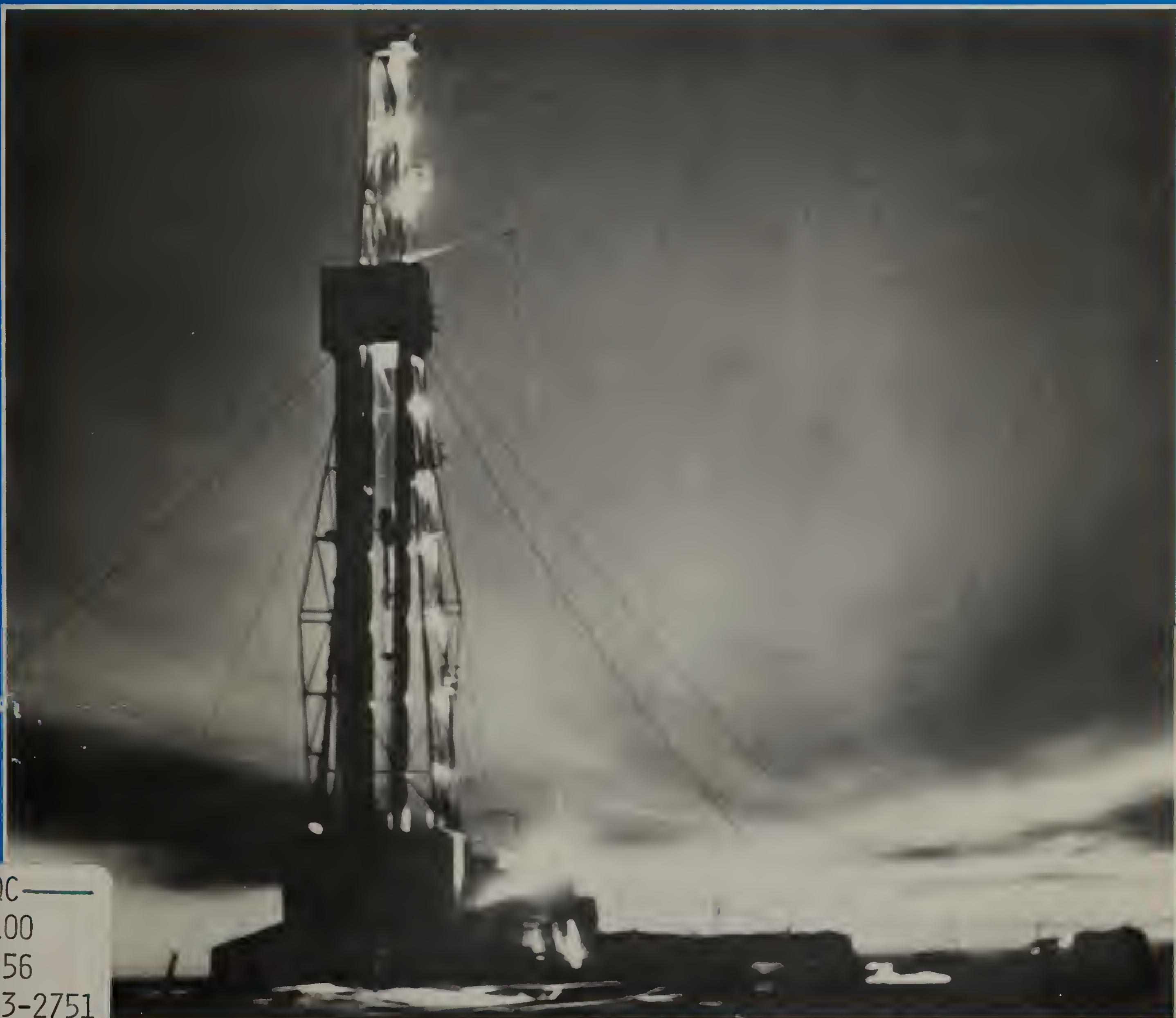
PROCEEDINGS

OF THE INTERNATIONAL WORKSHOP ON THE PERFORMANCE OF OFFSHORE CONCRETE STRUCTURES IN THE ARCTIC ENVIRONMENT

Held at the National Bureau of Standards, Washington, D.C.

MARCH 1 and 2, 1983



COVER PHOTO: Arctic oil drilling rig

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ABSTRACT

A workshop was held March 1 and 2, 1983 at the U.S. National Bureau of Standards. The objective was to bring together an international group of experts for the purpose of information exchange on the subject of the performance of Arctic offshore concrete structures. The workshop participants were divided into four working groups to discuss the following subjects related to Arctic offshore concrete structures: 1) design; 2) materials; 3) construction; and 4) inspection and repair. Each working group addressed the following topics within their subject: past experiences, current projects, and recommended research areas. The chairmen of each group prepared reports summarizing their group's deliberations. These reports are incorporated into this workshop summary.

Key words: Arctic; concrete; construction; design; inspection; offshore structures; repair; research; structural engineering; technology assessment; workshop.

RÉSUMÉ

Les 2 et 3 mars 1983 a eu lieu l'atelier du U.S. National Bureau of Standards. Son but était de réunir un groupe international d'experts pour favoriser un échange d'information sur la performance des stations de haute mer en béton dans l'Arctique. Les participants à l'atelier étaient divisés en quatre groupes pour discuter des sujets suivants, se rapportant aux stations de haute mer en béton: 1) conception; 2) matériaux; 3) construction; 4) inspection et réparations. Chaque groupe de travail a traité des thèmes ci-après à l'intérieur de leur sujet: expériences passées, projets en cours, domaines de recherche recommandés. Le président de chaque groupe a préparé un rapport résumant leurs délibérations. Ces rapports sont inclus dans le présent sommaire de l'atelier.

Mots-clés: Arctique; béton; construction; conception; inspection; stations de haute mer; réparation; recherche; génie mécanique; évaluation de la technologie; atelier

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1. INTRODUCTION

Construction of concrete offshore structures for mineral exploration in the Arctic environment offers some of the most severe challenges to our technology. There are many unknown factors related to the design, materials selection, construction methods, and maintenance of such structures. New knowledge must be sought in order to enhance our capabilities in each of the above areas. But before research can be planned, it is necessary to know the latest available information. To address these needs, an international workshop dealing with offshore concrete structures in the Arctic environment was held March 1 and 2, 1983 at the National Bureau of Standards (NBS). This report summarizes the findings of the workshop.

The workshop was organized by the Center for Building Technology (CBT) and the Canada Centre for Mineral and Energy Technology (CANMET). Funding was provided by the Technology Assessment and Research Branch, Minerals Management Service (MMS), U.S. Department of the Interior. Additional support was provided by CANMET for publishing this report.

The workshop objective was to bring together an international group of experts in the field of offshore concrete structures for the purpose of information exchange in the following subject areas:

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

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

3. Recommended topics for research and development needed to enhance our capability to construct viable Arctic offshore structures.

The workshop planning committee (composed of N.J. Carino (NBS), chairman; H.S. Lew (NBS); V.M. Malhotra (CANMET); R.W. Revie (CANMET); and C.E. Smith (MMS) identified a distinguished group of individuals who were invited to participate in the workshop. The participants were divided into four working groups dealing with the following topics:

1. The DESIGN of Arctic offshore concrete structures.

2. Required characteristics of MATERIALS for Arctic offshore concrete.

3. Problems related to the CONSTRUCTION of Arctic offshore concrete structures.

4. Problems associated with the INSPECTION and REPAIR of Arctic offshore concrete structures.

The working groups were asked to discuss past experiences, ongoing projects, and research needs in their specific area. The appendix includes the workshop agenda.

Each working group was assigned a chairman who volunteered to perform the following tasks: 1) prepare a position paper to initiate group discussion; 2) prepare a draft report of the group's discussion for presentation at the plenary session; and 3) submit a final report to be incorporated into the workshop proceedings. The Group Chairmen were as follows:

- Mr. Ben C. Gerwick, Jr. - Design Group

- Mr. Robert E. Philleo - Materials Group

- Mr. Peter Pullar-Strecker - Construction Group

- Dr. Roger Browne - Inspection/Repair Group

The reports of the Group Chairmen are presented in the following chapters.

