Offshore Concrete Structures in the Arctic: Research Needs

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OFFSHORE CONCRETE STRUCTURES IN THE ARCTIC:

RESEARCH NEEDS

by

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ABSTRACT

A study of research needs to enhance the capability to design, maintain, and approve concrete offshore structures for the Arctic was carried out by the National Bureau of Standards on behalf of the Minerals Management Service, Department of the Interior. The study was composed of three activities: a letter survey of key individuals in the field; an international workshop on the subject; and a review of available literature. Data gathered from these activities were used to develop a comprehensive list of research needs in the following areas: design, materials, construction, inspection and repair.

Key words: Arctic environment ; concrete; construction; design; durability; inspection; marine; offshore structures; repair; research.

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 PURPOSE

It has been reported that the Beaufort Sea has the greatest potential of any region in North America in terms of oil and gas production [1]. To tap these reserves will require the construction of permanent offshore exploration, production and storage structures so that year round operations can be performed. Many of these structures will be constructed of concrete [2,3,4]. It has been shown that properly constructed concrete structures can be extremely durable and maintenance-free when exposed to marine environments [5-10]. In addition, concrete structures can provide the mass and rigidity that may be required to survive the extreme loading conditions of the Arctic.

The offshore Arctic environment represents a frontier in terms of the design and construction of permanent structures. There are very few case histories of structures in Arctic waters by which to judge the appropriateness of proposed materials and methods of design, construction, inspection and repair. These unknown factors make it difficult to assess, with a high degree of confidence, the expected performance of proposed structures.

Within the last decade, a considerable amount of resources have been expended to answer some of the questions, and research results have appeared in a variety of symposia, conferences and journals dealing with offshore structures. In order to make efficient use of additional resources, it is necessary to assess the current state of knowledge, and thereafter identify in which direction future efforts should be directed. Recognizing this need, the Minerals Management Service(MMS), Department of the Interior, contracted with the National Bureau of Standards to perform such a study and identify fruitful areas of research. This report summarizes the results of the study.

1.2 STRUCTURES IN THE ARCTIC

Within the 1970's, 14 large structures have been constructed in the North Sea [11,12], and their successful performance up to now has confirmed the adequacies of their design and construction [5]. While much of this experience can assist in predicting performance of structures in the Arctic, there is one factor that still has many unknowns associated with it, namely, the severe ice loading conditions. The proposed locations of many of the offshore Arctic structures will expose them to a wide variety of ice forms, ranging from small floating fragments to pack ice four or more meters thick [13,14]. Some data have been gathered from the performance of concrete lighthouses exposed to ice [15], but these experiences have not included conditions of Arctic severity. A considerable amount of research effort has been devoted to the subject of ice mechanics, ice loading of structures and ice movement in the sea. The American Bureau of Shipping has recently completed an extensive literature review of this topic [16], and it was concluded that much additional research is required on this complex subject.

The North Sea structures have been placed in water depths of around 150 meters and have been designed to resist wind and wave loadings. The structures proposed for the Arctic will be founded in shallower water, typically less than 60 meters, and will be required to resist tremendous ice pressures [13]. Various design concepts have been proposed for different site conditions [2-4,17-20]. In order to acquaint readers unfamiliar with these proposals, a brief review of the basic concepts is presented. The review follows the ideas in ref. [3], which summarizes the main attractions and limitations of each concept.

The structures proposed for the Arctic can be divided into four generic categories:

- Artificial islands
- Caisson-retained islands
- Conical gravity structures
- Caisson gravity structures

Figure 1 provides schematic cross-sections of these types of structures. The possibility exists for hybrid structures which combine one or more features of the above concepts.

Artificial Islands:
In shallow waters, a working platform may be constructed by simply building a gravel mound projecting above the water surface (Fig. 1a). The artificial island achieves its strength to resist ice forces by its large mass, and ice rubble build-up around the perimeter enhances the structure's resistance.

Advantages:
- Large production capacity due to large deck area and weight capacity
- Can accommodate large number of wells
- Separation of production, drilling and accommodation platforms
- Can resist all ice formations expected in the Arctic

Limitations:
- Requires readily available source of materials
- Sensitive to weather window (ice free period) and environmental conditions during construction of upper portion of island
- Oil storage would have to be accommodated on top of island
- Permanent ice rubble around island during winter may hamper access by supply and maintenance vessels
- Feasibility in deep waters restricted by ability to construct steep slopes with dredged sand

Caisson Retained Islands:
With increasing water depth, an excessive quantity of material would be required for artificial islands. An alternative approach is to construct a rigid peripheral wall and place earthfill within the wall (Fig. 1b). The wall can be constructed from concrete segments, which are precast at a temperate location, towed to the installation site and joined together. Ice forces are resisted by the large mass of the combined wall-earthfill structure.

Advantages:

- -Substantial production capacity due to large deck area and weight capacity
- -Relatively inexpensive structure depending on water depth and ice features
- -Scouring and erosion around the structure is expected to be moderate within its design life
- -Can be designed to avoid substantial grounding of ice rubble, thereby allowing vessel access to structure

Limitations:

- -Installation, hook-up and commissioning works require significant on-site operations
- -While some oil storage can be accommodated by hollow wall elements, large volumes would have to be stored on top of the structure
- -Installations of wall segments and earthfill are sensitive to weather conditions

<u>Conical Gravity Structures:</u>
This type of structure is composed of a large diameter base, a cone section and the deck section (Fig. 1c). The large base serves to provide stability against sliding and overturning and provides buoyancy during towing of the structure from its fabrication point to the installation site. The conical section is intended to cause flexural failure of the ice rather than crushing, as in the caisson retained island. The cone section is of a relatively small diameter so as to reduce the total ice load on the structure. In a variation of the basic concept, the conical section is an adjustable collar to permit use of the same structure in different water depths. The basic principle of this concept is to permit the moving ice to flow past the structure with minimum resistance.

Advantages:

- -The entire structure can be fabricated at a moderate climate location
- -Significantly lower costs than other concepts for water depths in the range of 40 to 70 meters
- -Adaptable to a range of foundation conditions
- -Shallow draft requirements
- -Fabrication period is relatively short
- -Permanent ice pile-up all around the structure is not expected, so vessel access should be feasible most of the time

Limitations:

- -Limited production capacity due to deck and well restraints
- -Minimum oil storage capacity in structure
- -Mating of deck system and lower structure must be performed in the Arctic
- -Large ice island invasion will probably require temporary relocation

of the structure
-Concept relies on good understanding of ice environment and ice/structure interaction
-Upper part of structure will require reliable corrosion protection and maintenance approach
-Direct tanker loading probably not feasible

<u>Caisson Gravity Structures:</u>
This concept differs from the conical structure in that a very large polygonal caisson is used; the walls may be vertical or sloped (Fig. 1d). The caisson relies on its great mass and strength to resist ice loads.

Advantages:

-Platform is constructed and fully integrated in a moderate climate
-Substantial oil storage capacity can be incorporated in the structure
-Large production capacity due to its large size and strength
-Minimal construction operations required in Arctic
-Minimal structure maintenance requirements
-Can be designed to avoid substantial grounding of ice rubble, permitting vessel access downstream of ice movement
-Concrete shell will have low sensitivity to high local ice pressures

Limitations:

-Good foundation materials required
-Requires substantial draft during towing to Arctic, will probably require ice breaking assistance during tow
-Feasibility of direct tanker loading not proven
-Not certain that structure can survive worst possible ice features with adequate integrity

In addition to the above generic concepts, hybrid structures have been proposed that combine the advantages of the individual concepts and attempt to minimize the limitations. Other proposals include floating caisson structures tethered to the sea bed.

As of this writing (1983), most of the completed Arctic structures have been artificial gravel islands. The only exception is the Tarsiut caisson retained island completed in October 1981, in 21 meters of water [21]. The peripheral wall is constructed of four lightweight concrete caissons resting on about a 15-meter thick sand berm. The structure has been extensively instrumented to monitor its performance during ice loading [22]. The data gathered from this pioneering structure will provide valuable information to assist in the design of future platforms.

Another significant structure is scheduled for installation in the U.S. Beaufort Sea in August 1984. The structure is called a concrete island drilling system (CIDS), and is a submersible drilling unit for use in water depths between 9 and 15 meters. The structure will be 29 meters high and is built in three sections: a steel mud base to sit on the sea bed; a concrete caisson structure to rest on the steel base; and an upper steel deck for equipment and living modules [23]. Plans are to produce an artificial grounded ice rubble on the windward side of the structure to reduce ice loadings. An extensive monitoring system will be installed to monitor forces on the structure as well as its displacements.

1.3 SCOPE

As previously stated, the purposes of this study were to assess the state of knowledge relative to the performance of offshore concrete structures in the Arctic environment, and to identify the research needed to enhance the present capability to design, maintain and approve such structures. Since the subject of offshore technology is quite extensive, the study was limited to concrete structures, and to the following aspects:

- Design
- Materials
- Construction
- Inspection
- Repair

To meet the stated objectives, the project consisted of three tasks:

- Conducting a letter survey of key individuals knowledgeable in the subject
- Organizing and sponsoring an international workshop
- Performing a review of the available literature

The next three chapters summarize the results of each task. Based on the acquired information, recommendations for future research were developed, and these are reported in chapter 5.

