, thus resulting in a tensile stress at the root of the crack which will cause it to extend. As the crack extends, the stress at its root increases and it propagates faster until the cover splits completely. The resulting crevice provides an escape for gas, and oil may also flood the track.

To determine the stress at the root, the problem of an infinite plane on an elastic foundation with a pressure distribution resulting from snow removal along the track must be solved. A standard solution is not available yet, though similar problems with a circular stress distribution have been reported.

An approximate solution may be obtained to demonstrate the fact that buoyancy forces will be sufficient to propagate the crack. It is assumed that the removal of snow will produce an upward force, W_{si} equal to the weight of snow removed. As this snow is piled up on both sides, it will add a downward force of 0.5 W_s. In assuming that half of the cleared snow weighing 0.5 W_s is moved to the side, this means that, in effect, a bending moment M_o is added to the centre of the ice cover at the edge of the cleared track, as shown in Figure 36.

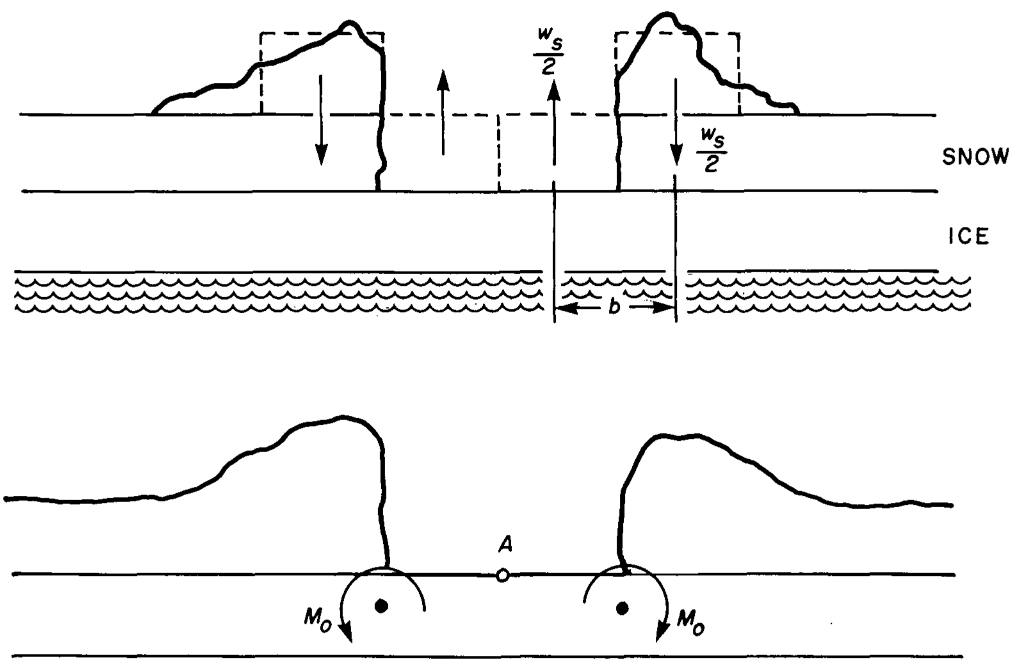


Fig. 36 The mechanics of crack propagation

Using the equation of a beam of unit width on elastic foundation subject to a bending moment M_o, the moment at the centre point A is:

$$M_a = \left(\frac{M_o}{2} D_{\lambda x}\right) \times 2 \qquad (46)$$

where

$$D_{\lambda x} = e^{-\lambda x} \cos\lambda x$$

$$\lambda = \sqrt[4]{k/4EI}$$

$$x = -b/2$$

and

k = foundation modulus of water = 1000 . b kg/m
b = width of cleared track
E = elasticity modulus of ice = 33×10^7 kg/m^2
I = area moment of inertia = $h^3/12$
h = ice thickness

The stress at A is determined from:

$$\sigma_a = 6\ M_a/h^2 \tag{47}$$

$$= 6\ M_o\ D_{\lambda x}\ /\ h^2$$

but,

$$M_o = \frac{1}{2}\ \gamma_s\ h_s\ b^2 \tag{48}$$

where

γ_s = weight density of snow = 556 kg/m^3
h_s = maximum height of snow = 0.6 m

Substituting for M_o find:

$$\sigma_a = 3\ \gamma_s\ h_s\ D_{\lambda x}\ (b/h)^2 \tag{49}$$

$$D_{\lambda x} = e^{\lambda b/2} \cos(-\lambda b/2) \tag{50}$$

$$\lambda = \sqrt[4]{k/4EI} \tag{51}$$

Using these equations the plots of Figure 37 are determined from which the minimum track width required to propagate the crack is determined for each ice thickness.

Thus, it is reasonable to think in terms of Arctic sea ice fracturing along the line of a thermal crack passing near the blowout. Forming the thermal crack requires rapid removal of the overlying snow. Snow which has fallen onto highways, airports or other surfaces is removed and disposed of in one of three ways. The simplest way is to mechanically dissaggregate the snow in the solid state using plows or blowers. Snow can also be removed by altering its properties from a solid to liquid phase (melting) or from a solid phase directly into the vapour phase. The latter method is not practical and is not considered further.

10.2.2 Important Snow and Operating Parameters. Snow is its natural state may have a very wide range of densities. Freshly fallen snow generally has a density between 0.06 and 0.16 gm/cc, although values in the order of 0.03 gm/cc can occur when snow falls in dry air and forms light dendritic crystals. After being deposited, the density of snow cover increases due to natural processes such as setting, fragmentation and agitation by strong winds. By late winter, snow cover densities can readily increase to 0.24 to 0.32 gm/cc. Under the influence of melting temperatures the specific gravity may increase to values greater than 0.40 gm/cc. The specific weight of very dense snow compressed under high overburden pressures and melting conditions may increase to values approaching that of ice about 0.91 gm/cc.