Each report is organized into three sections: section 1 gives background information; section 2 summarizes the current state of knowledge as derived from each group discussion; and section 3 presents the recommended research areas. Since the reports are contributions of the Chairmen, they are presented in their entirety as submitted to the editor, and only minor editorial changes were made to keep the format uniform.

1. INTRODUCTION

L'édification de stations de haute mer en béton pour l'exploration minérale en milieu arctique représente l'un des plus grands défis pour notre technologie. Il existe plusieurs facteurs inconnus reliés à la conception, au choix des matériaux, aux méthodes de construction et à l'entretien de telles stations. Nous devons chercher à développer nos connaissances pour accroître nos compétences dans chacun des domaines mentionnés ci-haut. Mais avant de plaxifier de la recherche, nous devons être au courant des toutes dernières informations. C'est en vue de ces besoins qu'a eu lieu les ler et 2 mars 1983 l'atelier international du National Bureau of Standards (NBS) sur les stations de haute mer en béton en milieu arctique. Le présente rapport résume les conclusions tirées de cet atelier.

Organisé par le Center for Building Technology (CBT) et le Centre canadien de la technologie des minéraux et de l'énergie (CANMET), cet atelier fut subventionné par le Technology Assessment and Research Branch, Minerals Management Service (MMS), U.S. Department of the Interior. Le CANMET a fourni un appui financier additionnel pour la publication de ce rapport.

L'atelier visait à réunir un groupe international d'experts dans le domaine des stations de haute mer, afin d'échanger des informations sur les domaines suivants:

1. Expériences précédentes relatives à la conception, la construction, et la performance des stations de haute mer en béton, dans les eaux arctiques.

2. Projets en cours et programmes de recherche sur les stations de haute mer dans les eaux artciques.

3. Sujets recommandés pour la recherche et le développement nécessaires à l'amélioration de nos compétences pour construire des stations en haute mer dans l'Arctique, qui soient valables.

Le comité responsable de la planification de l'atelier (composé de N.J. Carino (NBS), président; H.S. Lew (NBS); V.M. Malhotra (CANMET); R.W. Revie (CANMET); et C.E. Smith (MMS) a identifié un groupe de personnes choisies pour participer à l'atelier. Les participants étaient divisés comme suit, en quatre groupes de travail:

1. La CONCEPTION des stations de haute mer en béton pour l'Arctique.

2. Les caractéristiques requises pour les MATÉRIAUX de construction des stations de haute mer en béton pour l'Arctique.

3. Les problèmes reliés à la CONSTRUCTION des stations de haute mer en béton pour l'Arctique.

4. Les problèmes associés à l'INSPECTION et à la RÉPARATION des stations de haute mer en béton de l'Arctique.

On avait demandé à chaque groupe de travail de discuter de leurs expériences précédentes, de leur projets en cours, ainsi que de leurs besoins de recherche dans leur domaine particulier. L'ordre du jour paraît dans l'annexe.

Pour chaque groupe, on avait désigné un président chargé des tâches suivantes: 1) préparer un document de prise de position pour initier la discussion; 2) préparer le premier jet d'un rapport sur les discussions du groupe, afin de le présenter à la scéance plénière; et 3) soumettre le rapport final destiné à être inclus au procès-verbal de l'atelier. Voici les présidents de groupe:

- M. Ben C. Gerwick, Jr. - Conception

- M. Robert E. Philleo - Matériaux

- M. Peter Pullar-Strecker - Construction

- M. Roger Browne - Inspection/Réparation

Les chapitres subséquents présentent les rapport des quatre présidents.

Chaque rapport comprend trois sections; la première donne les renseignements préliminaires, la deuxième résume l'état actuel de nos connaissances, selon chaque groupe de discussion, et la troisième suggère des domaines de recherche. Les rapports étant la contribution des présidents, ils sont présentés dans leur forme entière, tels que soumis au rédacteur, et on n'a effectué que quelques changements minimes pour conserver l'uniformité du format.

2. REPORT OF THE DESIGN WORKING GROUP - By Ben C. Gerwick, Jr.

2.1 BACKGROUND

The design of structures for the Arctic is dominated by the forces imposed by sea ice, both locally and globally. These can be quasi-static winter ice conditions or highly dynamic actions occurring during break-up or summer pack ice invasion, e.g., multi-year floes. The peripheral ice wall must resist these intense local forces without "punching through" or "local holing" and must have a ductile failure mode against such high intensity loads so as to prevent progressive collapse.

Experience with ice breakers have shown that it is the relatively stiff frames behind the exterior shell which are most subject to damage. Similarly, for concrete structures, the internal structure must also transmit high global forces through shear walls to the base and thence to the foundation. Ductility and redundancy against progressive collapse should be incorporated into the design of these walls. The base of the structure must resist "hard spot" concentrated reaction loads, and must be capable of spanning uneven and irregular sea floor profiles.

The impact effects of moving sea ice can develop a ratcheting effect, with short-period peaks of force. Hence, low-cycle fatigue may be a design consideration in some portions of a structure.

The harsh environment requires careful design to ensure durability against freezing and thawing attack, especially in saturated zones: also against ice abrasion, corrosion of reinforcement, and corrosion of prestressing steel and anchorages. Local details must be designed to prevent damage from internal freezing. Steel fittings may be subject to low temperatures, hence material properties should be selected so as not to have brittle failure under impact load.

Severe thermal strains, both locally and globally, are imposed due to the external extreme cold, and the internal heat from operations and produced oil.

Structures for the Arctic will normally be built in temperate climates and towed to the Arctic. Designers therefore need to consider buoyancy, floating stability (including damaged stability), and dynamic response during tow. Structures must be capable of deployment through partially ice-covered waters. To meet the shallow water conditions around Point Barrow and elsewhere, structural lightweight concrete of special high strength may be required.

The interfaces with mechanical, instrumentation, and drilling systems must not be overlooked, especially as they affect possible hydrostatic pressure differentials on the structure during ballasting, deballasting, and accidental rupture; and also as they affect thermal strains, watertight integrity, and foundation conditions.

The utilization of concrete sea structures in the North Sea over the past decade has led to the development of design rules and practices relevant to the marine environment and high dynamic loads. The relevant guidelines which are currently available include API Bulletin 2N, ACI 357R-78 (now being revised), the FIP Recommendations for Concrete Sea Structures (4th edition in preparation), the DNV Rules (1981 printing) with their appendices, the work of the FIP subcommittees on Arctic Operations and Sea Operations, and the draft rules of ABS.*

Important current technological developments to be addressed include the use of condensed silica fume and other pozzolanic admixtures to increase strength and impermeability, coatings to reduce friction and abrasion, multi-axial stress-

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* API: American Petroleum Institute

ACI: American Concrete Institute

FIP: Fédération Internationale de la Précontrainte

DNV: Det Norske Veritas

ABS: American Bureau of Shipping

strain effects and their implications for shear resistance, crack-width control mechanisms, epoxy coated reinforcement, and mechanical anchorages and splices for reinforcing steel (especially compression bars and stirrups).

Perhaps the most critical of all design-related matters is that of the peripheral ice wall when subjected to extremely high local concentrated loads with intensities in the range of 100 tons/ft^2 (10 MPa). Slabs and shells are subjected to high flexural and membrane stresses as well as internal diagonal tension and compression. Extremely heavy concentrations of reinforcement, utilization of prestressing to increase shear capacity, and concentrated stirrups are required to develop the necessary resistance.

Concrete structures offer great potential for the safe and economical development of the Arctic but the environmental and operational demands are extremely severe, perhaps more severe than structural concrete has ever been asked to face in the past. Hence, special care is required and suitable research must be carried out on a continuing basis to develop and verify the means of improved performance.

The following is a list of items for special consideration in the design of concrete structures for use in the Arctic:

1. Impact of ice features such as multi-year floes against structures; energy dissipation.

2. High local ice loads ("punching shear" plus "flexure").

3. Failure modes of thick concrete walls, shells, and slabs, heavily reinforced and/or prestressed, under intense local ice loads.

4. Improved stirrup details and/or use of headed stirrups.

5. Multi-axial stresses: potential for enhancement of compressive and shear strengths, reduction of tensile strength on minor axes.