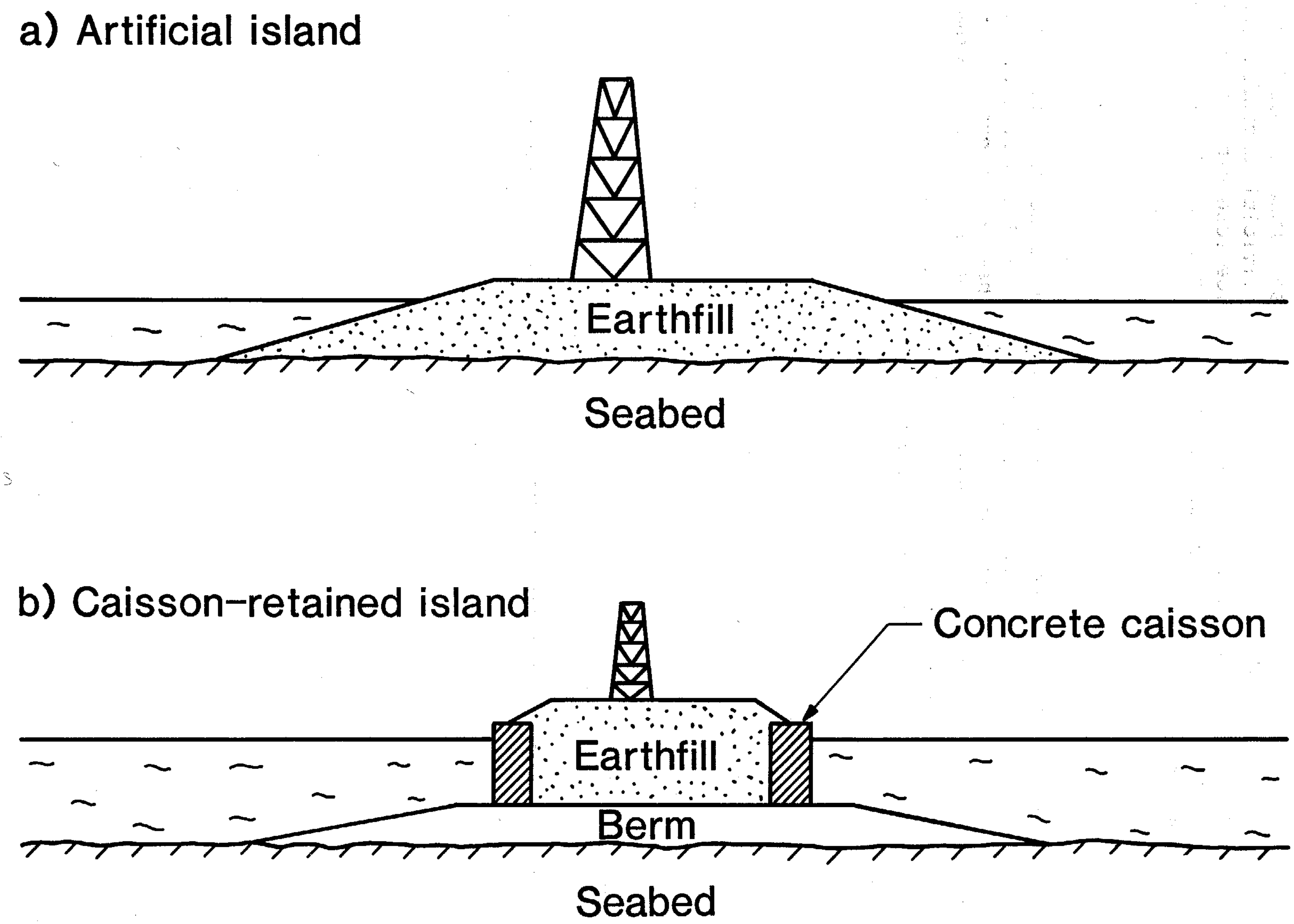

Figure 1 Generic types of offshore structures proposed for the Arctic

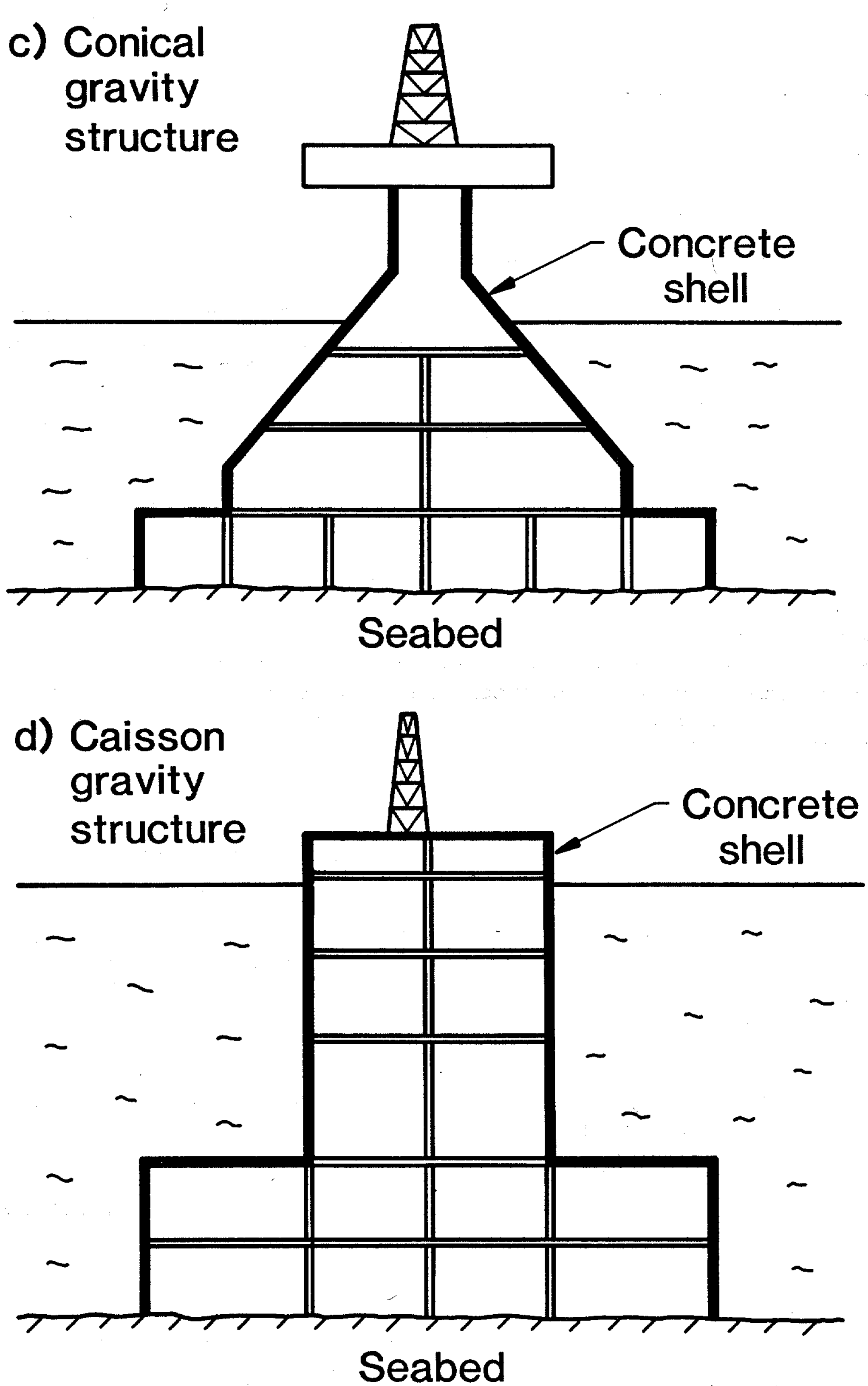

Figure 1 Generic types of offshore structures proposed for the Arctic

2.0 RESPONSE TO SURVEY

2.1 QUESTIONNAIRE

In order to gain preliminary information on needed research related to offshore concrete structure, a questionnaire was sent to a number of individuals knowledgeable in this subject. The questionnaire requested four responses:

1) Which areas related to the design, construction or service ability of concrete structures are lacking the information you would require if you were involved in a project in Arctic regions?

2) What are the names and addresses of other persons who could provide additional information?

3) What recent research on this subject are you aware of? Who is conducting the research and will the results be made public?

4) Do you have any additional comments that may be of assistance?

The responses to question #2 assisted in developing the list of invited participants for the NBS Arctic Workshop, which is discussed in Chapter 3. The answers to question #3 were incorporated into the list of research projects presented in the Appendix. The following section summarizes the responses to questions #1 and #4.

2.2 SUMMARY OF RESPONSES

The following topics were identified as areas of needed research:

Ice Loading:

A coherent approach is needed to relate Arctic structures to structures in other areas with respect to overall level of reliability, taking account of service life, return periods of ice features, level of expected safety, etc.

Analysis of ice statistics is needed in order to arrive at load levels for checking the ultimate, serviceability and fatigue limit states. There might be a need to consider a "survivability" limit state, similar to that used for design of structures in seismic regions.

There is a need for establishing magnitudes and distributions of local pressures on structures due to various ice features.

Structure:

There is a need for a rational approach for designing against punching shear failure of normalweight and lightweight reinforced concrete sections subjected to local ice pressures.

There is a need to enhance our understanding of ice-water-structure-soil interactions during earthquakes.

Criteria need to be established to safeguard structures against degradation due to freezing and thawing of water within cracks.

The applicability of lightweight concrete and high-strength concrete to Arctic structures should be studied.

<u>Materials:</u>

Establish the long-term performance characteristics of the following in the Arctic environment, especially in the near sea surface zone:

- Concrete, both normalweight and lightweight
- Reinforcing steel, prestressing tendons and anchorages with particular reference to brittle fracture
- Abrasion resistance of concrete surfaces, and the application of fiber-reinforcement to improve abrasion resistance
- Coatings for reducing ice adhesion forces (adfreeze)
- Polymer-impregnated concrete for increasing strength and reducing permeability

<u>Operation:</u>

Effective ice management methods need to be identified for keeping the structure ice free and accessible.

Waste heat management should be studied to reduce ice adhesion bond with concrete surfaces.