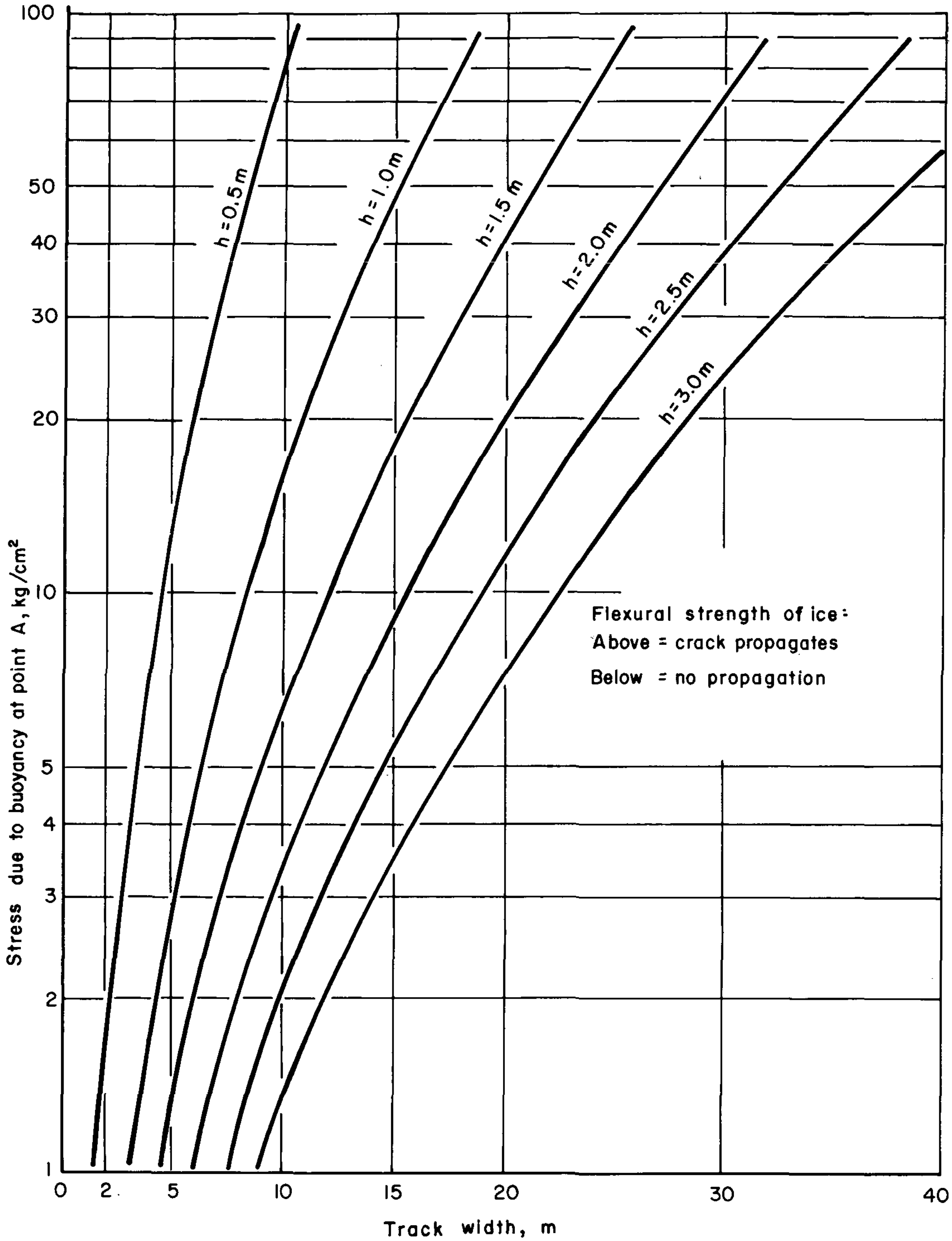


Fig. 37 (a) Stress σ_a for different thicknesses and different track widths

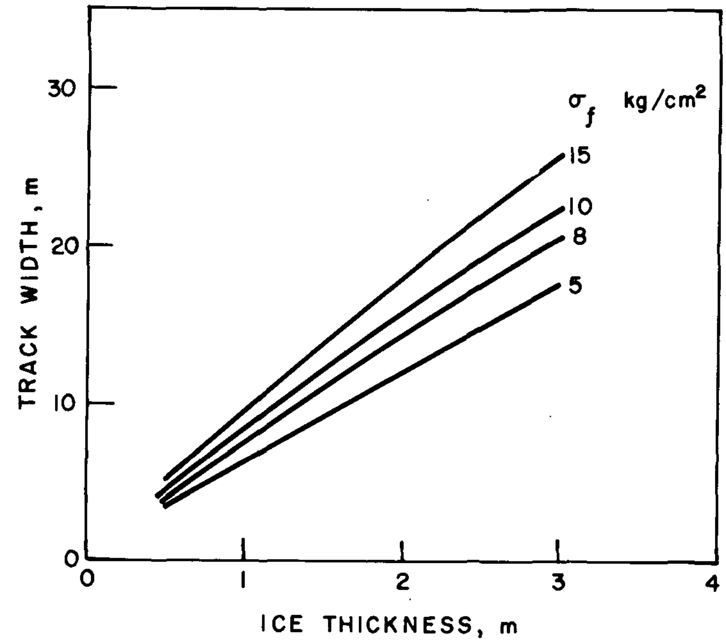


Fig.37(b) Minimum track width for various ice thicknesses σ_f = 10 kg/cm²

Snow strength is an important parameter affecting the performance of mechanical snow-removal equipment. Strength increases with increasing density bonding between snow crystals and snow age and with decreasing temperature. When initially deposited snow is a cohesionless material, however, over time the grains sublimate and bond together with a resulting increase in strength.