6. Shear: how to treat membrane and flexural shear under static, dynamic, and cyclic action. Use of rational concepts of "diagonal tension" and "diagonal compression" instead of artificial concept of "shear", in order to avoid being trapped by empirical requirements of building codes.

7. Fatigue aspects of concrete walls under ratcheting effects of continuous crushing of ice.

8. Distribution of intense concentrated forces through structure: peripheral walls, diaphragms, and shear walls.

9. Failure modes of diaphragm walls and shear walls under high compression plus shear: means of increasing ductility.

10. Resistance of saturated concrete against freeze-thaw attack. Effect of coatings. Migration of water vapor through concrete. Impermeability.

11. Resistance of concrete to ice abrasion. Friction of ice against concrete. Adfreeze.*

12. Coatings for exposed concrete surfaces to reduce friction, adfreeze, and abrasion.

13. Use of epoxy-coated reinforcement to reduce required cover, or to enhance durability of concrete, especially when salt may be applied to deck surfaces to prevent icing.

14. Concrete cover: effects on crack control, thermal strains, corrosion, and performance under high concentrated loads.

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* Adfreeze refers to the adhesion of ice to the concrete surface.

15. Long-term protection of prestressing anchorages from freeze-thaw attack and corrosion.

16. Thermal gradients in thick-walled structures due to heated interior. Global thermal deformations when lower or internal portions of the structure are in water (0°C) and exposed portions are at temperatures as low as -50°C. Producing wells may raise internal temperature to as high as 35°C.

17. Protection of internal compartments and voids, empty ducts, reentrant angles, etc., against rupture from freezing water. Use of polyurethane buffers.

18. Use of structural lightweight concrete: considerations of freeze-thaw resistance, tensile and shear strength, and abrasion resistance. Should field tests be conducted at Treat Island (Corps of Engineers Facility)?

19. Use of condensed silica fume and other pozzolans: effects on strength, failure modes (ductility), vapor impermeability, freeze-thaw resistance, and abrasion resistance. Proper design of reinforcement to ensure proper post-elastic behavior of the very high strength and high modulus concrete obtained by use of silica fume.

20. Need for rugged, reliable, ice force sensor panels, which may be used to determine local ice forces. Questions on how to interpret data from intermittent seasons when applied to local and global load predictions.

2.2 SUMMARY OF DISCUSSIONS

The Design Group held three spirited and highly interesting sessions, covering three topics: past experiences, current research and development projects, and areas of needed research.

The morning discussion addressed the past experiences in the design, construction and performance of offshore concrete structures. Mr. S. Maxwell of Gulf Canada Resources gave a detailed report on the Tarsiut caisson-retained island, augmented by Mr. Tony Boyd of Swan and Wooster, the designer, and Ben C. Gerwick, Jr., a consultant on the project.

The concrete structures themselves had performed well, with no apparent freeze-thaw or ice abrasion damage. Some structural cracking had occurred during initial set down on uneven support, due to a surveying error. Other narrow cracks are apparently due to thermal strains during construction. The cracking was not serious and had not led to further deterioration due to freeze-thaw attack. This shows the effectiveness of the well-distributed reinforcement in restraining crack growth. There was no evidence of damage due to local concentrated ice loads or ice impact. Minor spalling has occurred due to impact of large steel barges without fenders. In summary, these prestressed lightweight concrete caissons have given very satisfactory and predictable behavior.

Mr. Maxwell reported that global and local ice loadings during the winter of 1982-83 had been the most severe yet encountered. He also reported that industry now favored a concrete caisson or caissons for the Hibernia field, largely because of the ability to resist small ice features (500 to 10,000 tons (5 to 90 MN)) at wave-driven velocities, as well as large bergs of mass and velocity appropriate to the 100-year recurrence.

Kurt Eriksson of VBB-SWECO reported on the 40 concrete lighthouses in the Baltic Sea and their generally satisfactory behavior in the ice environment. For up to 25 years, they have been subjected to moving annual ice sheets and rubble pile build-up but have not shown any significant abrasion nor deterioration. Dynamic amplifications and resonance effects had occurred on a few platforms. These have been well instrumented and documented and give valuable information on ice-structure-foundation interaction. A paper was distributed describing some ice load prediction methods against the background of Swedish experiences.*

Mr. Sedillot of C. G. Doris reported on the design of concrete offshore platforms for Texaco in the Baltic Sea.

The highly successful experiences of 15 concrete platforms in the North Sea were briefly presented and attention was directed to the current design and construction of the shafts to resist supply boat and barge impact with concentrated loads of comparable intensity to iceberg and ice floe impact loads.

The first afternoon session was devoted to a presentation of current research and development projects. Many of these are proprietary: however it was pointed out that any responsible party, including the Government may buy into these projects. Among the many current R & D projects are:

1. High-strength lightweight concrete

   - freezing and thawing behavior
   - adfreeze
   - friction of ice on surface
   - heat of hydration
   - abrasion by ice

   Objective of future work is to develop design specifications plus a quality assurance/quality control program so as to enable an engineer to design with confidence in this material.

2. Concrete elements subjected to high local forces imposed by ice (commonly referred to as "punching shear"): elasto-plastic behavior;

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* "Ice Force Design of Offshore Structures" by Alf Engelbrektson, prepared for an international conference: "Offshore Göteborg 83".

need to develop appropriate design criteria for shear in highly reinforced concrete; progressive failure mechanisms. Behavior of slabs and shells which have previously been cracked, repaired, and are then subjected to high loads. Ultimate load studies of the collapse mechanism and energy absorption under impact. Several participants agreed that "shear" was an inadequate concept for these cases and that it was preferable to consider "diagonal tension" and "diagonal compression". The importance of support conditions to the behavior of peripheral ice walls was emphasized: these can significantly influence the behavior under high local loading.

3. Composite-construction: "steel-concrete sandwich" construction, also called "hybrid design". Utilization of internal supporting structures of structural steel, connected by studs or similar means to develop composite action with concrete slabs.

4. Impact of ice floes on structures: ice floe-structure-soil interaction and compliance of the structure-soil system as well as crushing of the ice and hydrodynamic dissipation of kinetic energy. Peak stresses are of very short duration: hence, applicable concrete strength may be 30 percent or so higher than static cylinder strength.

5. Risk-reliability-consequences evaluation. Loading and Systems Management as it affects risk. Consequence evaluation as it affects safety factors and levels. Provision of redundancy to prevent simultaneous or progressive collapse.

6. High strength normal weight concrete, with strengths in excess of 14,000 psi (100 MPa).

7. Ductility of highly compressed members, including compression members subject to prestress. DNV is currently proposing a research program in this area: other programs are underway in New Zealand and Japan.

8. A detailed inspection will be made this year of the Swedish concrete lighthouses in the Baltic to ascertain their performance under up to 25 years of annual ice attack.

9. The U.S. Coast Guard is continuing tests with the Polar class ice breakers to determine sea ice pressures, and the Minerals Management Service is continuing with its program of ice forces against structures and ice mechanics.

10. FIP has a Commission currently studying multi-axial stresses in concrete structures.

11. There are a number of programs studying durability of concrete in the Arcic environment. These include SOHIO's field tests, and joint industry studies on durability, abrasion, friction, etc.

12. The University of California (Berkeley) has recently completed tests on the behavior of prestressed lightweight concrete under cyclic, fully reversing membrane stresses at low temperatures and is now commencing a program for testing cyclic, fully reversing shear effects.

Mr. Roger Stacey of NORDCO, Ltd. described a proposed program on a 1:10 scale of a concrete platform subject to iceberg impact, to determine actual forces and responses.

Several members directed attention to the current programs of AOGA, APOA, CIRIA and C-CORE (Canada), also to current programs in Norway, Germany, The Netherlands, France, and Japan.*

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* AOGA: Alaska Oil and Gas Association

APOA: Arctic Petroleum Operators Association

CIRIA: Construction Industry Research and Information Association (U.K.).

Descriptions were presented of some of the structural concepts currently being developed for use as exploratory drilling and production platforms in Arctic and sub-Arctic waters. These include only those which have been publicly reported:

1. Permanent caisson-retained production island at Tarsiut, (ATOLL), using concrete caissons protecting a sand fill island.