<u>Inspection and Repair:</u>

Improved inspection methods need to be developed.

Methods need to be developed to repair the following:

- Damaged concrete surfaces
- Ruptured concrete sections
- Reinforcing steel and prestressing tendons
- Damaged coatings

As will be seen in the following chapter, many of the above research areas were also identified in the NBS Arctic Workshop.

3.0 NBS WORKSHOP ON THE PERFORMANCE OF ARCTIC OFFSHORE CONCRETE STRUCTURES

3.1 WORKSHOP FORMAT

In order to bring about an exchange of information on the subject of offshore concrete structures, an international workshop was held at the NBS on March 1 and 2, 1983. The workshop was organized by NBS, MMS and the Canada Centre for Mineral and Energy Technology (CANMET). Funding was provided by MMS and CANMET contributed by publishing the workshop report.

The objective of the workshop was to bring about an exchange of information in the following areas:

- Past experiences in the design, construction and performance of Arctic offshore concrete structures.

- Current projects and research programs related to Arctic offshore structures.

- Recommended areas for further research and development in order to enhance the capability to construct viable Arctic offshore concrete structures.

The workshop planning committee invited a recognized group of international experts in various areas related to offshore concrete structures. A total of 51 individuals participated in the workshop. The participants were divided into four working groups each dealing with one of the following subjects:

- The **DESIGN** of Arctic concrete structures.

- Required characteristics of **MATERIALS** for Arctic offshore structures.

- Problems related to the **CONSTRUCTION** of Arctic offshore structures.

- Problems associated with the **INSPECTION** and **REPAIR** of Arctic offshore structures.

Each working group had a chairman who volunteered to prepare a position paper to initiate group discussion and a final report of the discussions. The chairmen were as follows:

- Mr. Ben C. Gerwick, Jr. - Design
- Mr. Robert E. Philleo - Materials
- Mr. Peter Pullar-Strecker - Construction
- Dr. Roger Browne - Inspection/Repair

The chairmen's reports have been incorporated into the workshop proceedings [24]. Each group's report was organized into three sections: background; summary of discussions; and recommendations for future research. The following sections summarize the group reports including recommended areas of research.

3.2 DESIGN GROUP

A highlight of the workshop discussions was a presentation on the performance of the Tarsiut caisson retained island. It was reported that the concrete structures had performed well. Some structural cracking had occurred during initial set-down of the caissons because of uneven support resulting from a surveying error. The cracking was not considered serious and had not led to further deterioration due to cyclic freezing and thawing. Additional damage, in the form of minor spalling, had occurred due to impact of steel barges without fenders. The measured global and local ice loadings during the winter of 1982-83 were reported to have been the most severe yet encountered. In summary, it was concluded that the prestressed, lightweight concrete caissons have displayed satisfactory and predictable behavior.

There was discussion about the generally satisfactory behavior of Swedish lighthouses exposed to ice environments. For up to 25 years, these concrete structures have been exposed to moving ice sheets and rubble pile build-up without showing significant abrasion or deterioration. Some lighthouses have been well instrumented and documented, providing valuable information on ice-structure-foundation interaction.

The highly successful experiences of 15 North Sea structures were discussed. Attention was directed to the current design of the shafts to resist boat impacts of intensity comparable to ice loadings expected in the Arctic.

One of the discussion sessions was devoted to presentations of current research and development projects. While many of the projects are proprietary, it was pointed out that any responsible party may buy into them. The following projects were noted:

- The mechanical and durability properties of high-strength lightweight concrete under Arctic conditions.

- The behavior of reinforced and prestressed concrete elements under the action of concentrated loads, including the behavior of repaired elements.

- The behavior of steel-concrete composite elements.

- The response of structures to impact of ice floes, considering the ice-structure-foundation interaction, which includes the compliance of the structure-foundation system and energy dissipation due to ice crushing and hydrodynamics.

- The evaluation of risk and reliability,and the consequences of local failure on overall safety levels.

- The properties of high-strength normalweight concrete, with strength in excess of 14,000 psi (100 MPa).

- The ductility of highly compressed members.

- Detailed inspection of Swedish concrete lighthouses in the Baltic Sea to ascertain their performance under up to 25 years of annual ice loading.

-Ice pressures on Polar class icebreakers, ice forces against structures and ice mechanics.

-Multiaxial stresses in concrete structures.

-Various studies on the performance of concrete in the Arctic environment, such as durability, abrasion resistance, friction forces, etc.

-Behavior of prestressed lightweight concrete under cyclic, fully reversing membrane and shear stresses at low temperatures.

-Study of a model platform subjected to iceberg impact.

The above projects, plus those listed in the Appendix, give a good indication of the scope of recent and current research efforts related to concrete structures.

In addition to research projects, the following examples of concepts being developed for use as exploratory and production platforms in Arctic and sub-Arctic waters were presented:

-Global Marine's Concrete Island Drilling Structure (CIDS), utilizing concrete "honeycomb" modules which are joined together horizontally and vertically at the site to complete the structure.

-SOHIO's Arctic Module System (SAMS), a prestressed lightweight concrete caisson in which shear transfer of ice forces to the foundation is augmented by spuds.

-The Arctic Cone Exploration System (ACES), a prestressed conical structure being designed for a consortium of oil companies including Shell, Exxon and Chevron.

-Brian Watts Arctic Caisson System (BWACS), a lightweight concrete honeycomb caisson employing the wick and drain method to improve the shear resistance of weak soils.

-Exxon's concrete production island caisson with elevated deck, designed for 30 to 100 ft (10 to 30 m) water depths in Norton Sound.

-A concrete caisson for Norton Sound designed by a nine-company consortium headed by Chevron.

-The TRIPOD 300 concrete caisson, originally designed for 300 plus meters in the North Sea, now being considered for the Southern Bearing Sea.

-Exxon's concrete gravity base MONOTOWER proposed for deep water in the St. George Basin.

-Fixed concrete caisson for the Hibernia field, off Newfoundland, designed to resist iceberg impact.

-Floating caisson drilling, production and storage structure designed for use in deep water and featuring dynamic downward breaking of ice.

In the discussions of research needs, the problems of ice loading, dynamic structural response and soil-structure interaction were identified to be of great importance for all structures in the Arctic. Other general needs include probabilistic approaches to design for ice loads and appropriate serviceability criteria. The point was raised that the standard design criteria for reinforced concrete buildings may not be applicable to thick concrete sections having high percentages of multi-axial reinforcement. Additional discussion dealt with some of the severe environmental conditions that must be endured by concrete structures, such as large thermal gradients, ice abrasion, and cyclic freezing and thawing.

The following specific research areas were identified by the Design Working Group:

-The behavior of concrete slab and shell elements subject to concentrated out of plane forces plus the simultaneous action of membrane stresses. Investigations should address the following:

Tests of large scale and reduced scale specimens to identify any "scale effects".
Use of realistic support conditions and loadings characteristic of ice in order to corroborate non-linear numerical analyses.
Methods of reinforcing to ensure high load resistance and high energy absorption capacity.
Acceptability of the concept permitting repairable local damage under extreme loadings provided damage does not result in progressive collapse of entire structure.
Guidelines for evaluating the resistance of heavily reinforced thick sections subjected to concentrated loads and membrane stresses.

-Investigate means for enhancing the resistance and energy absorption of shear walls and diaphragms subjected to high compressive and shearing stresses.

-Determination of peak local forces generated during the impact of large ice features against the peripheral wall. The effects of hydrodynamic damping, ice fracture energy absorption and soil-structure compliance on the peak loads should be considered.

-Low-cycle fatigue behavior of structural elements, especially peripheral walls, under the "ratcheting" effects of continuous ice crushing.

-Establishment of deterministic and parametric (and eventually probabilistic) ice loading criteria.

-Recommendations for load factors for ice loadings. Determination of appropriate serviceability criteria. Guidelines for appropriate load combinations to be considered in design; e.g., earthquake and ice, or waves and small ice features ("bergy bits") impelled at high velocity by waves.

- The abrasion of external walls by ice, and the effects (if any) of sand and silt particles in sea ice contacting the structure.

- The adhesive bond of ice to concrete and the probable range of friction forces.

- The freezing and thawing behavior of concrete, especially in the splash zone. The effectiveness of air entrainment and silica fume.

- Evaluation of the effects of thermal gradients, both through wall and global. Evaluation of the effects of concrete properties, reinforcement and prestressing details, and structural configurations on limiting the cracking due to thermal strains.

- Performance and design criteria of steel-concrete composite elements. Investigation of methods for assuring effective composite action, effects of thermal gradients and effects of freezing and thawing.

- Risk, reliability and consequence evaluation principles for Arctic concrete structures.

- Details for protecting post-tensioning anchorages against freezing and thawing action.

- Field durability tests of post-tensioned and reinforced high strength, lightweight concrete incorporating condensed silica fume.

3.3 MATERIALS GROUP

The majority of the discussions dealt with questions of concrete durability under the extreme Arctic conditions. There were two recurrent ideas during the discussions:

- For improved durability, impermeability is the most important property for concrete exposed to seawater, particularly in the tidal and splash zones.

- Existing criteria for concrete cover and crack control in permanently submerged structures are too conservative. Consideration of the factors necessary for steel corrosion suggests that active corrosion in these areas is highly unlikely. Yet for certain members the crack control criterion for corrosion protection is reported to be more critical than the wave criterion in designing the quantity of reinforcement.

Much of the discussion dealt with the points addressed in Chairman Philleo's position paper, and is summarized in the following paragraphs.

There is no evidence to support an upper limit of tricalcium-aluminate content for cement exposed to seawater. Sulfate attack is not a problem in high quality, impermeable concrete. Alkali content of cement was not seen as a problem except where reactive aggregates are used. It was further mentioned that for important structures exposed to sea water, reactive aggregates should not be used.