Snow strength is usually measured by unconfined compression tests similar to that used in soil testing. Excluding temperature and intergranular bonding, the unconfined compressive strength of snow can be broadly related to density, as shown in Figure 38.

As the ambient air temperature increases towards 0°C, the water content of snow increases. This results in denser snow slush that adheres to removal equipment and is difficult to handle.

One of the most important snow properties for the design of snow-removal equipment is surface friction and adhesion, particularly at temperatures close to 0°C. The coefficient of sliding friction of snow on a steel plate is generally between 0.03 and 0.16. At low temperatures when snow is dry and resistant to compaction, the coefficient of friction with rubber-tired vehicles may be as high as 0.4, which is adequate for braking. This value falls to about 0.2 at temperatures around -10°C and can be as low as 0.05 at melting temperatures. In contrast, the coefficient of sliding friction for a tire on concrete or asphalt is between 0.5 and 1.0.

Ice and refrozen snow can adhere very well to most solids and in contact with metals may have adhesive strengths between 5,00 and 8,500 gm/sg cm. These strengths are approaching the tensile strength of ice and failure may occur within the ice or snow matrix rather than at the ice-metal

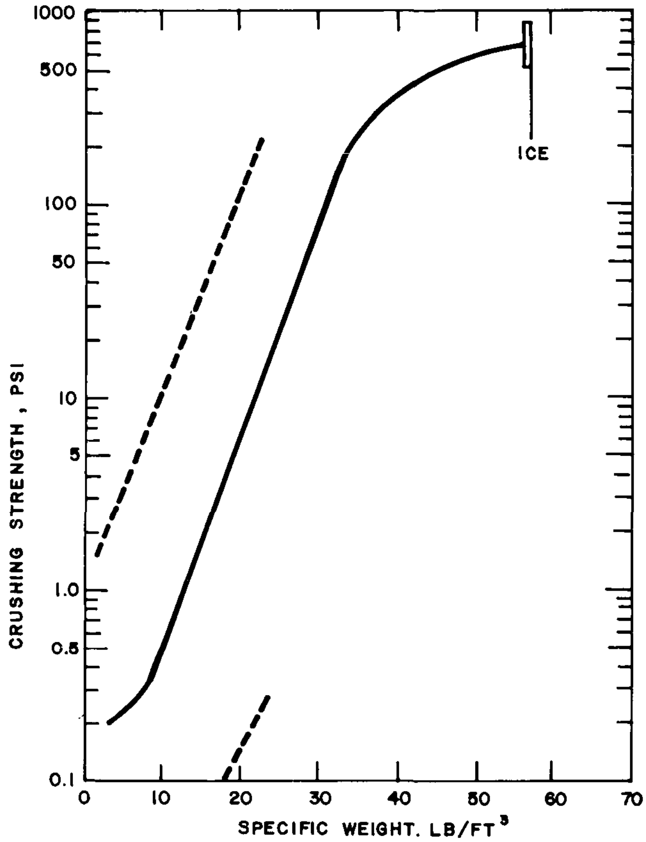


Fig. 38 Approximate dependence of average strength of natural snow on Specific Weight

or snow-metal boundary. Should the snow or ice adhere to metal operating surfaces, severe operational difficulties could be anticipated.

For snow-removal methods based upon melting, the specific heat and latent heat of snow are important. Clean, dry snow has a specific heat of about 0.5. The latent heat of snow is approximately 80 calories/gm depending upon the water content.

10.2.3 ***Plows.*** The most common snow-removal method is to displace snow mechanically or with rotary plows. Power brushes can be used in conjunction with mechanical means. The following classification scheme has been developed by L.D. Minsk:

1. *Blade or Displacement Plows:*
   - a) Front-mounted
     - (i) V-blade
     - (ii) One-way blade
       - –Fixed position (right or left cast)
       - –Reversible (swivel or roll-over)
   - b) Underbody
     - (i) Truck-mounted
     - (ii) Road grader
   - c) Side-Mounted (wings)
   - d) Towed (drags)
2. *Rotary Plows:*
   - a) Two-element (impeller) type
     - (i) Auger
       - –Horizontal axis
       - –Vertical axis
       - –Swept-back axis
     - (ii) Cutters
       - –Helical
       - –Horizontal breakers (rakes)
   - b) Single-element (no impeller) type
     - (i) Scoop wheel
     - (ii) Drum
3. *Pure Blowers:*
   - a) Compressor fed
   - b) Combustion jet
4. *Power Brooms*

5. *Hybrid Machines:*

a) Combination Blade and Impeller
b) Combination Blade and Cutter
c) Combination Broom and Blower

6. *Specialized Devices:*

a) Pressure Cutting Edges
   (i) Wobble wheel
   (ii) Spiral ro lls
   (iii) Scarifier (serrated blade)
b) Melters
c) Hammers

Blade or displacement plows are the simplest type of snow-removal equipment and generally are the least expensive to operate. Such plows can be low-speed blade types operating like bulldozer blades or under-graders. Such low-speed systems will not cast snow any significant distance in the transverse direction. Depending upon snow cover thickness and density, these low-speed displacement systems generally operate at speeds less than 16 km/hr.

Higher speed displacement plows have been evolved from the simple pusher blade. The blades on such plows are designed to maximize snow casting in a transverse direction and to enable the vehicle to operate at higher speeds. Blades for these high-speed plows are generally v-shaped and are designed to maximize the angles of snow ejection vertically and horizontally.

High-speed displacement plows are analogous to blades on turbines or pumps and as such, the force in the longitudinal direction (F_x) is:

$$F_x = BH \rho V^2 (1 - {}^{c}v \cos \alpha \cos \beta) \qquad (52)$$

where
B = width of plow swath
H = depth of snow being plowed
ρ = snow density
V = forward velocity
α = elevation angle of ejection quite above horizontal plane
β = deflection angle in horizontal plane
${}^{c}v$ = a velocity, performance coefficient depending upon friction, α, β and other variables.