2. Global Marine's Concrete Island Drilling Structure (CIDS), utilizing concrete "honeycomb" modules, joined together at the site, both transversely and vertically, in "brick" fashion.

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

4. The Arctic Cone Exploration System (ACES), a prestressed lightweight concrete conical structure, being designed by Brian Watt Associates for a consortium of companies including Shell, Exxon, and Chevron.

5. Brian Watts Arctic Caisson System (BWACS), a lightweight concrete honeycomb caisson structure designed for Zapata, to improve shear resistance in weak soils by drainage using the wick sand drain method.

6. Exxon's concrete production island caisson, with elevated deck, designed by ABAM Engineers for 30 to 100 ft (10 to 30 meter) depths in Norton sound.

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

8. Norwegian Contractors TRIPOD 300 concrete caisson, designed originally for 300 plus meters of water depth in the northern North Sea, now being considered for the southern Bering Sea.

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

10. Fixed concrete caisson structures proposed by Norwegian Contractors and by C. G. Doris for the Hibernia field, off Newfoundland, designed to resist iceberg impact.

11. Floating caisson-shaped drilling, production, and storage structure designed by Exxon for use in deep water. This features dynamic downward breaking of ice to reduce mooring forces.

During the second afternoon session, members presented and discussed areas for which they felt additional research and development are important. Some of the most critical areas relate to ice loadings and the dynamic response of structural systems, hence are not specific to concrete structures but apply to all materials. Similarly, the matter of soil-structure interaction was judged to be of great importance, especially for Arctic marine structures, due to the high ratio of lateral to vertical loads and the special qualities of Arctic sea floor soils.

Considerable discussion was directed to the complex phenomena associated with the impact of a large multi-year ice floe or an iceberg with a structure, and the need to consider elastic and inelastic responses of the entire system, including soil, structure, water, and ice. The concept of permitting limited local failure under extreme overload was presented and parallels were drawn to current design practice for extreme earthquake action.

Probabilistic approaches to design for ice loads and structural responses were discussed. The current need for parametric or deterministic design values was strongly stated, in order to permit safe and rational designs pending the acquisition of sufficient data upon which to base a probabilistic approach. With deterministic and parametric loadings, it should then be possible to prepare integrated design guidelines, with recommended load factors and safety indices. There is also a need to develop appropriate serviceability criteria.

The ACI 318 Standard for design of reinforced concrete buildings may not be fully applicable to the case of heavy concrete sections which have high percentages of multi-axial reinforcement.

The dynamic nature of the continuous crushing of ice against a structure was noted. Cyclic peak stresses may be sufficiently close to the structure's natural frequency to lead to dynamic amplification. In other cases, it is felt that the structure's natural period of response may determine the crushing period of the ice. These peak stresses, occurring at periods of 0.5 to 1.0 seconds, indicate the need to consider low-cyclic high-amplitude fatigue and perhaps high-cycle fatigue as well.

Thermal strains may exist in an Arctic concrete structure on two scales: the local through-wall thermal gradients, and the global strains between the lower portion of the structure submerged in water at -2°C and the upper portion which may be in air at -50°C. Meanwhile, oil production operations and waste heat may have developed internal warm areas.

The external surfaces of a concrete structure are subjected to a relatively few cycles of intense freezing and subsequent thawing. Near the water line, there may be many more cycles due to thawing by wave action. This zone also may be subject to saturation and water vapor transmission. Tests on this phenomenon have been carried out over many years at Treat Island, Maine, but do not include the most recent concretes such as high-strength lightweight aggregate concretes which include condensed silica fume.

Abrasion of the external concrete surface by ice is another research area. Near shore, the ice may have picked up silts, sands, and even gravel as a result of ice gouging, and hence have greater abrasive effect.

Friction of ice on the surfaces of the structure may be important in determining ice loads especially the clearing of ice over conical surfaces. These values vary with relative temperatures and with surface roughness, which may be subject to change with time as a result of abrasion and freeze-thaw action.

The behavior of concrete structural elements under multi-axial stress or strain conditions was discussed. Under tri-axial compression, the apparent strength in compression and shear is dramatically increased, whereas under biaxial compression, the tensile capacity along the third axis may be decreased, requiring special reinforcement.

The joining and connecting of small and large precast segments of concrete together present an opportunity for the development of innovative designs to reduce time and costs of construction. They require attention to detail and careful execution.

Deployment of large structures in a fragmented ice cover and the subsequent relocation during periods of fast ice or fragmented cover is a feature which could have major economical impact. It may be possible to shape the structure, or one side of it, as an ice-breaking bow to facilitate operations in fast and broken ice.

The group emphasized again the needs for parallel development in systems which support concrete offshore structures of all types and the need to integrate them into concrete structure systems. These include;

- Instrumentation
- Foundation engineering
- Mechanical systems (ballast, drainage, etc.)
- Active and passive means of reducing or controlling ice forces.

Finally, the group briefly discussed hybrid designs, in which steel and concrete work in composite structural action. Steel may permit a reduction in weight and give added ductility, while prestressed reinforced concrete has excellent performance at low temperatures, high durability, high fatigue resistance and high redundancy and toughness.

2.3 RESEARCH NEEDS

1. Concrete slabs and shell subject to very high local concentrated loads ("punching shear") plus flexure plus membrane compression). Physical model tests at large scale (to eliminate scale effects), realistic support conditions and loadings representative of ice are needed to corroborate nonlinear numerical analyses.

   Methods of reinforcing to ensure high resistance and a ductile (non-brittle) mode of failure. Determine collapse mechanism and energy absorption after passing peak resistance.

   Examine acceptability of concept of permitting repairable local damage under extreme and infrequent loadings, provided it does not lead to progressive collapse.

   Guidelines for evaluating resistance of very heavily reinforced thick concrete sections to flexural and shear loads.

2. Shear walls and diaphragms supporting the peripheral ice wall are heavily loaded in compression and shear. Means of enhancing resistance and ensuring a ductile behavior under overload.

3. Determination of peak local forces generated during impact of large ice feature against peripheral wall. Effects of hydrodynamic damping and energy absorption and of compliance of structure-soil system in reducing peak stresses.

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

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

6. Abrasion of external walls by ice. Are sand and silt particles probable in sea ice at structure locations, and, if so, what is their effect on abrasion?

7. Adfreeze of ice on concrete surfaces. Friction under the probable range of conditions.

8. Freezing and thawing behavior of concrete, especially in splash zone; effect of coatings. Effectiveness of air entrainment and of condensed silica fume.

9. Thermal strains, both through-wall gradients and global. Consideration of recent research in USSR on thermal strains. Evaluation of effects of concrete properties, reinforcement and prestressing details, and structural configuration in limiting cracking due to thermal strains.

10. Performance and design basis for steel-concrete composite structural elements. Methods of ensuring composite behavior. Effect of thermal gradients and freezing-thawing action.

11. Risk, reliability, and consequence evaluation principles for concrete structures in the Arctic.

12. Optimum details for protection of post-tensioning anchorages in saturated concrete subjected to freezing-thawing action in the Arctic.

13. Field durability tests on post-tensioned and conventionally reinforced high strength lightweight concrete made with addition of condensed silica fume. Use of Treat Island test facility.

14. Recommendations for load factors to be applied to ice loadings. Determination of appropriate serviceability criteria. Guide as to load combinations, e.g., earthquake and ice, or waves and small ice features (e.g., "bergy bits") impelled at high velocity by the waves.

3. REPORT OF THE MATERIALS WORKING GROUP - By Robert E. Philleo

3.1 BACKGROUND

Concrete materials technology, developed over several generations, has served the design profession well. Recent developments, however, require a re-examination of certain well established principles. The quality of concrete, for example, has traditionally been designated by its water-cement ratio. A variety of materials now being used as a part or all of the cementitious component of concrete may not lend themselves to treatment by normal water-cement ratio criteria. Furthermore, some of the physical properties of both normal weight and lightweight high-strength concrete may not be well understood, particularly when the concrete contains relatively new materials such as superplasticizers and condensed silica fume. Some of the design parameters are merely extrapolated from normal strength concrete. The important problem of steel corrosion has been dealt with in specifications piece meal without recognition of the several interrelated parameters.