Pozzolans, such as fly ash and condensed silica fume, and slags are useful for concrete in sea water because they reduce permeability, and thereby reduce the ingress of chloride ions. Since the traditional concepts of water-cement ratio may not fully characterize concrete with pozzolans, interest was expressed in using permeability as a criterion for quality. This would require improvements in permeability testing of concrete and the development of methods for measuring in-place permeability.

More work is needed to answer the question of whether or not accelerators containing chlorides should be permitted in offshore structures. It was mentioned that high strength, prestressed concrete has served successfully in the presence of high chloride content. The basic question is whether chlorides need to be limited if steel is protected by high quality, impermeable concrete.

The use of high-range water reducers (superplasticizers) was deemed to be necessary both for placing concrete in the heavily reinforced sections and for allowing the use of condensed silica fume, which is extremely fine and requires high water content for workability. The evidence indicates that durable concrete can be made with high-range water reducers, but there are some questions about the existing criteria for the necessary air void system.

Concerning the need for proper admixtures for use with tremie concrete, it was mentioned that there probably will be little underwater placement in Arctic offshore structures. In addition, there are available proprietary systems which permit underwater placement without using tremies.

Lightweight aggregates can be useful materials where weight reduction is an important consideration. Further knowledge is needed about the thermal properties and failure mechanisms of lightweight concrete.

In important offshore structures, sea water should not be used for the mixing water.

It was noted that there are practical limits to using low permeability concrete as a means of reducing concrete cover. For example, a minimum amount of cover is required for proper concrete placement between formwork and reinforcing bars. In addition, the critical zone of a structure (tidal and splash zone) may be a relatively small portion of the total, and reduced cover may not generate large cost savings. Below the water line, cover is not critical for durability. However, when design requirements call for limited cover in the critical zone, highly impermeable concrete and epoxy-coated reinforcing steel is a practical solution. Where there is no need for thin cover, there is likewise no need for epoxy-coated reinforcement as steel can be adequately protected by sufficient cover of high quality concrete. The use of epoxy-coated bars may be cost effective in the exposed working platforms, where calcium chloride is likely to be used for deicing.

Additional discussion covered topics not mentioned in the position paper. For example, the subject of ice abrasion was addressed, and it was concluded that more information is needed in this area. The potential of fiber reinforced concrete has yet to be realized in offshore structures. There is a need for structural design criteria to supplement the wealth of test data on this material.

During the plenary session two topics related to materials were brought up. One dealt with cathodic protection. While differences of opinion were noted, it appears that some of the existing criteria may overestimate the problem of galvanic corrosion of steel projecting from concrete in the submerged zone. The other question dealt with the low temperature behavior of ASTM A 706 reinforcing steel (60 ksi, weldeable deformed bars). However, it was noted that tests conducted in Norway and the United Kingdom on steels with presumably similar composition indicated adequate performance at low temperatures.

The following research needs were identified by the Materials Group and are listed in the priority order suggested by the Group:

-Establishment of permeability criteria with adequate test techniques including means to test in-situ concrete.

-Establishment of realistic chloride limits when very low permeability concrete is employed.

-Re-examination of air void spacing criteria for freezing and thawing durability.

-Properties of high-strength, lightweight concrete made with condensed silica fume and superplasticizer.

-Early age properties of high strength concrete.

-Methods of test and criteria to determine whether or not tendon ducts have been effectively grouted.

-Development of suitable test methods and criteria for ice abrasion resistance of concrete.

-Development of thixotropic concrete for underwater placement.

-Design criteria for fiber reinforced concrete.

-Mechanical properties of high-strength concrete, such as shear resistance, to replace those assumed values extrapolated from normal strength concrete.

-Adequate design procedures for lightweight concrete.

-Establishment, if necessary, of a minimum limit for tricalcium aluminate content of cement.

3.4 CONSTRUCTION GROUP

One of the key points in the Construction Group's discussions was that many of the construction problems arise from the design requirements. While the demands of designers can usually be met (at a price), a good designer will avoid excessive construction costs by keeping the design simple. The special problems associated with Arctic offshore construction are the difficulties in transporting units and equipment from temperate areas to the site, and the short time period during which the site is accessible through the water. These problems arise because of the generally shallow water and ice infestation associated with the Beaufort Sea.

It was suggested that many of the construction problems can be avoided by ensuring that the units are as complete as possible before being shipped to the site. Construction operations at the site should be minimized, and those that are required should be kept simple. However, transportation problems increase as the size of the units increase.

The Group addressed the problems that may arise because of the Jones Act. The law is intended to protect American trade but may actually encourage construction of large structures at non-USA sites, since US-registered vessels (few of which are suitable) would not be needed for transport to the final destination.

The following areas of needed research were identified by the Construction Group:

Foundations for structures:
Gravity structures will usually be required to rest on fill material. Techniques for construction of the mounds and the final leveling of the surface are areas where additional knowledge is needed. In addition, the following topics should also be investigated:

- means of determining the relevant properties of potential fill materials
- methods of pumping and consolidating fill materials
- the influence of ice particles in the fill
- means of protecting mounds from erosion
- grouting under cold sea water

Berms for protection from floating ice:
Sand and gravel berms may be required to protect the structure from floating ice. Research needs are similar to those above for foundations.

Moving platforms through ice-covered waters:
Moveable drilling structures would normally be useable at only one location per season because they can only be moved when the sea is sufficiently free from ice. In order to permit drilling at more than one location per season, it is necessary to consider techniques for moving structures through ice-covered waters. Topics to be investigated might include:

- the design of structures as ice-breaking hulls

-the power requirements for moving structures
-the economics of moving and re-using structures

Efficient utilization of equipment:
At the construction site, lifting equipment such as crane barges will be needed to assemble prefabricated units. To minimize the size of the required equipment and to reduce the time when the equipment is needed, novel designs and installation techniques should be investigated.

Transportation of structures from fabrication to installation sites:
Structures destined for the Arctic will have to be prefabricated in temperate climates and towed or transported to their final destination through seas which can be stormy, ice-laden and, in places, shallow. These conditions pose technical and practical problems, but the Jones Act poses additional problems. The Act restricts the use of non-U.S. hulls to carry loads from one U.S. location to another. Therefore, if a suitable U.S.-hull is not available to transport a structure from a U.S.-fabrication point to a U.S.-installation, the structure will have to be fabricated outside the U.S. Thus, legislation enacted to protect U.S.-trade can have opposite effects. Research topics related to transportation of structures might include:

-Examination of the effects of the Jones Act, and recommendations for appropriate exemptions
-Collection of data on wind, wave and currents in a publicly funded program which would ensure accessibility to the information
-Collection of data on ice movement, scour and hydrography in a similarly funded program

Assembly of units on site:
Assembly operations should be quick and simple, and should require a minimum of equipment. Research areas include the following:

-Required tolerances for interlocking units
-Materials and construction methods for load-distributing intermediate layers
-Tolerances to local crushing
-Design and construction of connections which can be subsequently dismantled
-Protection techniques for connectors subject to corrosion or accidental damage
-Mooring systems for use during assembly operations

Risk during transportation and installation:
A topic for further study is the loading that can arise from ice, wind, waves and current during transportation and installation, and an evaluation of the consequences of the loading.

Risks and consequences of accidental spillage:
Spillage of oil, grout or even mud may have a large impact on the Arctic environment. The fear of such accidents may lead to very strict requirements

in an attempt to avoid them. The extra construction work that arises from that strictness may itself be harmful to the environment. The risks and consequences of accidental spillage and the effects of the construction process on the environment need to be evaluated in factual terms so that the required controls can be appropriate in both method and degree. Further study is needed on the impact of construction and operation in this region, and this study should be performed under authoritative and independent control so that the results are acceptable to all parties.

3.5 INSPECTION/REPAIR GROUP

While advances in inspection and repair technology have occurred for offshore structures, the Arctic poses additional problems by virtue of the extremely low temperatures (down to -50°C) that can occur and the presence of ice in varying forms. In addition, the nature of the damage which may be sustained is varied, ranging from punching failure to ice abrasion of peripheral walls. The discussions of the Inspection/Repair Group dealt with re-evaluation of the existing inspection and repair procedures for offshore structures in light of the extreme environmental conditions of the Arctic.

The first topic of discussion was materials performance. A thorough understanding of the mechanical and durability characteristics under Arctic conditions is required when undertaking damage analysis and developing repair strategies.

The available inspection methods for monitoring steel corrosion, concrete quality and structural performance were reviewed. It was noted that many of these techniques will have to re-evaluated in light of the operating conditions encountered in Arctic structures.

The Group reviewed the various forms of damage that can be expected: steel corrosion, mechanical damage, freezing/thawing damage and foundation distress. The need to undertake repairs must be assessed in terms of the significance of the damage on the successful operation of the structure. Some damage may require immediate action while in other cases repair may be delayed until suitable conditions arise.

The techniques and materials currently available for repairing offshore structures were discussed and the special requirements for Arctic applications were addressed. The primary need is for durable materials that can be applied under very cold conditions.