Rotary plows are best suited for deep, compact snow. Generally, impeller blades are helically mounted in a transverse axis with snow fragments being ejected by means of ducting. The ability of rotary plows to cast snow depends upon the ease of fragmenting the snow and the range of fragment sizes. Larger snow chunks are likely to travel further than fine-grained particles. Hence, operations should attempt to proceed at a speed sufficient to maximize the size of fragments handled.

The size of fragments handled by a rotary plow can be determined by the following equation and Figure 39:

$$Z = \frac{2\pi V \sin \theta}{n \quad w} \qquad (53)$$

hence, the maximum fragment size is when $\theta = 90°$ i.e. $Z = \frac{2\pi HV}{nw}$

The quantity of snow removed is:

$$q = \frac{2\pi \; HV}{n \quad w} \qquad (54)$$

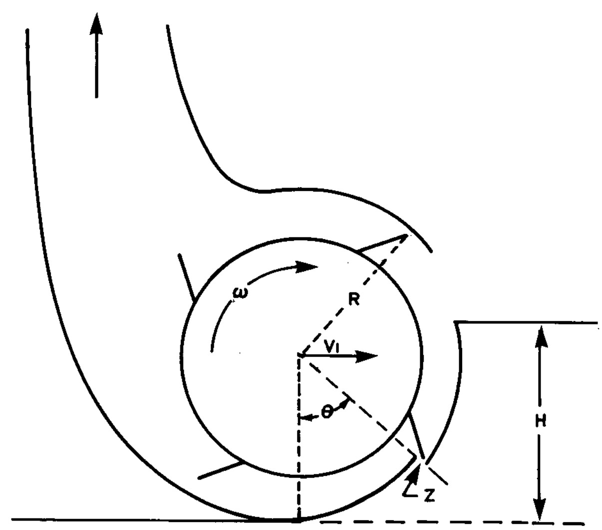


Fig. 39 Rotary plow schematic

Rotary plows are frequently used to rehandle snow which has been pushed into windrows using displacement or blade plows. This procedure is particularly useful in clearing large surface areas such as airfields.

The power required to disaggregate snow using a rotary plow is considerable and depends on the density of the snow being handled. Butkovitch (1956) observed that to handle 36,000 kg of snow per minute with a density of 0.49 gm/cc requires less than 0.75 kilowatts. However, this value rises rapidly with snow density and reaches 6 kilowatts for snow at 0.56 gm/cc.

10.2.4 Snow-Melting Equipment. Of the two common methods of melting snow or ice, one might be particularly useful for promoting thermal cracking of Arctic ice. While snow is sometimes melted within units that are fed with snow collected by other equipment, such as plows and trucks, a second technique involves the direct application of thermal energy to the snow and ice surface. The energy requirements of thermal units are very high and these systems are usually only adopted in urban areas where little space exists to store plowed snow. Such a unit requires very high heat output and generally travels at very low speeds (less than 3 km/hr). Such units are not commonly used, but when they are, usage is generally directed at ice removal rather than that of snow. In melting the overlying snow they would ensure that the upper ice surface is raised to 0°C, thus enhancing the thermal shock with thin snow covers.

10.2.5 Chemical Application. While freezing-point suppressing chemicals are commonly used to melt ice and thin snow cover, they could not be used to induce thermal shock as they remove the snow cover too slowly.

10.2.6 Snow-Removal Logistics. Snow removal is generally undertaken to enable various transportation modes to continue operating. Hence, most snow-removal equipment is developed to operate either on rail lines or on relatively smooth, accessible surfaces such as highways, urban streets or airports.

Snow removal is generally initiated as soon as possible during or after a snowfall. This is particularly true for military airfields. Snow-removal requirements may require runways in the order of 3,000 m long to be cleared in 15 to 30 minutes during heavy snowfalls (5 cm/hr). The demand for rapid, high-capacity snow-removal equipment has not been met by developing innovative techniques. Rather, it has been accomplished by increasing the size of existing machines and engines.

Snow removal is generally not undertaken in areas as hostile and remote as that envisioned for the thermal crack. It is doubtful if most existing equipment would operate satisfactorily. This is particularly true of those areas where ice surfaces are hummocked or contain pressure ridges.

Air cushion vehicles (ACV's) have been successfully used for numerous Arctic operations and have proven to be a highly versatile craft. Although ACV's have not reached their fullest potential for Arctic use and are still in the evolutionary stage, recommendations for even further use have been made. It is unlikely that operations normally carried out by air, ground or water vehicles would be taken over by ACV's. Rather, their use will likely grow on the basis of providing a new transportation mode where none other is viable. Once such potential use is to tow snow-removal equipment in areas such as those envisaged.

One severe drawback of the ACV for use on the sea ice surface in the southern Beaufort Sea is its inability to cross areas of severe ridging or hummocking. Craft such as the Boeing Aerospace Voyageur can only clear a 1.1-m vertical obstacle and cross a ditch less than 3.0 m. Smaller ACV's have similar vertical obstacle clearance requirements due to similar skirt depths, but have smaller ditch-crossing capability.

An ACV such as the Voyageur can operate at all speeds up to about 87 km/hr and has a drawbar pull of 3,000 to 4,000 kg. The temperature underneath the craft within the skirt is slightly above ambient and little melting of snow underneath would be expected. However, the craft can have a pressure under it of more than 250 kg/m^2, which could blow away considerable snow, particularly if it is low-density cover. Recent Transport Canada testing has also demonstrated that ACV's have considerable icebreaking capacity in their own right. This work is still in the demonstration stage.

No aerial-based snow-removal techniques using rotary wing aircraft have apparently been developed. It is possible that such craft could be used to tow equipment or as a platform to operate a tethered self-powered piece of equipment. Rotary wing aircraft generally cannot operate safely at horizontal speeds much less than 65 km/hr, and safety requirements necessitate that externally mounted loads be slung from a single-point, quick-release system.