3.2 SUMMARY OF DISCUSSIONS

There were two recurrent themes running throughout the discussions.

1. Impermeability is the most important property of concrete in the offshore environment, particularly in the tidal and splash zone.

2. Existing criteria for steel cover and crack control in the permanently submerged portions of offshore structures are too conservative. An understanding of all the factors necessary for corrosion suggests that corrosion in this part of structures is highly unlikely. Yet for certain members the crack control criterion is more critical in design than the wave criterion in establishing reinforcing steel quantities.

Much of the discussion may be summarized by relating it to the specific questions propounded in the Materials Working Group position paper.

1. For seawater exposure, what composition of cement, particularly in regard to tricalcium aluminate (C_3A) content and alkali content, is optimum?

There is no evidence to support an upper limit on C_3A content of cement. Sulfate attack is not a problem in high quality impermeable concrete. There was not agreement on the need for a lower limit to protect the steel from corrosion. This is still a fruitful area for research. Alkali content was not seen as a matter for serious consideration except where reactive aggregates are used.

2. What pozzolans and slags used in what proportions are useful in the exposures under consideration?

Pozzolans, such as fly ash and condensed silica fume, and slags are most useful in that they reduce the permeability of concrete and retard the ingress of chloride ions to the steel. The properties of silica fume were discussed at length. An additional contribution it makes to corrosion protection is increasing the electrical resistivity of concrete. Because pozzolan concrete in general, and silica fume concrete in particular, may not be well characterized by water-cement ratio, interest was expressed in using permeability as a criterion of quality. To do so, permeability testing techniques must be vastly improved, and in order to execute quality control there must be a means for determining permeability of in situ concrete. Silica fume is commonly restricted to a quantity equal to 5 percent of the weight of portland cement. The quantity of fly ash generally exceeds 20 percent.

3. Should only non-chloride accelerators be used?

The question of whether to permit chloride-containing accelerators is part of the larger problem of whether chlorides need to be limited if the steel is protected by adequately impermeable concrete. High strength prestressed concrete with extremely low permeability has been produced and has served successfully with relatively high chloride contents. More work is needed.

4. What is the applicability of high-range water reducers (superplasticizers)?

Superplasticizers were deemed to be necessary both to place concrete through the maze of reinforcing steel existing in off-shore structures and to take full advantage of silica fume, an extremely fine material with a high water demand. The preponderance of evidence indicates that durable concrete can be made with superplasticizers. However, existing criteria for air void systems may need to be re-examined.

5. What are the proper admixtures, if any, for use in tremie concrete?

There is little underwater placement in offshore structures. Where it is undertaken a workable cohesive concrete is required. No special admixtures are needed although both superplasticizers and pozzolans promote cohesiveness. Much of the discussion related to the fact that there are now available proprietary systems which appear to do an adequate job of placing concrete underwater without tremies. There is a need to develop non-proprietary methods to impart adequate thixotropy to concrete to make these techniques generally applicable.

6. What precautions concerning reactive constituents should be observed in selecting aggregates?

In important structures exposed to seawater, reactive aggregates should be avoided.

7. What is the role of lightweight aggregate, and what precautions should be observed?

Lightweight concrete can be a useful material where weight reduction is an important factor. It is abrasion resistant because it is inherently a ceramic material, but it is not resistant to percussive type impact because of its porous structure. There is a need for further knowledge of thermal properties in order to devise crack control measures during construction and a need for a better understanding of the failure mechanism of reinforced lightweight concrete.

8. Is there a place for use of seawater as mixing water?

In important reinforced concrete structures, seawater should not be considered as mixing water for concrete.

9. How do the permeability-water-cement ratio function and construction tolerances interact to produce the optimum combination of water-cement ratio and thickness of cover?

There are practical limits, having to do with placing tolerances and construction operations, to using low permeability as a means to reduce the cover of reinforcing steel to very small values. The critical zone of a structure (tidal and splash zone) is relatively small and therefore not conducive to generating large cost savings where a thick cover can be tolerated. One benefit of thick cover is that it provides a space for placing concrete in otherwise highly congested forms. Below the waterline cover is not critical for durability. In the deliberations of the Working Group on Design, however, it was pointed out that there are structures or portions of structures where functional requirements demand as thin a cover as possible. These include highly stressed regions where thick cover might be prone to spalling and where highly impermeable concrete and epoxy-coated reinforcing bars should provide a practical solution. It had been the opinion of the Materials Working Group that where there is no need for a thin cover there is likewise no need for epoxy coated reinforcement since bare steel can be adequately protected by high quality concrete. Other places where coated bars are probably cost effective are exposed decks of offshore platforms where calcium chloride is likely to be used for deicing. These surfaces are similar in exposure to bridge decks.

Other items not included in the original list of questions posed in the position paper were discussed as follows:

In some exposures ice rubbing on structures produces abrasion which might be counteracted by used abrasion-resistant aggregates. While the problem of impact of large masses of ice is primarily a design problem, there is a need for more information on ice abrasion, particularly when the ice carries as inclusions abrasive materials such as sand. It should also be noted that in some cases ice buildup on a structure may provide some resistance to abrasion.

Although there was difference of opinion in the final plenary session as to the extent of the problem of galvanic corrosion in the submerged zone, it appears that some existing criteria overestimate the problem of galvanic corrosion produced by steel projecting from concrete because much less oxygen diffuses to the steel than assumed. Some sacrificial anodes are superfluous.

The potential of steel fiber reinforced concrete is not being realized. The literature is full of test results, but there is not much in the way of design criteria. It is not inconceivable that in some structures fibers might replace conventional reinforcing. In others they might be useful in end blocks of prestressed concrete and in the cover of reinforcing bars. This is a fruitful area for research.

There is a need for a better knowledge of early age properties of high-strength concrete so that adequate crack-control procedures during construction may be devised.

Grouting of post-tensioning ducts can be critical in offshore structures exposed to freezing. More information on the subject is needed.

During the final plenary session a question was raised about the low-temperature behavior of ASTM A 706-steel. Floor discussion provided the information that tests of reinforcement, presumably similar in composition to A 706-steel, had been conducted at -140°C in Norway and at -163°C in the United Kingdom, and they had demonstrated satisfactory behavior.

The Working Group on Design requested information on the applicability of mechanical splices for large bars in compression. Substantial experience has indicated that they may be used for all large bars in compression.

3.3 RESEARCH NEEDS

The following research needs were identified and are listed in priority order.

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

2. Establishment of realistic chloride limits when very low permeability is attained.

3. A re-examination of air void spacing criteria for freezing and thawing durability.

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

5. Early-age properties of high-strength concrete.

6. Methods of tests and criteria to determine whether grout in ducts is effective.

7. Development of suitable ice abrasion resistance criteria and tests.

8. Development of thixotropic concrete for underwater placing.

9. Design criteria for fiber-reinforced concrete.

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

11. Adequate design procedures for lightweight concrete.

12. Establishment, if necessary, of a minimum limit for C_3A content of cement.

4. REPORT OF THE CONSTRUCTION WORKING GROUP - By Peter Pullar-Strecker

4.1 BACKGROUND

Methods of construction have to be chosen to suit what has been designed and design must of course take account of what it is possible to construct. Consideration of construction divorced from design has limited value, and the intentions in design will become essential data for the construction process.

All Arctic concrete offshore structures are likely to be massive and those intended for deep water will also be tall. Many of the construction problems will be those common to any massive concrete constructions. For cast-in-place construction, these include:

- Extraction and transportation of large quantities of aggregates, probably at remote sites.

- Supply of cement, reinforcement materials, fuel, equipment, power, accommodation and labor, in large quantities and over long distances.

- Continuous placing and compaction of high quality concrete in very large pours.

While precast construction will require provision of facilities for lifting, transporting and assembling large precast units.

The ability to cope with these general problems is the stock-in-trade of the large contractor and is not peculiar to Arctic offshore structures. The particular problems of constructing deep-water structures are within the recent experience and expertise of British and European contractors who have built more than a dozen such structures for offshore oil and gas extraction in the North Sea.