In developing a list of research needs, the Group found that the subject matter is not easily broken down into specific research items. The Group felt that in many cases, surveys, assessments and studies need to be performed to develop new and practical procedures as well as to further develop existing technology. The following research needs were identified for different categories:

Inspection during construction:

- Development of test methods for assessing in-situ material performance
- Procedures for recording structural detailing of the as-built structure
- Development of practical specifications for field use, including relevant testing and control procedures

Structure integrity monitoring:

- Evaluation of sensor and monitoring equipment performance under in-service conditions to ensure meaningful output data
- Development of efficient and reliable data processing techniques to ensure correct interpretation
- Development of optimum approaches for system design, installation monitoring and data interpretation

Inspection procedures:

- Development of systematic and practical recording systems to permit easy reference and updating during subsequent inspections
- Development of a practical system for coding and classifying visual defects

Inspection techniques:

- Evaluation of existing techniques for use underwater and/or in cold temperatures
- Development of alternatives to visual inspection for faster and more accurate scanning of the structure
- Development of equipment for use underwater with remote controlled vehicles
- Development of techniques and designs to permit inspection from within structures having walls

Repair procedures:

- Development and evaluation of procedures for damage-analysis, repair and after-repair inspection and evaluation

Repair techniques:

- Evaluation of the suitability of existing technology to deal with the various types of damage anticipated in the Arctic
- Development of materials and techniques for repairs that cannot be performed with existing technology

disruptive actions, such as sulfate attack, steel corrosion, freezing and thawing, etc.
- Development of test methods to measure permeability, including in-place methods for acceptance testing
- Investigation of optimum mixture proportions in terms of strength, impermeability and economy

<u>High-strength lightweight concrete:</u>
Due to the shallow waters along towing routes from fabrication to installation points, prefabricated structures must be capable of floating with low draft. The use of lightweight concrete can help to satisfy this need, but for efficiency the concrete must also be of high strength. There are questions about the mechanical and durability properties, and their interrelationships, of this new material. Areas to be investigated might include:

- Mechanical and thermal properties
- Resistance to freezing and thawing damage under saturated conditions, including a re-examination of the air-void system criteria to ensure adequate resistance against freezing and thawing
- Resistance to ice abrasion, which would include need to develop appropriate test methods
- Optimum mixture proportions
- Design criteria for structural elements

<u>Corrosion of reinforcement:</u>
An extensive amount of data have been accumulated on this subject, and it is generally agreed that corrosion is not a problem in the permanently submerged portion of an offshore structure. The problem is severe where concrete is exposed to alternating wetting and drying. Despite the wealth of research data, there are still unresolved issues such as the significance of cracking on corrosion rate and allowable levels of chloride ions. Conflicting conclusions have often been reported because of differences in testing conditions, or because of unforseen interactions among the factors affecting corrosion rate. There is a need to re-examine previous investigations in the light of our current understanding of steel corrosion in concrete, and develop practical and effective criteria for minimizing the probability of corrosion. The following points should be studied:

- Allowable chloride ion concentration, with due consideration to other factors such as concrete permeability and depth of cover
- The significance of cracking in relation to corrosion of reinforcing and prestressing steel

<u>Other areas:</u>
There are additional subjects that merit further study:

- Utilization of fiber-reinforced concrete to enhance the energy absorption capabilities of structural members
- Utilization of polymer-impregnated concrete to enhance strength and reduce permeability
- Coatings to reduce ice adhesion
- Establish criteria to safeguard against degradation from freezing and

thawing action on water-filled cracks

5.3 RESEARCH AREAS RELATED TO CONSTRUCTION

The construction of large North Sea structures has resulted in the technology required to successfully build and install concrete offshore facilities. The primary hinderances to direct utilization of this technology in Arctic construction are the shallow waters over which the structures must be towed and the short open water season. Identification of research areas related to construction is not a simple task, because we are often dealing with the development of techniques to solve a particular problem rather than trying to gain fundamental understanding about the nature of the problem. In addition, many construction problems can be avoided during the design stage by giving proper consideration to constructability. Areas requiring new approaches might include:

- Techniques for rapid preparation of subsea foundations and protective berms for gravity structures
- Techniques for towing structures through ice-covered waters
- Techniques for rapid joining of precast units at the installation site

As pointed out in the Workshop, the implications of the Jones Act should be carefully re-examined. If it is found that the Act will effectively eliminate the possibility of construction of structures at U.S. locations, means of permitting exemptions from the Act should be considered.

5.4 RESEARCH AREAS RELATED TO INSPECTION AND REPAIR

As in the case of construction, the inspection programs of North Sea structures have produced orderly procedures for surveying large surface areas and for efficient presentation of large amounts of data. In inspecting Arctic structures, consideration must be given to the fact that the structure will be ice-bound for the major part of the year. To assist in future inspections, consideration should be given during design for providing access into the structure so that some of the inspection can be performed without having to deal with the icy environment. Identification of research needs related to inspection is also difficult, because generally we are dealing with the development of new inspection methods, the modification of existing methods, or the evaluation of the applicability of existing methods in the Arctic environment. The following areas need investigation:

- Development of novel alternative techniques for rapid scanning of the structure, techniques such as infra-red thermography or radar are promising candidates
- Development of inspection techniques utilizing remote controlled vehicles with monitoring facilities on top of the structure
- Evaluation of performance of existing nondestructive test methods on frozen concrete

Repair techniques will be dictated by the nature of the damage. Some forms of damage will be unique to Arctic structures, such as abrasion by ice or punching failure due to unusually large local ice pressures. For these kinds of damage, new repair techniques need to be developed. For typical damage such as cracking or spalling, existing techniques may be used. However, the repair materials require careful evaluation to ensure that they will function as desired under cold temperature conditions. The following topics should be investigated:

- -Development of methods for repairing puncture damage, which would include methods of repairing damaged reinforcement and restoring prestressing if necessary
- -Development of techniques for evaluating the adequacy of repairs
- -Development of appropriate repair materials for the types of damage and environmental conditions unique to Arctic structures

6.0 ACKNOWLEDGMENT

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7.0 REFERENCES

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19) Gerwick, B.C.,, Prestressed Concrete Floating Terminal for Arctic Ocean Service, Proc 3rd Int Conf on Port and Ocean Engineering Under Arctic Conditions, Fairbanks, AK, Aug 11-15, 1975, pp 581-595

20) Gerwick, B.C., Utilization of Prestressed Concrete in Arctic Ocean Structures, Proc 1st Int Conf on Port and Ocean Engineering Under Arctic Conditions, Trondheim, Norway, 1971,pp 917-933

21) Fitzpatrick, J. and Stenning, D.G., Design and Construction of Tarsiut Island in the Canadian Beaufort Sea, Proc 1983 Offshore Technology Conf, May 2-5, 1983, Houston, TX, Vol. 2, OTC 4517, pp 51-60

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23) Anon., Exxon to Use Concrete Island to Drill in Beaufort, Oil and Gas Journal, Sept. 19, 1983, pp 82-83

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APPENDIX

A.1 ANNOTATED BIBLIOGRAPHY

DESIGN

Anon., Review of APOA Project 110 - Conical and Cylindrical Gravity Structures for Southern Beaufort Sea, APOA Review, V6, No 1, Spring/Summer 1983, pp 28-29

Reviews research project by Esso Resources Canada Ltd on design of monocone gravity structure. Important questions that require further investigation include the long-term water absorption properties and the shear and tensile strength of the proposed lightweight reinforced concrete. It is stated that the combination of cost and engineering difficulties of the monocone concept have led to suspension of work on bottom-founded gravity structures.

Engelbrektson, A., Ice Force Design in the Light of Experiences from the Baltic, Paper prepared for International Conference "Offshore Goteborg 83", VRM 057-003, 16 pp

Describes ice load prediction methods against the background of experiences gained from Swedish lighthouse structures in the Baltic. Discusses factors affecting ice forces on structures and the dynamic effects of ice forces. Design equations for predicting ice forces are presented, and it is suggested that they would be applicable in Arctic sites having similar ice characteristics to the Baltic Sea.

Almazov, V.O. and Kopaigorodski, E.M., Bearing Capacity of a Reinforced Concrete Shell in an Arctic Environment, Cold Regions Science and Technology,6(1982) pp 89-98

Discusses design requirements for offshore Arctic Structures in order to prevent cracking of concrete under external loads plus stresses due to temperature gradients. Describes research studies in USSR of model shell structures subjected to external forces plus stresses due to temperature gradients (0 to -50°C). Also describes tests on beam and compression members.

Furnes, O., Concrete and Other Alternative Platform Designs, Proc Int Petroleum Exhibition and Technical Symposium (SPE), Bejing, China, March 18-26, 1982, SPE 10001, 31 pp

Reviews the design and construction of North Sea platforms. Design principles and analytical procedures are outlined. Alternatives to concrete gravity platforms are discussed. It is concluded that concrete structures designed in accordance with current criteria are durable and maintenance-free even in the harsh North Sea environment.

Waagaard, K., Fatigue Strength Evaluation of Offshore Concrete Structures, in ACI SP-75 Fatigue of Concrete Structures, American Concrete Institute, Detroit, 1982, pp 373-397

Presents a summary of recommendations for fatigue strength evaluations of offshore concrete structures. The fatigue provisions of ACI, DNV, FIP, NPD and TNO are reviewed and compared. Cites the need to develop simplified evaluation methods to indicate whether fatigue will control structural design.

Yee, A.A., The Superiority of Concrete Honeycomb Construction for Marine Structures, Proc Arctic Offshore Drilling Platform Symposium, Los Angeles CA, October 7, 1982, pp 7-1 - 7-16

Discusses structural concept for concrete offshore structures composed of a honeycomb cellular core with composite top and bottom slabs. The design is claimed to result in economical use of materials, has material storage areas and low draft requirements. Concepts for use of such structures in the Arctic are described.

Fretheim, I.B., Offshore Structures for the Canadian Arctic, Proc of the Canadian Structural Concrete Conference, University of Toronto, Sept 17-18, 1981, pp 19-55

Discusses considerations and concept solutions to the design of production platforms. The main concepts include: conical gravity structures, caisson gravity structures, earth-filled caisson retained structures and earthfill structures. The positive and negative features of each concept are discussed. In addition, hybrid concepts which combine the strengths of individual concepts are presented.