It is possible that a rotary-wing-based snow-removal system could be developed which would be useful in the Beaufort Sea. Such a system could operate relatively effectively in hummocked and ridged areas. The system could likely be used during any winter month other than December and January. Although the probability of flights under VFR is low during the coldest winter months, aircraft can fly using instruments (IFR). However, for precise locating of the thermal crack, it is likely that some visual marking is required.

Under normal conditions mechanical snow-removal is frequently accomplished using a bulldozer or grader with an underbody blade. These vehicles could possibly be modified to operate under the extreme cold conditions that would be encountered. Also, new-tracked or sled-based systems could be developed. Assuming that a vehicle has adequate mechanical efficiency, its performance in snow is limited by the strength of the material underneath it. The snow or ice on which a vehicle operates must be capable of supporting it without excessive sinkage and must have a shear strength able to provide adequate tractive thrust for wheels or tracks. The deeper into snow a vehicle sinks, the greater the motion resistance becomes and the lower is its drawbar pull. Well-designed vehicles for over-snow transport, particularly those for use in virgin rather than processed snow, must be designed for high flotation and good traction. The viability and safety of surface vehicles (other than ACV's) will depend upon the sea ice topography and the distance from shore of the blowout. Most vehicles have a relatively small range, particularly heavier ones. During darkness and low-visibility periods, all trails will need to be well marked at close intervals. The safety of operating these vehicles on sea ice is also very questionable due to low visibility, frequency of ice leads and the possibility of toxic or explosive gas. However, these vehicles may have an application in nearshore areas.

In areas of shallow snow cover, such as the southern Beaufort Sea, almost any "mud vehicle" can operate satisfactorily. This includes true over-snow vehicles such as low-ground-pressure (up to 0.3 gm/cm^2 for tracked vehicles), high-ground-pressure tracked and wheeled cross-country vehicles, and construction equipment (bulldozers, scrapers). Rubber-tired vehicles may occasionally be inoperative on the sea ice surface due to lack of traction.

10.2.7 Evaluation and Selection of Snow-removal Techniques. A complete, defensible evaluation and selection of snow-removal equipment is not practical at present due to a lack of adequate information.

Rather, concepts and problems related to snow removal at various times of the year in each of the three ice zones are discussed.

Due to the relatively flat surface topography of the fast ice zone, most snow-removal methods could be considered for use. The inner fast ice zone is generally a smooth level, relatively stationary ice sheet. However, even this inner fast ice zone is not motionless throughout the winter. For example, severe pressure ridging commonly forms near Tuktoyaktuk in mid-winter.

Studies have been undertaken to assess the movement of the fast ice zone and values up to 20 m between January and May have been recorded. However, for purposes of this study it is assumed that the ice zone is stationary from freeze-up until breakup.

If all the gas resulting from the hypothesized blowout is vented off through the ice immediately above the drillhole, the oil would form in pods under the ice in sessile drops of thickness from 5 to 10 mm. During the first month at a blowout rate of 398 m^3/day, the area covered would be 1.2 to 2.3 sq.km. The area covered in subsequent months at a blowout rate of 239 m^3/day would be 0.7 to 1.4 sq.km. It has been reported that if gas is not vented off, the area contaminated by oil and gas would be about 140 times that contaminated by oil alone.

The actual slick dimensions would depend upon the surface currents under the ice cover. These are generally low but variable in direction in depths less than 20 m in the Beaufort Sea, which would be covered with fast ice. It has been reported (Beaufort Sea Technical Report #36) that an oil slick under this zone would have a length-to-width ratio of three and that the slick could be idealized as an elongated ellipse with the drillsite at one focus and oriented with its major axis parallel to the current direction.

Based upon this idealized shape, by early May the oil slick resulting from an early October blowout would be an ellipse with a minimum width (minor axis) of 1.5 to 2.1 km and a miximum length (major axis) of 4.5 to 5.4 km.

Also based upon this idealized shape, the maximum length of crack needed to release oil from under the fast ice zone is 5.4 km and this length would only be required for very thin sessile drops (5 mm). It is likely that this ellipse would be oriented in an east-west direction.

Due to the fact that most snowfall in the area occurs in the late fall and early winter, it may be best to remove snow several times during the winter season, enabling gas and oil to be burned throughout much of the winter. By early December the oil slick would have a maximum major and minor axis of 3.6 and 1.2 km respectively. Assuming that only one strip needs to be cleared and the ice thickness is 1.5 m, the area of snow to be removed is 3.6 km long by 82 m wide (Figure 37b). Assuming there is 18 cm of snow at a density of 0.3 gm/cc, the weight of snow to be removed is 15.9 x 10^6 kg.

It is likely that rotary or blade plows would work well. These systems could be self-propelled, towed by an ACV or slung from a helicopter. Ice-based operations should only be attempted after adequate determination of sea ice thicknesses and load carrying capacity. Such operations in the vicinity of the blowout will be dangerous due to the presence of methane gas.

In the outer reaches of the fast ice zone, operations on the sea ice surface will be much more difficult. Although this zone is relatively stationary, its morphology is much different from the level inner zone. The outer zone could be expected to have rubble fields, hummocking and heavy ridging frozen in place from early winter storms. Unlike the inner fast zone, this area contains isolated remnants of second and multi-year ice. From a natural containment point of view, this ice zone is the best one for a blowout. Oil rising up into this zone after consolidation of the rubble field will readily collect into thick pools, the position of which may be estimated from surface topography. Based on an average sea ice bottom roughness of 5 cm (average oil pool depth = 5 cm), the area contaminated by a blowout would be about 0.1 times the size of that in the inner fast ice zone. Assuming the same shape characteristics as those applying to an oil slick found in the inner zone, the elliptical slick would have major and minor dimensions of 0.5 by 1.4 km respectively by early May. By early December the slick would have idealized dimensions of 0.1 by 0.4 km.