Whilst there are probably very few new problems that could require research in construction, it is worth considering those familiar areas that are likely to need more than ordinary care and attention in the case of Arctic offshore structures. These include:

- Provision of quality control and testing of raw materials and concrete.
- Provision of batching facilities for a wide range of materials including large aggregates, lightweight aggregates, concrete admixtures, and cement replacement materials.
- Provision of back-up plant to allow uninterrupted pouring.
- Provision of means for transporting concrete from central mixing plants to points of placing which may become more inaccessible as construction proceeds.
- Grouting pre-stressing cables in very long ducts.
- Assembling and connecting large units under difficult site conditions.

Finally, there are some special requirements that will be peculiar to construction for Arctic works and that might give rise to a need for research and development:

- The scarcity of sheltered deep-water construction and assembly sites.
- The possibility of needing to renew structural units or fenders destroyed by abrasion from floating ice.
- The provision of very large working platforms founded in shallow water and transportable from one location to another.

4.2 SUMMARY OF DISCUSSIONS

The task of the group was to consider what new knowledge is needed for the efficient and economical construction of offshore concrete structures for use in Arctic waters. The definition of the task implied that certain related topics need not be considered: firstly, construction in temperate latitudes of units intended to be transported to the Arctic, since such construction was not likely to give rise to fundamentally new problems; and secondly, the design of structures, since this was to be considered by the Design Group.

The Construction Group therefore concentrated on that part of the construction work that would have to be carried out in the Arctic, including the transportation of units to the installation site. The Group realized that the requirements of the designers would influence or even dictate some of the construction problems, and that these problems would in turn have to be considered by the Design Group. For this reason ideas were exchanged between the two Groups during and after the working sessions. The Construction Group's view was that any of the demands of designers could be met, at a price, and it was part of good design to avoid excessive cost by designing for simple construction.

Not surprisingly, the special problems of construction in Arctic waters were seen primarily as those caused by the severe climate and remoteness. They can be broadly grouped as the high cost of getting work done in the region, the short time during which it is possible to move through the sea in the region, and the difficulty of transporting units and equipment to the region from temperate areas.

A separate cause of special problems was the need to avoid damage to the exceptionally sensitive environment of the region.

The Group thought it right to consider problems that were economic or political in origin, as well as those that were technical.

Sometimes it is better to avoid a problem than solve it. Many of the problems and costs peculiar to Arctic regions might be avoided by ensuring that construction is as complete as possible before units are brought into the region. Operations that really have to be done in the Arctic should not only be reduced in number by this means, but should also be reduced to those that can be done without expensive equipment. There is an obvious conflict to avoid: the more complete the unit is, the larger would be the equipment needed to handle it on site.

Transportation to the region from the primary building site becomes an increasing problem as units get more complete and therefore probably larger. A curious, non-technical difficulty added to the technical problems is that the effect of the Jones Act, intended to protect American trade, is actually to encourage the construction of larger structures for Arctic waters at non-USA sites, since US-registered vessels (of which few are suitable) would not be needed to carry them.

In any new venture, the assessment of risk must be based on theory and calculation rather than experience, and correctly evaluating risk is crucial to the economic success of the enterprise. Data and theory for this assessment, whether it concerns risk to life, the environment or property, is sparse or at any rate dispersed to an extent where it does little to create confidence. The collection or creation of information in this area, and its independent assessment and validation, could help greatly in promoting a confident and positive attitude towards the development of resources in the region.

These and more obvious technical considerations gave rise to a number of recommendations for areas where more knowledge is needed. These are listed in the following section together with recommendations that were passed to the Construction Working Group during and after the workshop meetings, by other working groups and by individuals.

The Group made no specific recommendations on how the knowledge should be collected or who should do the work, but it was agreed that since the information must be impartial and would be valuable to a large number of users, a professionally-managed program of projects, jointly funded by a numer of interested parties, would be an efficient way of putting effect to the recommendations. The UK Concrete-in-the-Oceans program is an example of a very successful program which was financed and managed in this way.

4.3 RESEARCH NEEDS

1. Foundations for Structures

Structures which are to be founded on the sea-bed are usually designed without any means of adjustment to suit an uneven installation site. Consequently, the seabed has to be prepared in some way so that it provides an acceptable surface to receive the structure. Often the preparation is the construction of a sand or gravel mound which serves the function of partially leveling the surface and also reduces the depth required for the structure.

The construction of the mounds and the final leveling of the surface, for example by pumping sand to fill voids beneath structures, are areas where more knowledge could contribute to efficient, safe, and economical working.

Topics which should be investigated include:

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

2. Berms for Protection From Floating Ice

A related problem is the construction of sand or gravel berms to protect structures from floating ice. The research needs are probably the same as those noted under item 1.

3. Moving Platforms Through Ice-covered Waters

Drilling structures are normally useable at only one location per season because they can only be moved into position when the sea is sufficiently free from ice. It if were possible to move structures through ice-covered waters, use at more than one location per season would become possible.

The possibility of designing structures so that they could be moved through ice-covered waters, even if only very slowly, is considered to be a worthwhile area of study.

Topics to be investigated might include:

- the design of structures as ice-breaking hulls;
- the power requirements for moving structures; and
- the economics of moving and re-using structures.

4. Poor Utilization of Equipment

The problem of being able to use drilling structures at only one location per season applies also to other equipment, such as crane barges, which can only be brought to the site when the sea is sufficiently free from ice. Under these conditions equipment utilization is very poor and may be as little as 6 weeks in a 3-year period.

It must be borne in mind that the high cost of doing any work in arctic sites makes it desirable to complete structures as much as possible at temperate construction sites and this could result in the production of units so large that heavy lifting and installation equipment would normally be needed at the working location.

By appropriate design it might, however, be possible to dispense with or reduce the need for such equipment.

Topics to be investigated might include those in item 3 (but in relation to equipment) and the design of structures that can be installed on site with a minimum of equipment.

5. Transportation of Structures from Fabrication to Installation Sites

Structures for use in Arctic waters have to be built at sites in temperate climates and must be towed or transported in vessels through seas which can be stormy, ice-laden and, in places, shallow.

These conditions already impose many practical and technical problems, but, it addition, a piece of legislation known as the Jones Act adds a problem which appears to be quite unnecessary. The Jones Act restricts the use of non-USA hulls to carry loads from one USA location to another. If, therefore, a suitable USA hull is not available to transport a structure to a USA installation site, the structure must be built outside the USA, for example in Japan. Thus legislation enacted to protect USA trade can have the opposite effect.

Transportation is a very major problem in developing the resources of the Arctic waters and is an area where new knowledge could make an important contribution.

Topics that need consideration are:

- examination of the effects of the Jones Act and recommendations for appropriate exemptions;
- collection of data on wind, wave, and currents in a Government-funded program which would ensure the accessibility of the information; and

- collection and publication of data on ice movement, scour, and hydrography in a similarly funded program.

6. Assembly of Units on Site

It has already been said that structures should be as complete as possible before they are brought to the installation site, but it is accepted that some assembly on site will continue to be needed.

Assembly operations should be quick and simple, and should need a minimum of equipment.

More knowledge is needed on:

- the tolerances required for interlocking units;
- materials and construction methods for load-distributing intermediate layers;
- tolerance to local crushing;
- the design and construction of connections which can subsequently be dismantled;
- the protection of connectors from corrosion and accidental damage; and moorings for use during assembly operations.

7. Risk During Transportation and Installation

Risk from ice, wind, and currents while the structure is being transported or installed have to be assessed somewhat theoretically because of the limited actual experience of construction operations. Such risks can be reduced both by appropriate design and by suitable construction methods, but to do this economically the risks and their consequences have to be evaluated.

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 their consequences.

8. Risks and Consequences of Accidental Spillage

Spillage of oil, grout or even mud could have an apparently large impact on the unspoilt environment of the Arctic. The fear of such accidents may lead to very strict requirements in an attempt to avoid them and the extra construction work that arises directly from that strictness may itself be harmful to the environment. For example, the work of burying pipelines at great depth is likely to cause more environmental damage than burying them at shallow depths, though the latter could be enough to protect them.

The risks and consequences of accidental spillage and the effects of construction processes in creating pollution of air, land, and water need to be evaluated in factual terms so that the control of construction and operation can be appropriate in both method and degree.