Gerwick, B.C., Concrete Offshore Structures -- A State of the Art, Proc of the Canadian Structural Concrete Conference, University of Toronto, Sept 17-18, 1981, pp 3-17

Identifies problem areas for concrete structures in the Arctic: the properties and behavior of lightweight concrete; coatings for concrete; punching shear resistance of walls; fatigue properties in a marine environment; thermal strains; freezing and thawing; steel corrosion; stability of structures during towing and installation; earthquake response; freezing of water in confined spaces; grouting of ducts; connection of deck to substructure; and repair of damage.

Gerwick, B.C., Litton, R.W. and Reimer, R.B., Resistance of Concrete Walls to High Concentrated Ice Loads, Proc 1981 Offshore Technology Conf, May 4-7, 1981, Houston, TX, Vol. 3, OTC 4111, pp 425-436

Addresses the resistance of walls to local concentrated ice forces. Design of walls according to current building code practice results in excessively thick walls that present flotation problems. A finite element analysis of a wall segment was performed to gain insight into the structural performance under high local loading. It is suggested that the required punching resistance may be achieved by prestressing through the thickness. For ductility, stirrups should be anchored.

Jarlan, C.E., Hibernia Oilfield Development of a Prestressed Concrete Drilling and Production Platform, Proc Symposium on Production and Transportation Systems for Hibernia Discovery, St. Johns NF, Feb 16-18, 1981, pp 18-26

Presents a design concept for a prestressed gravity platform for the Hibernia field. Features of the structure are derived from previous concepts and knowledge related to installations in ice infested waters. The structure is similar to the Ekofisk tank in the North Sea except that it is adapted to resist ice impact. The hydrodynamics of moving icebergs are presented. A rubble mound is suggested to dampen iceberg impact forces. Suggestions are given for hydraulic model studies.

Letourneur, O. and Falcimaigne, J., Concrete Production Floating Platforms, Proc Symposium on Production and Transportation Systems for Hibernia Discovery, St. Johns NF, Feb 16-18, 1981, pp 122-133

Discusses the design of a floating concrete production platform for use in the Hibernia field. The structure is patterned after similar platforms used in the North Sea. Upon the approach of a large iceberg, the platform would be disconnected and moved away from the approaching ice.

Lundrigan, H. and Lindgren, J., Potential Concrete Structures for Hibernia, Proc Symposium on Production and Transportation Systems for Hibernia Discovery, St. Johns NF, Feb 16-18, 1981, pp 27-38

Discusses in general terms the construction schemes for structures off of Newfoundland; the methodology is patterned after proven techniques in North Sea construction. Three design approaches for fixed platforms to withstand iceberg impact are discussed. The fixed structure may be surrounded by protective berms or fendering to absorb impact energy of the icebergs, or the structure is designed to resist impact by elastic energy absorption.

Anon., Other Platforms Show Possibilities, Offshore and Gulf Coast Oil Reporter, V40, No 5, May 1980, pp 173-177

Describes different platform concepts for the Arctic. Concrete structures include conical hull structures that are gravity or pile supported and are intended for water depths up to 250 ft. For deeper waters, a floating concrete caisson has been proposed.

Jahns, H.O., Arctic Platforms, Proc Symposium on Outer Continental Shelf Frontier Technology, Marine Board Assembly of Engineering, Nat Res Council, Nat. Academy of Sciences, Wash. D.C., 1980, pp 41-71

Presents a survey of existing and proposed platforms for use in areas where resistance to ice forces is major design consideration. Man-made islands identified as being the most technically and economically attractive structures in shallow waters with large ice forces. Gravel and ice islands are discussed. Concepts for use in deeper Arctic waters are presented. Extensive reference list.

Allan, A. and Pallister, J., The Mechanical Properties of Ice: The Second Step, APOA Review, V 2, No 2, June 1979, pp 7-11

Reviews research programs on the properties of ice. Various test methods developed for in-place testing are described.

Bercha, F.G. and Stenning, D.G., Arctic Offshore Deepwater Ice-Structure Interactions, Proc 1979 Offshore Technology Conf, April 30-May 3, 1979, Houston, TX, Vol. 4, OTC 3632, pp 2377-2386

Interactions of ice formations with monocone gravity structure are described. Authors conclude that design loads can be predicted by judicious application of modern and classical ice mechanics. However, there are still unanswered questions about: scale effects; the statistical descriptions of input data; extension of interaction analyses to other processes; and a comprehensive probabilistic analysis of all interactions.

Pallister,A.E. and Pallister, J., Ice Covered Waters -- A New Offshore Petroleum Environment, APOA Review, V 1, No 2, May 1978, pp 12-17

Provides a general description of the various ice forms that are encountered in the Arctic. A glossary of ice terms is provided, and two research projects on ice conditions in the Arctic are reviewed.

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de Long, J.J.A. and Bruce, J.C., Design and Construction of a Caisson Retained Island Drilling Platform for the Beaufort Sea, Proc 1978 Offshore Technology Conf, May 8-10, 1978, Houston, TX, Vol. 4, OTC 3294, pp 2111-2120

Describes design of a set of caissons for construction of retained island in the Beaufort Sea. While the specific design is steel, the economics and operational principles apply equally to a concrete structure. The justification for such structures is the reduction in fill material to create an artificial island.

Jazrawi, W. and Khanna, J., Monocone - A Mobile Gravity Platform for the Arctic Offshore, Proc 4th Int Conf on Port and Ocean Engineering Under Arctic Conditions, St. Johns, NF, Sept 26-30, 1977, pp 170-184

Discusses the "monocone" concept-- a single column gravity structure resting on a large circular base and fitted with a moveable conical collar intended to cause downward flexural failure of the ice. Design criteria are discussed and it is stated that the monocone is an efficient and versatile structure capable of being set down in water up to 41 m deep. The structure is intended to provide year-round operation.

Gerwick, B.C., The Future of Offshore Concrete Structures, Proc Int Conf on The Behavior of Off-Shore Structures (BOSS '76), Trondheim, Aug 2-5, 1976, V 1, pp 978-1000

Future developments in the field of offshore concrete structures are described. The following areas are addressed: new design concepts for new environments; advances in design procedures; improved construction methods; development of new concrete materials; and improvements in management and contractual capabilities to carry out large and complex projects.

Kivisild, H.R., Offshore Structures in Arctic Ice, Proc Int Conf on The Behavior of Off-Shore Structures (BOSS '76), Trondheim, Aug 2-5, 1976, V 2, pp 249-266

A general treatment of the problems associated with structures in the Arctic. The main features of the ice environment are presented, and the various design concepts for coping with ice forces are described. The possible interactions between different ice formations and platform structures are discussed. The magnitude of the ice forces depend on the nature of the ice formation and the structure's geometry.

Gerwick, B.C., Prestressed Concrete Floating Terminal for Arctic Ocean Service, Proc 3rd Int Conf on Port and Ocean Engineering Under Arctic Conditions, Fairbanks, AK, Aug 11-15, 1975, pp 581-595

Describes conceptual design of large prestressed concrete floating terminal, which would be designed for downward breaking of the ice. Advancements in concrete materials technology and in the understanding of shear-resistant mechanisms are cited as factors that will further the application of prestressed concrete in the Arctic.

Gerwick, B.C., Utilization of Prestressed Concrete in Arctic Ocean Structures, Proc 1st Int Conf on Port and Ocean Engineering Under Arctic Conditions, Trondheim, Norway, 1971,pp 917-933

Discusses ways in which prestressed concrete can be effectively used in Arctic offshore construction. Conceptual designs of prestressed concrete drilling and production platforms in shallow and deep waters are described.

MATERIALS

Ivanov, F.M., Vinogradova, E.A., Gladkov, V.S., and Usachev, I.N., Frost Resistant Concrete for Offshore Structures, Operational Life (in Russian), 691.327:666.972.53, pp 40-41

Discusses requirements to assure concrete capable of withstanding many cycles of freezing and thawing: use materials with proven service records, optimize concrete mixture including appropriate admixtures; maintain correct curing conditions to assure durable hardened paste and minimize thermal stresses; and use proper consolidation procedures. Service record of 15 years shows that when properly made concrete can withstand severe exposure to freezing and thawing in the Arctic environment.

Arthur, P.D., Earl, J.C. and Hodkiess, T., Corrosion Fatigue in Concrete for Marine Applications, in ACI SP-75 Fatigue of Concrete Structures, American Concrete Institute, Detroit, 1982, pp 1-24

Reports on studies of the fatigue life of reinforced concrete beams exposed to sea water. Under low cycle fatigue (ocean wave frequency), found that fatigue life in sea water is better than in air; this is explained by deposition of solid material in the cracks (crack blocking). At higher frequencies (3 to 5 Hz), crack blocking did not occur and fatigue life in sea water was reduced. Data on reversed bending and with prestressed concrete are being obtained.

Mehta, P.K. and Gerwick, B.C., Cracking-Corrosion Interaction in Concrete Exposed to Marine Environment, Concrete International, V 4, No 10, October 1982, pp 45-51

Physical and chemical processes which lead to enlargement of microcracking in concrete are classified, and the chemical processes of corrosion are reviewed. A necessary factor for active corrosion is the presence of an adequate supply of oxygen. Increasing concrete permeability increases the access of oxygen to steel. The primary effect of increased microcracking is to increase concrete permeability.

Browne, R., Mechanisms of Corrosion of Steel in Concrete in Relation to Design, Inspection and Repair of Offshore and Coastal Structures, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 169-204

Reviews research carried out in the UK and other countries to answer questions about the expected performance of North Sea structures. Discusses 4 key factors related to steel corrosion: chloride ion penetration, loss of concrete resistivity, availability of oxygen and concrete cover. Unanswered questions relative to these factors are presented. Different levels of repair are suggested based on the level of chloride ions and deterioration.