It would be difficult, if not impossible, to safely operate ice-based snow-removal equipment in this area. The height of hummocks and ridges would likely preclude the use of even an ACV, although this is not certain due to the relatively small areas contaminated. The possibility of high methane gas levels still makes ice-based operations very dangerous. It is probable that aerial methods would be most suited for snow removal in the outer fast ice zone.

Behaviour of oil and gas released under the shear zone is much different from that in the stationary fast ice zone. Idealizing the situation in this area, the ice, even when ice cover is virtually complete, may be envisaged as continually moving over the blowout. Due to severe ridging and hummocking, this ice has rather deep keel depths. Oil is therefore retained both under the relatively flat ice surface and along the ridges, similar in manner to the retention of oil behind an oil boom. Hence, the oil swath which results will generally be thicker than that under the fast ice zone or will contain higher oil volumes per unit length of the swath. Oil thicknesses under the level ice surface will still be in the same order as that under the fast ice, but by adding to this the oil retained by under-ice morphology, considerable oil can be retained.

Numerous studies have estimated the mean ice drift rates in the southern Beaufort Sea shear zone. Generally, long-term values of 2.2 to 2.7 km/day westward are recorded during most of the winter and values up to 10 km/day or more have been recorded in the spring. Adjusting these values for meandering, average westward paths of 4.8 to 9.6 km/day have been derived. Although the long-term mean westerly drift rate is known fairly accurately, the path taken by any particular ice particle is virtually random along its sinuous course. Hence, attempts to create a thermal crack to relieve oil and gas a long time after any particular floe passes over the drill site will likely result in considerable wasted effort and difficultly in finding oil-contaminated ice. It is recommended that, to the extent possible, snow be removed from the shear zone surface in the vicinity of the blowout.

Removing snow in this zone will be dangerous for surface-based operations. Not only will the area contain methane, but it will contain open-water leads even in the winter. It is likely that an ACV would not operate successfully in this zone, not only because of the above factors, but also because of ridge heights and their frequencies.

Most oil would be contained under the relatively level sections of ice in this zone, particularly those areas surrounded by ridges. It appears possible to remove snow over level areas even in areas with heavy ridging, since the maximum ridge frequency in this area is about 9 ridges/km. Hence, snow could, on the average, be removed for short stretches (0.11 km). It does not appear feasible or necessary to remove snow from major ridges. Further, it is possible that an insufficient width of snow could be removed to yield a deep enough crack, this being of particular significance in areas where the level ice is thick and hummock frequency is high.

Snow removal in the polar pack will have problems similar to those in the transition zone. The polar pack consists of first, second and multi-year ice, as well as open leads. In the winter about two-thirds of all ice in this zone is low-salinity multi-year ice. The surface topography of this ice zone is very irregular and level portions are generally confined to the first-year ice areas constituting about one quarter of the area in the polar pack. Although ice ridging is generally less severe in the southern Beaufort Sea than that in the Arctic Basin, conditions are highly variable. Typical ice ridge spatial densities are 10 to 20 ridge/km with average heights of about 3 m.

The polar pack movement is anticyclonic under the influence of the Beaufort Gyre. Movement is relatively constant at about 2.6 km/day, although resistance in the winter months does tend to reduce this velocity. Oil under ice in this zone would be in a swath where length could readily be determined from the westward gyral motion. The swath would likely be less sinuous than that under shear zone ice and measure 20 to 30 m based on the plume impingement under the ice.

It is probable that surface-based snow-removal operations would not be possible during winter on the polar pack, with the reasons for this being similar to those which are applicable to the shear zone. A further accompanying problem would be the fact that the polar pack is virtually innaccessible to surface-based equipment. Even ACV's would not operate safely in winter months in this zone. The safety of airborne operations over this ice zone during winter months are unknown and considered questionable.

10.2.8 Summary of Thermal Cracking. There is some basis for expecting that thermal cracking could be induced by removing a strip of snow cover from floating Arctic ice. Further, forces can be envisioned which would allow substantial fracturing and local flooding to occur. If this could be reliably demonstrated, snow-removal methods are available which could allow implementation of thermal cracking as a countermeasure to reduce dispersion of the oil and perhaps allow some burning. On the other hand, the process is logistically feasible only in limited ice conditions and locations. This approach could be recommended over impact techniques only when helicopter-towed snow-removal equipment has been developed and efficacy has been demonstrated in the field.

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12 APPENDIX A: CONTAINMENT AND DISPOSAL TECHNIQUES REPORTED IN THE LITERATURE

12.1 Skimmers

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2. Koburger, Charles W., "Oil spill problems in cold climate: The Coast Guard attacks the Alaskan oil spill problem", Naval Engineers Journal, December 1974. p. 59-64.

3. Getman, J.H., "United States Coast Guard oil pollution program", Proceedings of Joint Conference on Prevention and Control of Oil Spills, 1975, p. 259-264.

These two latter reports discuss testing of commercially available cleanup equipment by the U.S.C.G. Booms, skimmers and support equipment were tested in ice-infested conditions.