Further study is needed of the impact of construction and of operation in the environment of the region, and this study should be carried out under authoritative and independent control so that the facts it produces are acceptable to all parties.

5. INSPECTION/REPAIR WORKING GROUP - By Roger Browne

5.1 BACKGROUND

In the last decade considerable effort has been put into the development of inspection tools and repair methods for concrete structures. In the U.K. much of this effort has been related to North Sea gravity structures, some of which have now been in operation for 10 years. The rapid growth of construction in the Middle East with all of its inherent durability problems has also necessitated the rapid development in inspection and repair technology. In the U.S.A., the corrosion of over 200,000 highway bridges has similarly drawn attention to the need for effective repair techniques.

Whilst for land based, coastal and offshore structures, inspection and repair techniques have advanced considerably in recent years, the Arctic presents additional problems by virtue of the extremely low temperatures which can occur, often as low as -50°C, and the presence of ice in varying forms. The extreme cold influences the properties of not only the concrete and steel but also repair materials which require particular properties for low temperature curing; and inspection tools may not operate satisfactorily. In addition, thermal stresses may be generated of sufficient magnitude to cause cracking. The ice creates problems of access, particulary when flowing. Also the nature of damage which can occur is unique, ranging from punching failure to severe abrasion. Ice also bonds well to concrete necessitating the use of coatings to prevent adfreeze or design for increased lateral loading.

Existing procedures for inspection and repair must therefore be re-evaluated in the light of these extreme environmental conditions, taking into account the types of structures which are to be installed and the nature of damage which can occur.

5.2 SUMMARY OF DISCUSSIONS

Arctic Structures

Various systems are currently being developed for offshore exploration and production in the Arctic. These include tower structures, artificial islands, ballasted caissons and berm islands, conical structures, and floating systems.

The type of structure to be used for a particular application will depend to a large extent on the water depth, the severity of the ice environment and the rate of ice flow. The ice loads on an Arctic structure may include flows and ice sheets, multiyear ridge plus flow, adfreeze, rubble pit, and summer impact.

In the severe ice conditions which can exist in the Beaufort Sea, conical structures are proposed to induce flexural failure in the ice at loads about an order of magnitude less than required to fail the ice by crushing.

When the ice environment is relativley light, with no multiyear ice, tower structures may be used, such as those in Cook Inlet. When there is a reasonable open water season, floating structures may be used.

The ways in which inspection and repair can be undertaken will be determined by the type of structure in relation to its configuration, exposure conditions and open water season. In particular, access may be difficult to large areas of a structure. The nature of the damage which may occur will also be influence by the configuration of the structure.

Environment

The term "Arctic" in the context of this chapter will be used to describe any area which encounters sea ice on an annual basis. This may comprise solely of first year ice which may vary from 1 to 6 feet (0.3 to 2 m) in thickness, or multiyear ice which has lasted through more than one season, is appreciably harder than first year ice and can extend down to the seabed.

Below the water (or ice) level, inspection and repair may be extremely difficult if not impossible to achieve during the winter freeze. Not only will the ice layer prevent direct access to large areas of the structure, but also the movement of the ice will create a serious hazard to divers and make the use of remote control vehicles (RCVs) difficult. Similar problems are likely to exist due to the severe currents below the ice. Above the ice or inside the structure the problems will be less severe.

Fortunately, in most of the lease sale areas there is a period of open water each season. This may be as little as 60 days in the Beaufort Sea to at least 6 months in the Bering Sea. During this period, inspection and repair methods similar to those currently employed in the North Sea may be applicable. However, it may not be possible to wait for a weather window and consideration must therefore be given to means of inspection and repair during the winter freeze when temperatures may be as low as -50°C.

Materials Performance

In addition to the normally aggressive exposure conditions in a marine environment, Arctic structures are also required to withstand extreme freeze-thaw cycling, severe ice abrasion, impact loading, and differential thermal gradients. For this reason, considerable effort has been put into the design of high quality concretes with the current trend being towards the use of high strength, air-entrained, lightweight concrete using superplasticizers and alternative cementitious materials such as condensed silica fume. The aim is to achieve:

- Low permeability which reduces the ingress of water
- Prevention of freezing and thawing damage when the small amount of absorbed water freezes
- Reduced likelihood of steel corrosion

Extensive laboratory and field studies on concretes up to 80 years old have highlighted the importance of low permeability in achieving durable structures. However, whilst materials such as silica fume are currently being investigated by numerous researchers, there is as yet only limited field performance data. To assess in situ performance using conventional corrosion monitoring techniques may require re-calibration of the equipment and perhaps a change in the interpretation of results.

It must be noted that the properties of both the concrete and steel are influenced by temperature. Research has shown that:

- The compressive strength of a typical structural concrete will increase, typically 30 percent when cooled from 20°C to -50°C.

- Concrete tensile strength, flexural strength and bond strength to rebar will increase in proportion to the compressive strength.

- Deformation due to load is reduced and impact and crack resistance are increased.

These changes in properties are related directly to the natural moisture content of the concrete which is typically 4 to 5 percent. In this condition the voids are not fully saturated and freezing need not present a problem.

The characteristics of reinforcing steel must also be considered. Steel tends to embrittle at low temperatures. Conventional tests for Impact Transition Temperature, such as the Charpy Notch Impact test, indicate that conventional rebar may embrittle at temperatures as high as 0°C. On the other hand, tests on full size bars have indicated that hot rolled steel may behave in a ductile manner at temperatures below -50°C.

All these factors must be taken into account when undertaking damage analysis, particularly when computer modelling is employed. The increased strength, stiffness and crack resistance will all significantly influence predicted performance.

Reasons for Inspection

In the North Sea there are statutory requirements to inspect concrete structures, in order to provide a certificate of fitness. These are defined by:

- Offshore Minerals Working Act (U.K.)
- Dept. of Energy Guidance (U.K.)
- BS 6235 (U.K.)
- DNV Regulations

Each structure must be fully inspected within a 5 year period with a minimum inspection requirement each year. Regular inspection enables potential problems to be identified prior to serious defects occurring, and may avoid the need for extensive repairs by the use of simple preventative measures. With the level of understanding already achieved it may be possible to predict the life of the structure prior to the need for repair.

Prudent construction inspection will minimize the extent of in service inspection and aid the detailed location of rebar, prestressing steel and hardware where damage occurs or modification to the construction is required. Localized inspection is required in the event of damage and after the repair is completed.

Survey Methods

Standard methods are available for in situ corrosion monitoring. These include:

- Potential measurements to identify activation of the steel
- Concrete resistivity measurements to assess the rate of corrosion
- The use of resistance probes in conjunction with a Corrosometer to assess the rate of corrosion
- Chloride diffusion measurement using the applied voltage technique
- Measurement of chloride ingress into drilled core samples
- The use of a covermeter to determine depth of steel
- Visual inspection (divers, RCVs)

Using these techniques it is possible to make a reasonable estimate of the rate of corrosion and to predict the life of a structure before significant maintenance is required.

Nondestructive tests can be made to assess the quality of concrete. These include:

- Ultrasonic pulse velocity measurement
- Measurement of surface hardness by the Rebound Hammer test

Core samples have value in providing a more direct means of assessing concrete strength and other properties such a permeability, resistivity, and oxygen diffusion.

The following points should be noted:

- Many of these techniques have been used in the North Sea and some have been adapted for use underwater.

- Their performance at low temperature in unknown and modifications may be necessary to enable satisfactory operation in Arctic conditions.

Various detection devices such as accelerometers, embedded strain gauges and thermocouples can provide valuable information which can be used to assess in service structural performance. Strain devices have been used extensively in a range of nuclear structures and dams and have operated successfully at temperatures as low as −165°C. The use of embedded strain gauges also provides the designer with full scale model test results against which to assess the analytical techniques used in the design, enabling more rational design of subsequent structures.

Many problems with instrumentation have resulted from fragmentation of responsibility of installation through to data analysis. Lack of instrument reliability, and over excessive data production can make data interpretation extremely difficult.

Improvement in the value of instrumentation will be achieved by:

1) single part responsibility for design, installation, operation, data processing and evaluation; and

2) better reliability of the instrumentation, particularly under low temperature conditions.