Fidjestol, P. and Nilsen, N., Field Test of Reinforcement Corrosion in Concrete, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 205-221

Reports on the results of research aimed at answering questions about the relationship between crack width and corrosion. Precracked beams were placed in sea water, and electrochemical measurements were made along with examination of the reinforcment at periodic intervals. The conclusions were that the corrosion rate in saturated concrete is very low due to a low oxygen concentration and that crack widths within the normal range and under static load have minor importance.

Gerwick, B.C., Research Requirements for Concrete in Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 577-587

Reviews recent research projects aimed at answering questions about the performance of concrete structures in hostile marine environments. Future research should be performed in the areas of structural response, environmental degradation, new materials, methods of construction and repair, and new design concepts. It is suggested that joint industry-government research programs are a means for undertaking large and expensive research projects.

Haynes, H., Permeability of Concrete in Sea Water, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 21-38

Discusses relationship between porosity in concrete and permeability. It is the capillary pores in hardened paste that controls permeability. Tests indicate that the permeability of concrete exposed to sea water decreases with time, which is postulated to be due to chemical reactions that produce solid products that block pores in the paste.

Holm, T.A., Performance of Structural Lightweight Concrete in a Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 589-608

Reviews performance of lightweight concrete structures exposed to sea water. Laboratory freezing and thawing tests are reviewed, as well as tests on cores recovered from a concrete ship built in 1919. It was concluded that properly proportioned lightweight concrete can provide excellent performance in marine applications.

Makita, M., Mori, Y. and Katawaki, K., Performance of Typical Protection Methods for Reinforced Concrete in Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 453-471

Discusses the use of resin coatings, galvanizing, cathodic protection, concrete coatings and inhibitors as possible means of protecting steel in concrete. Powder epoxy coatings gave best protection. Urethane concrete coatings proved to offer no protection, likewise for sodium sulfite based inhibitors. Galvanizing was found to not always be satisfactory in the splash zone.

Mehta, P.K., Durability of Concrete in Marine Environment -- A Review, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 1-20

Reviews investigations of the durability of concrete exposed to sea water. Presents chemical reactions associated with the deterioration of concrete and steel corrosion. It is concluded that impermeability is the most important property governing the durability of concrete. In addition, individual processes of deterioration tend to limit themselves to different parts of the structure. The tidal zone is the most vulnerable part of a marine structure.

O'Neil E.F., Study of Reinforced Concrete Beams Exposed to Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 113-132

Reports on long-term study of reinforced beams exposed to sea water in the tidal zone and to freezing and thawing. Major conclusions were that with air entrained concrete the years of exposure did not lower the flexural strength below design values, and that larger crack widths increased the amount of corrosion. Crack widths less than 0.4 mm did not result in corrosion.

Okada, K. and Miyagawa, T., Chloride Corrosion of Reinforcing Steel in Cracked Concrete, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 237-254

Examines the influence of cracks on the mechanism and rate of corrosion of reinforcing steel. It was concluded that the corrosion rates decreased with time, and under conditions of wetting and drying the corrosion rate increased during drying. A clear relationship between crack width and corrosion rate was not established.

Paterson, W.S., Fatigue of Reinforced Concrete in Sea Water, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 419-436

Reports on results of research to study the fatigue life of cold worked reinforcement (Torbar) in sea water. Found that cracks in reinforced concrete beams filled up with deposits during tests. Tests did not identify a fatigue limit for the steel reinforcement.

Sharp, J.V. and Pullar-Strecker, P., The United Kingdom Concrete-in-the Oceans Program, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 397-417

Reviews UK research program. Seven projects are discussed; three of them deal with corrosion, three deal with structural aspects and one deals with inspection of existing offshore structures. Findings of the corrosion projects are summarized: cracking affects initiation of corrosion but other factors affect its rate; there will be little or no corrosion in permanently submerged structures; in the splash zone adequate concrete cover is required to prevent corrosion.

Vanden Bosch, V.D., Performance of Mortar Specimens in Chemical Accelerated Marine Exposure, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 487-507

Reports results of tests on the chemical resistance of portland and blast furnace slag cement. Concluded that 70% slag addition results in concrete with high resistance to sea water attack. Excellent performance of marine structures in the Netherlands is cited as demonstration of the durability of slag cement concrete.

Gjorv, O., Vennesland, O. and El-Busaidy, A.H.S., Electrical Resistivity of Concrete in Oceans, Proc 1977 Offshore Technology Conf, May 2-5, 1977, Houston, TX, Vol. 1, OTC 2803, pp 581-588

Reports on laboratory experiments aimed at providing information on the electrical resistivity of concrete. The degree of saturation was found to have the greatest effect on the resistivity value. In general, the same factors that affect permeability were found to influence resistivity, such as degree of hydration, water/cement ratio, and maximum aggregate size. Cracking tended to reduce resistivity.

Matsuishi, M., Nishimaki, K., Takeshita, H, Iwata, S. and Suhara, T., On the Strength of New Composite Steel-Concrete Material for Offshore Structure, Proc 1977 Offshore Technology Conf, May 2-5, 1977, Houston, TX, Vol. 1, OTC 2804, pp 589-594

Describes composite material composed of concrete placed between steel plates. Beams were made and tested in center-point loading. The composite material is reported to provide large energy absorption capacity. A method for computing the ultimate strength of the composite material is presented. Test results are compared with non-linear finite element analysis.

Browne, R.D. and Domone, P.L.J., The Long-Term Performance of Concrete in the Marine Environment, Proc Conf Off-Shore Structures, ICE, London, Oct 7-8, 1974, pp 49-59

Reviews previous studies on the durability of concrete in marine environments. It is concluded that in order to produce durable concrete: use materials with proven history, especially cement composition; use correct mixture proportions to permit low permeability along with ease of placement; use proper design details, such as cover, especially in the splash zone; and adopt proper quality control procedures during construction.

Gjorv, O.E., Durability of Marine Concrete Structures Under Arctic Conditions, Proc 1st Int Conf on Port and Ocean Engineering Under Arctic Conditions, Trondheim, Norway, 1971, pp 934-943

Reviews the results of inspections of marine structures along the Norwegian Coast. The most serious durability problems were associated with chemical deterioration of concrete and steel corrosion. The tidal zone was identified as being most vulnerable to environmental attack, and deterioration appears to result from interactions of several processes. In general, the inspected structures were in good condition even after 50 years of service.

CONSTRUCTION

Fitzpatrick, J. and Stenning, D.G., Design and Construction of Tarsiut Island in the Canadian Beaufort Sea, Proc 1983 Offshore Technology Conf, May 2-5, 1983, Houston, TX, Vol. 2, OTC 4517, pp 51-60

Presents a summary of the design and construction considerations for the Tarsiut Island. The island is constructed of four concrete caissons arranged in a square, backfilled and resting upon a submerged sand berm. The advantage of lightweight concrete is highlighted. The structure was completed in Oct. 1981 and has survived two winters. The construction process is outlined.

Anon., E&P Spending in Canadian Frontier Areas to Hit $1.2 Billion in 1982, Oil and Gas Journal, July 12, 1982, pp 84-93

Discusses status of Canadian oil exploration in the Arctic regions. The Tarsiut Island project is highlighted as the first step in planning for a series of larger islands.

Anon., Operator Interest Keen in U.S. Beaufort Sea, Oil and Gas Journal, July 12, 1982, pp 71-77

Discusses status of US oil exploration in the Alsaka region.

Moksnes, J., Quality Assurance for Concrete Platforms in North Sea Oil Fields, Concrete International, V 4, No 9, September 1982, pp 13-19

Describes the quality assurance program employed in the construction of North Sea oil platforms. The quality control procedures employed during construction are also described. It is reported that rigorous requirements for these structures have resulted in a general improvement in project management, construction procedures and concrete technology.

Anon., Encouraging Strikes Spur Search in U.S., Canadian Beaufort Sea, Oil and Gas Journal, Dec 21, 1981, pp 21-26

Discusses results and future plans for exploration and production drilling in the Beaufort Sea. The Canadian development plan is described, and it calls for the construction of a significant number of artificial islands.

MacLeod, N.R. and Butler, J.H., The Evaluation of Dredging Materials for Island Construction in the Beaufort Sea, Proc 1979 Offshore Technology Conf, April 30-May 3, 1979, Houston, TX, Vol. 4, OTC 3633, pp 2387-2397

Describes three-phase program to obtain suitable materials for construction of the Issungnak gravel island in 20 m of water. The phases included: a reflection seismic survey to locate prime borrow areas; sampling of sediments; and dredging tests to verify that required production rates could be achieved.

Long, J.E., Experience in Prestressing and Grouting Concrete Offshore Structures, Proc Conf Design and Construction of Offshore Structures, ICE, London, Oct 27-28, 1976, pp 115-119

Reviews experiences gained during construction of North Sea platforms. Most pioneering work has been in the area of grouting very tall vertical ducts. Procedures are suggested for successful grouting of vertical ducts.

Werenskiold, K., Maritime Operations Relative to Construction of Large Concrete Offshore Structures, Proc Conf Design and Construction of Offshore Structures, ICE, London, Oct 27-28, 1976, pp 97-105

Describes the tasks of maritime operations related to the construction of offshore structures towed to their final locations. It is emphasized that careful planning and consideration of many details is essential for a successful operation. Back-up systems must be available and all participants must be properly briefed.

Doughty, S.C., Deep Sea Construction, ASCE Journal of the Construction Division, V101, No 3, Sept 1975, pp 607-622

Discusses the complexity of deep sea construction; the special problems associated with Arctic structures are mentioned.

Eriksson, K., Concrete Caissons for Offshore Lighthouses, Proc FIP Symposium on Concrete Sea Structures, Tbilisi, 1972, pp 79-83

Describes construction techniques of Swedish lighthouses and suggests that techniques are applicable to offshore arctic structures. Experiences indicate that as little construction as possible should be performed at sea. At sea the most difficult work encountered was the preparation of the seabed.