4. Weatherford, E.J., "Oil slicks skimmer", U.S. Patent 3860529. *A barge used as a decanter.*

5. Bagnulo, L., "Skimming apparatus", U.S. Patent 3853768. *A decantation chamber.*

6. Mohn, F., "Pumping apparatus for skimming and recovering an oil layer from a body of water", U.S. Patent 3853767. *An oil pump surrounded by a bowl or disc, the periphery of which was adapted to be positioned exactly at the plane of separation between water and oil.*

7. Aulisa, G., "Rotary skimmer", U.S. Patent 3844950. *A rotary trough moving about a central motor.*

8. Glaeser, J., Weisert, G. and Cunningham, G., "Motion decoupled skimmer for removing oil from the surface of calm or disturbed water", U.S. Patent 3830370. *A floating weir with a pump floating separately on the end of a hose.*

9. Favrest, U., "Apparatus for recovering oil substances from the surface of a body of water", U.S. Patent 3836004. *A precisely positioned suction skimmer.*

10. Gascoigne, P., "Oil recovery system operates effectively in rough water", World Oil, Vol. 178, No. 7, p. 93-94, June, 1974. *Describes the Marco Pollution Control skimmer.*

11. Bergman, H., "Method and a device for collecting substances floating on a liquid surface", U.S. Patent 3817385. *A belt skimmer.*

12. Oxenham, J., "Apparatus for controlling a pollution liquid", U.S. Patent 3810546. *A drum skimmer with four drums facing out at different directions.*

13. Crisafulli, A., "Oil skimmer module with free floating weir trough", U.S. Patent 3822789. *A floating weir and pump with a barge.*

14. Farrell, J., Bianchi, R., and Johanson, E., "Floatage collecting apparatus and methods", U.S. Patent 3804251. *A belt skimmer on a barge.*

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16. Tudor, A. and Tudor, E., "Floating skimmer", U.S. Patent 3762557.

17. Penton, J., "Oil skimming apparatus", U.S. Patent 3762556.

18. McCombie, F., "Removal of surface layers from liquids", U.S. Patent 3759390. *A suction skimmer with a water pump.*

19. Bell, E. and Padden, T., "Suction oil decanter", U.S. Patent 3760994. *A suction skimmer using a blower.*

20. Verdin, S., "Apparatus and method for collection of oil from the surface of the sea", U.S. Patent 3754653. *A suction skimmer with decanter barge.*

21. Crisafulli, A., "Oil skimmer module", U.S. Patent 3756414. *A weir skimmer for mounting in front of a floating barge.*

22. Hoffman, B., "Pollution skimmer", U.S. Patent 3753497. *A windmill array of weir troughs.*

23. Ekdahl, G., "Method of recovering oil from a water surface", U.S. Patent 3747760. *A suction skimmer taking oil from the head waves in front of a moving barrier.*

24. Olsen, M., "Method and apparatus for removing reclaiming oil slick from water", U.S. Patent 3745115. *This suction skimmer has floating collectors, but they are connected octopus fashion to a central decantation drum.*

25. Brydoy, S. and Sletsjoe, A., "Vessels for the removal of oil on water", U.S. Patent 3737040. *A self-propelled belt skimmer with protruding arms.*

26. Prewitt, C., "Skimming systems", U.S. Patent 3730346. *A suction skimmer tethered to a decanter craft.*

27. Damberger, C., "Oil skimming apparatus", U.S. Patent 3726406. *A boat with a noose boom, hot-water jets and a suction skimmer.*

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29. Stebbens, G., Stebbens, J. and Becker, J., ''Floating oil-skimming apparatus with oil and water separator'', U.S. Patent 3722687.

30. Markel, A., Wirsching, R., ''Apparatus for extracting oil or the like from the surface of the sea'', U.S. Patent 3722689.

31. Wirsching, R., ''Sea surface oil extractor'', U.S. Patent 3722688. *These last three items are all weir devices.*

32. Anonymous, ''Shell Oil develops a new barge for quick spill recovery'', Offshore, Vol. 32, No. 11, p. 106, October, 1972. *The barge was developed for temperate climates.*

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35. Harrington, J. and Milne, E., ''Skimmer for pollution control device'', U.S. Patent 3707232. *A weir-type skimmer.*

36. Cross, R., ''Oil removal device'', U.S. Patent 3706382. *A weir-type skimmer.*

37. Maksan, J., ''Oil skimming devices and methods'', U.S. Patent 3702297. *An absorbent belt skimmer.*

38. Craggs, D., and Gillen, R., ''Floating oil skimmers'', U.S. Patent 3704784. *A weir device.*

39. Covey, ''Open sea oil skimmer'', Undersea Technology, Vol. 13, No. 8, p. 28, August, 1972. *Describes a 2,000-gallon-per-minute skimmer unit for use in the open sea with 8-foot waves and 3-knot currents.*

40. Richards, F., ''Oil skimmer'', U.S. Patent 3700108.

41. Lasko, C., ''Apparatus for removing floating liquids from the surface of a body of water'', U.S. Patent 3700109.

42. Schell, O., ''Skimmer for removing floating water from a body of liquids'', U.S. Patent 3701429.

43. Tuttell, R., ''Oil skimmers, U.S. Patent 3701430.

44. Flaviani, E., ''Apparatus for recovery of floating substances'', U.S. Patent 3700107.

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46. Pogonowski, I., ''Water surface skimmer with check valve'', U.S. Patent 3693801.

47. Marcocchio, A., ''Apparatus for removing oil slick from water surfaces'', U.S. Patent 3688506.

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50. Ayers, R., ''Barge-based skimming system for oil slicks'', U.S. Patent 3684095. *A weir system with a decanting barge.*

51. Fitzgerald, D. and Koepf, E., ''Oil skimming apparatus'', U.S. Patent 3612280. *Depressing planes mounted at wings of the sides of a vessel.*

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55. Valdespino, J., ''Oil entrapment and containment water crafts'', U.S. Patent 3615017. *A suction skimmer with elaborate vacuum control.*

56. Van Stavern, M. et al, ''Method of recovering oil from an oil slick'', U.S. Patent 3612277. *A double drum skimmer.*

57. Will, R. and Grutsch, J., ''Oil-water separating process'', U.S. Patent 3617522.

58. Ginsberg, I. and Will, R., ''Method and apparatus for removing oil and debris from water'', U.S. Patent 3617555.

59. Cole, E. and Hess, H., ''Irradicating oil slicks'', U.S. Patent 3617556.

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61. Yahnke, R., ''Method of removing floating oil from a surface of a body of water'', U.S. Patent 3578585.