INSPECTION/REPAIR

Weaver, J.S. and Berzinis, W., The Tarsiut Island Monitoring Program, Proc 1983 Offshore Technology Conf, May 2-5, 1983, Houston, TX, Vol. 2, OTC 4519, pp 67-74

Presents a description of the monitoring programs used during the construction of Tarsiut Island and during drilling of exploration well. A quality assurance program was used to assure that the structure was built as required. Procedures are described for controlling the grain size of the berm fill material, for assessing the shear strength of the seabed, and for monitoring the sandfill densities. The instrumentation for the operational monitoring program is discussed.

Wright, B.D. and Weaver, J.S., Tarsiut Winter Alert Warning, Proc 1983 Offshore Technology Conf, May 2-5, 1983, Houston, TX, Vol. 2, OTC 4518, pp 61-66

Describes methodology, procedures and experiences associated with the Tarsiut Island monitoring program. The ice conditions surrounding the island are discussed. Instrumentation was installed to measure ice loads and the island's response. The objectives were to provide real time monitoring of structural performance and to provide data for improved design criteria. Observed ice forces during the 1981-82 winter were less than the design values.

Faulds, E.C., Structural Inspection and Maintainance in a North Sea Environment, Proc 1982 Offshore Technology Conf, May 3-6, 1982, Houston, TX, Vol. 3, OTC 4360, pp 713-724

Reviews experiences and lessons (technical and financial) learned from inspections of North Sea structures. Statutory requirements and inspection philosophy are reviewed. Inspection plans are presented and the application of inspection equipment and techniques are described. The superiority of concrete over steel structures in terms of less frequent inspections and maintenance is mentioned. Repair procedures are described for damages incurred by some structures.

Fjeld, S. and Roland, B., In-Service Experiences with Eleven Offshore Concrete Structures, Proc 1982 Offshore Technology Conf, May 3-6, 1982, Houston, TX, Vol. 3, OTC 4358, pp 687-693

Discusses possible deterioration sources of concrete structures: overloads; concrete degradation; steel corrosion; and foundation scouring. Presents general considerations in planning an inspection program. Visual inspection is the most feasible and reliable method for underwater inspection of concrete structures. Results of inspection of 11 structures in the North Sea revealed excellent performance. The only significant damages were due to accidental local impact loads.

Browne, R.D., Doyle, V.J. and Papworth, F., Inspection of Concrete Offshore Structures, Journal of Petroleum Technology, V 33, No 11, Nov 1981, pp 2243-2251

Discusses the inspection philosophy and procedures used to inspect an offshore concrete structure. Critical areas are defined for detailed inspection. Procedures are presented for dealing with the vast data collected during an inspection. Areas of research related to repair are discussed. The development of underwater NDT methods to locate defects covered by marine growth, to assess and monitor corrosion, and to evaluate the effectiveness of repairs are critical areas of needed research.

Geymayr, G.W., Repair of Concrete in Tropical Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 527-556

Corrosion mechanisms for reinforced concrete in sea water are reviewed. Various repair techniques are discussed. Use of epoxy mortar for underwater repairs on actual structures is described. The proper use of vapor barriers is discussed.

Heneghan, J.I., Shotcrete Repairs of Concrete Structures in Marine Environment, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 509-526

Presents discussion of causes of damage to marine structures. Proper proportioning of shotcrete mixtures including use of accelerators and latex emulsions. Procedures for surface preparation, anchoring of reinforcing steel and shotcrete placement are presented. Case studies of successful shotcrete repairs are discussed.

Schrader, E., Dikeou, J. and Gill, D., Deterioration and Repairs of Navigation Lock Concrete, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 557-576

Reports on test program to evaluate alternative materials and methods to repair damaged walls of navigation lock. A thin coat of glass fiber reinforced and latex modified shotcrete was chosen as the most cost effective repair method.

Wiebenga, J.G., Durability of Concrete Structures Along the North Sea Coast of the Netherlands, in ACI SP-65 Performance of Concrete in Marine Environment, American Concrete Institute, Detroit, 1980, pp 437-452

Reports on inspection of 64 North Sea structures ranging in ages from 3 to 63 years. Most were built with blast furnace slag cement. Depth of carbonation in splash zone was found to be low. Fifty-six structures did not have evidence of corrosion. Where corrosion was found, it was associated with a long period of exposure and insufficient concrete cover.

Browne, R.D., Domone, P.L. and Geoghegan, M.P., Inspection and Monitoring of Concrete Structures for Steel Corrosion, Proc 1977 Offshore Technology Conf, May 2-5, 1977, Houston, TX, Vol. 1, OTC 2802, pp 571-580

Reviews existing inspection methods for embedded steel, such as: visual; reinforcement location with covermeter; chloride content determination of cored samples; electrochemical potential of in-place steel; and measurement of concrete resistivity. None of existing methods are totally adequate, and development of new approaches is needed. A possibility is to develop a method which continuously monitors embedded steel.

A.2 RESEARCH PROJECTS ON OFFSHORE CONCRETE STRUCTURES

ALASKA OIL AND GAS ASSOCIATION

- #10 Arctic Marine Terminal Facilities, Chukchi Sea
- #11 Offshore Oil Terminal Structure Facilities in the Chukchi Sea
- #22 Investigation of Ice Forces on Cylindrical and Conical Offshore Structures
- #61 Conical Structure Test Program
- #75 Sea and Subsea Floor Properties
- #77 Superstructure Icing
- #83 Seismic Risk Analysis for the Gulf of Alaska
- #106 Arctic Cone Test Strucuture - Phase I
- #113 Conical Structure Test Program, 1979-80
- #121 Preliminary Design of an Arctic Cone Test Structure with Indirect Load Measurement
- #124 Beaufort Sea Multi-year Ice Ridges and Land-fast Ice Crystal Orientation
- #152 Punching Shear Resistance of Concrete Structures
- #155 Evaluation of Artificial Islands for Norton Sound
- #156 Ice Interaction with Sloping Barriers
- #162 Norton Sound Production Structure
- #174 Design of an Arctic Cone Exploration Structure-- Phase I

ARCTIC PETROLEUM OPERATORS ASSOCIATION

- #57 Adfreeze Study
- #85 Adfreeze on Conical Structures
- #86 Study of Pressure Ridge/Cone Interaction
- #103 Interaction Between Ice Sheets & Wide Structures
- #104 Measurement of Ice Pressures on Artificial Islands (Phase I)
- #105 In-Situ Ice Pressure Measurements Around Artificial Islands (Phase II)
- #110 Conical and Cylindrical Gravity Structures for Southern Beaufort Sea
- #122 In-Situ Ice Pressure Measurements 1976/77
- #125 Experimental Ridge-Caisson Retained Island Interaction 1976/77
- #143 Model Experiments to Determine the Forces and Behavior of Moving Ice Fields Against a Concrete Drilling Caisson
- #145 Caisson Retained Island Design
- #197 Tarsiut Caisson Island Data Acquisition 1981/82
- #197 Tarsiut Caisson Island Data Acquisition 1982/83
- #204 Arctic Offshore Production Platform Evaluation
- #205 Environmental Design Criteria for Arctic Offshore Platforms

DET NORSKE VERITAS

- Behavior of Concrete Structures in Deep Water
- Ductility Performance of Offshore Concrete Structures
- Impacts and Collisions Against Offshore Platforms
- Ice-Structure Interaction
- Dynamic Response of Fixed Structures Under Impulsive and Cyclic Ice Loading

STUDIES FOR OFFSHORE NEWFOUNDLAND

- Fixed Platform Feasibility Study
- Offshore Storage and Loading Facilities Feasibility Study
- Ice Protection Studies
- Gravity Base Structure -- Feasibility Design
- Gravity Base Structure -- Geotechnical Studies
- Gravity Base Structure -- Concrete Punching Shear Analysis
- Risk Assessment Study

NETHERLANDS INDUSTRIAL COUNCIL FOR OCEANOLOGY

- Concrete Mechanics
- Durability of Concrete Offshore Structures
- Fatigue of Concrete
- Probabilistic Safety of Offshore Structures

UK CONCRETE-IN-THE-OCEANS PROGRAM

- Fundamental Mechanisms of Corrosion of Steel Reinforcement in Concrete Immersed in Sea Water
- Designing Against Corrosion in Offshore Structures
- Exposure Tests on Concrete Samples Under Different Exposure Conditions
- Effects of Temperature Gradients on Walls of Oil Storage Structures
- Survey of Existing Reinforced Concrete Marine Structures
- Strength of Large Prestressed Concrete Members in Shear
- Fatigue Strength of Reinforced and Prestressed Concrete in Seawater
- Modes of Failure of Concrete Platforms
- Fatigue Analysis of Reinforced Concrete Marine Structures
- Review of Punching Shear and Impact Resistance of Concrete Slabs
- Location of Potential Areas of Corrosion in Concrete Offshore Structures
- Corrosion Under Water Undetectable by Visual Inspection
- Criteria for Cover and Control of Cracking
- Classification of Typical Visible Defects
- Fatigue Strength of Repaired Beams
- Impact Damage to Cell Roofs

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11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

A study of research needs to enhance the capability to design, maintain, and approve concrete offshore structures for the Arctic was carried out by the National Bureau of Standards on behalf of the Minerals Management Service, Department of the Interior. The study was composed of three activities: a letter survey of key individuals in the field; an international workshop on the subject; and a review of available literature. Data gathered from these activities were used to develop a comprehensive list of research needs in the following areas: design, materials, construction, inspection and repair.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Arctic environment; concrete; construction; design; durability; inspection; marine; offshore structures; repair; research.

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