62. Ries, H. and Gabor, J., ''Method and apparatus for removing contaminants from water'', U.S. Patent 3587860.

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72. Getman, Lt. J.H., Schultz, L.A., Deslauriers, P.C., ''Tests of oil recovery devices in ice-covered waters'', Third International Conference on Port and Ocean Engineering under Arctic Conditions, University of Alaska, 1976.

73. Norton, R., Lench, D., ''An oil recovery system for the San Francisco Bay Area'', Conference on the Prevention and Control of Oil Pollution, San Francisco, March 1975.

74. Deslauriers, Paul C. and Schultz, Lawrence A., ''Oil spill equipment and oil behavior in cold regions'', prepared for University of Alaska Agricultural Experiment Station, by Arctec, Incorporated, Columbia, Maryland, September 1976.

Deslauriers and Schultz reviewed more than 35 weir-type skimmers and decided "none are judged to be suitable in their unmodified condition for use in the presence of broken ice cover".

Deslauriers and Schultz also reviewed 11 belt-type oil recovery devices and concluded that "while none of the belt-type skimmers offer a universal capability for operation in cold regions, three units offer promise, with or without moderate modifications, for some limited applicability".

These three units are the Oil Mop, the JBF DIP and the Bennett Oil Skimming System. The Oil Mop has a rated capacity of up to 100 barrels per hour. Deslauriers and Schultz reviewed disc-type oil recovery devices and recommended only the Lockheed Clean Sweep model. It is their review of drum and Vortex skimmers that reveals no suitable candidates for Arctic operations. Deslauriers and Schultz also reviewed current research in the area and recommended as suitable for the Arctic envnironment, a streaming fibre oil spill control concept under development at Seaward Inc., and an air jet collection system being developed by Tetradyne Corp. Deslauriers and Schultz also reviewed available pillow-bag-type oil storage containers, but their limited capacity and transport ability rendered application to a undersea blowout questionable.

12.2 Booms and Barriers

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2. Getman, J.H., "United States Coast Guard Arctic Pollution Program", Proceedings of the Joint Conference on the Prevention and Control of Oil Spills, 1975, p. 259-264. *The report contains numerous practical suggestions about various booms for use in ice conditions.*

3. Deslauriers, Paul C. and Schultz, Lawrence A., "Oil spill equipment and oil behavior in cold regions", prepared for University of Alaska Agricultural Experiment Station, by Arctec, Incorporated, Columbia, Maryland September 1976. *The report reviews 52 commercially available containment booms. Only the Supermax boom manufactured by American Marine Inc. and the Sea Curtain manufactured by Kepner Plastic Fabricators showed any promise for application beyond light brash ice conditions.*

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5. Rudd, C.H., "Floatation type of water sweep boom and methods", U.S. Patent 3852965. *A boom with floats and a complex towing procedure.*

6. Thurman, R.K., ''Modular oil containment booms'', U.S. Patent 3868824. *A boom held together by zippers and floated by foam-filled drums.*

7. Preux, P., ''Inflatable barrier for substances floating on water'', U.S. Patent 3849989. *An inflatable boom.*

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11. Green, L.G., ''Boom as a barrier for oil slicks and the like on the surface of water'', U.S. Patent 3839869. *A number of non pneumatic floats wrapped in a webbing weighted to form a skirt.*

12. Benson, R.A., ''Floating barrier'', U.S. Patent 3818708. *A solid vertical dam with outrigger floats.*

13. Miller, E., Lindenmuth, W. and Altmann, R., ''Analysis of lightweight oil containment systems sea trials'', Hydronautics Inc., Laurel, Maryland, NTIS AD-770344. *Sea trials of an air bag boom.*

14. Ballu, L., ''Floating anti-pollution barrier device'', U.S. Patent 3811285. *A floating rubber boom.*

15. Oberg, P., ''Floatable boom structure'', U.S. Patent 3798911. *A boom made of buoyant tubular sections.*

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17. Hof, G., ''Boom arrangement for confining oil'', U.S. Patent 3803848. *A rigid sinusoidal boom.*

18. Auberg, P., ''Floating boom structures'', U.S. Patent 3807171. *A curtain hung from air-filled cloth bags.*

19. Tanksley, N., ''Floating boom'', U.S. Patent 3807178. *A boom with outriggers.*

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22. Cerasari, N., ''Floating booms'', U.S. Patent 3800542. *An inflatible boom deployed from a ship.*

23. Preus, T., ''Control of waterborne oil slicks'', U.S. Patent 3795315. *A boom with an oil-absorbing skirt.*

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25. Smith, R., ''Auto-reclaiming device for removing oil from the surface of water'', U.S. Patent 3785496. *A large distended paddle wheel of booms.*

26. Gambel, C., ''Method and system for the containment and salvage of chemicals on oils at seas'', U.S. Patent 3783622. *A rigid boom system.*

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28. Steltner, H., ''Dynamically effective oil-guide boom and method for purifying water employing the same'', U.S. Patent 3779382.

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33. Belin, M., ''Floating barrier for circumscribing oil pools or like refuse'', U.S. Patent 3739584.

34. Larsson, E., ''Floating boom structures'', U.S. Patent 3757526.

35. Rolfson, E., ''Apparatus for confining floating pollutants'', U.S. Patent 3764015.

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37. McCombie, F., "Method and apparatus for removal of surface liquid", U.S. Patent 3748264. *A flexible, reel-mounted barrier.*

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39. Fossberg, R., "Flexible oil boom for high seas", U.S. Patent 3740955. *A boom with outriggers and struts.*

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55. Gadd, P., ''Apparatus for gathering and cleaning water surfaces of pollution'', U.S. Patent 3584462.

56. Bogosian, T., ''Elastomeric oil slick boom'', U.S. Patent 3685296.

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