Damage Analysis

Limited studies on damage caused by impact have been undertaken, leading to the development of computer programs which can predict the mode of failure. Experience with impact damage which has occurred to structures in the North Sea has provided support to the theoretical studies.

Tests are being undertaken to establish the punching shear resistance of typical concrete elements under ice load conditions as part of the development of the ACES program in England. This can provide a basis for further investigation of the mode of failure of Arctic structures. Work has now been extended to include repairs to the damaged elements to assess the post-repair performance.

Analysis of inspection survey results also enables a potential damage assessment to be made, predicting where problems are likely to arise. In this case preventative measures can be taken before the damage becomes either structurally or aesthetically unacceptable.

Types of Damage

1. Corrosion of Rebar

In conventional marine structures, corrosion of the rebar presents the greatest problems particularly in the splash zone. This area is subject to a build-up of salts which diffuse into the concrete, activating the steel in the previously passive alkaline environment. Once corrosion starts, oxygen, which may also diffuse through the cover zone, fuels the corrosion process. In addition, moisture in the concrete reduces the resistivity hence increasing the corrosion current. Damage due to steel corrosion initiates as cracks which result from the bursting stresses generated by the corroding steel. These enlarge until the concrete spalls from the surface. Corrosion of steel in concrete may also lead to loss of structural integrity as the uncorroded steel section reduces. In addition, bond to concrete can be reduced.

2. Mechanical Damage

Mechanical damage may occur due to ice impact, abrasion, gouging, ship impact, dropped objects, fire and explosion, and thermal shock from gradients (values to 110°C can occur in the Arctic). Damage of this type may affect only the surface of the concrete or induce severe structural damage with loss of concrete and rupture of the rebar or prestressing steel. It is most likely that damage due to impact will be local whether caused by ice, dropped objects, or supply boats. Surface damage due to abrasion is likely to be more general.

3. Freezing and Thawing Distress

Freezing and thawing damage must also be considered, including the ratcheting effect of ice in cracks.

4. Foundation Distress

Cracking distress of structures has resulted from differential settlement or under-base scouring of soils.

In certain areas, seismic damage may also cause distress.

Repair Requirements

The need to undertake repairs must be assessed in relation to the significance of damage as it affects the successful operation of the structure:

- Is immediate action required or can the repair be delayed?

- Can a temporary repair be carried out or is permanent reinstatement necessary?

- The open water period may be the best time to undertake repairs when there is no ice to hinder progress.

The significance of different types of damage must therefore be defined. This already exists to some extent in current Codes of Practice which recommend for example, maximum acceptable crack widths. Broadly, repair requirements can be considered in the following categories:

- Structural/maintenance/cosmetic
- Local or general
- Permanent or temporary

If a permanent structural repair is required, this may involve:

- Cutting out damaged concrete;
- splicing and protecting damaged rebar or prestressing steel;
- reinstating the prestress load; and
- replacing concrete and protecting the surface

Alternatively, a simple grouting operation may be sufficient.

If damage is in the form of surface abrasion or gouging, immediate repairs may not be required. This would be assessed by considering the importance of concrete cover and the rate of erosion in the prevailing environmental conditions.

Repair Methods and Materials

1. Concrete

Currently, repairs to concrete in offshore structures are undertaken using cement or resin based grouts, mortars, and concretes.

Specialized materials are used to overcome specific conditions related to a repair situation. These are generally acceptable for use at temperatures down to about 0°C, but sub-zero temperatures may present problems with curing times and viscosity. Little is known about the properties of some of these materials at low temperature, particularly in the long term.

2. Rebar and Prestressing Steel

A range of methods are available for restoring damaged steel in the concrete. These include the following:

- Epoxy materials are used in resin bonded couplers for the repair of damaged rebar. In this case it is important that thermal compatability exists between the epoxy and steel if bond is to be maintained.

- Reinstatement of prestress presents particular difficulties and a variety of schemes have been investigated. These include systems using cast-in flat-jacks, external Macalloy bars and direct replacement of tendons.

- For corrosion protection it is possible to coat the rebar prior to concreting and in some situations coatings are also applied to the surface of the concrete. Such protection may be unnecessary if adequate protection from the concrete cover exists. Fiber reinforcement may provide a partial substitution for replacement reinforcing steel.

3. Coatings to Concrete

The performance of low-friction, concrete coatings under Arctic conditions is currently being evaluated as part of the ACES development program. The materials examined are required to bond to concrete, reduce adfreeze and provide abrasion resistance against ice. A range of materials are being evaluated including polyurethane, epoxy and polyethylene. One criterion for selection is the need for in-service repair.

A critical feature of any coating system is the practicality of adequate adhesion in the long term and after damage repair.

4. Concrete Placement

Damaged areas can be repaired by installing concrete or steel panels, mechanically attached to the structure. Placement of concrete repair materials can be by pump, skip, tremie, shotcrete or hand trowel, depending on the size and location of the damaged area. Techniques are developed to place special concretes (e.g. Hydrocrete) to depths of 200 m in the North Sea.

5. Crack Sealing

A range of cementicious and resin-based products with suitable injection techniques have been developed for marine crack repairs.

<u>Special Repair Considerations</u>

Repair materials used in an Arctic marine environment are required to possess properties not always essential for land based repairs.

- They must be moisture tolerant in order to cure in the damp conditions. Moisture presents no problem for cement-based materials but can impair the performance of some of the epoxies and polyurethanes.

- They must also be stable under the severe exposure conditions if continual maintenance is to be avoided.

- They must provide adhesion to frozen substrate.

In addition, the materials must be permited to cure adequately. For low temperature applications some special epoxy materials have been developed which will cure at temperatures as low as -20°C. For lower temperature application either special materials must be developed, or heating must be provided to maintain a satisfactory temperature regime under the severe freezing environment. The latter might be achieved by electrical heating of the rebar, by heated formwork or enclosures, or perhaps by some form of microwave system. If this should prove necessary, a thermal analysis must be carried out to establish the likelihood of excessive thermal stresses with associated cracking or degradation of the surrounding concrete.

Logistics

In the North Sea and Arctic, supply of equipment and materials is generally by helicopter. The equipment used must therefore be suitable for this means of transportation. For example, present UK regulations prohibit toxic/explosive/poisonous materials being carried by helicopter.

The availability of materials and equipment must also be considered. Are they locally available? If not, what is the transit time? Is there a justification for keeping repair equipment on the rig or at base camp?

Access to the damaged area must be considered. For a conical structure, such as ACES, there is a large surface area to be inspected perhaps in a relatively short weather window. Cranage should preferably be available to all external parts of the structure. If normal cranage is insufficient then provision for installing special equipment should be made. Internal access to the structure is also desirable to enable inspection and repair work to be undertaken internally where possible.

If external work is required below sea levels, RCVs or divers must be employed. Should this be required, it would be desirable to wait for the open water period. Pre-placed identification marks on the concrete surface facilitate underwater inspection.

During the winter freeze, access through the ice could be dangerous particularly if the ice is moving. Exploding ice, breaking on the structure, and large blocks of multiyear ice may present significant hazards for both divers and equipment.

For safety reasons it is essential that all equipment complies with the relevant petrochemical regulations.

5.3 RESEARCH NEEDS

In considering the current needs regarding inspection and repair of Arctic structures, it was appreciated that a number of the topics listed below overlapped with the activities of the other working groups.

The Inspection/Repair Working Group found that the subject matter is not easily broken down into specific research items. In many cases, surveys, assessments and studies need to be carried out to develop practical procedures as well as the further development of existing inspection, monitoring, and repair techniques.

Inspection During Construction

The efforts involved in undertaking in-service inspection and in assessing the need for repair are dependent on the structural detailing, the material selection for "fitness for purpose", and the quality control exercised during construction. The implications are as follows:

1. Tests need to be developed, if not available, to establish the fitness for purpose of the materials as supplied, or in the case of concrete, manufactured and cast on site. Such tests include:

- Brittleness of steel at low temperature, bearing in mind the need to test full size bars or prestressing wires rather than smaller samples of steel.

- Freezing and thawing resistance characteristics of the in situ concrete (e.g., by testing cores).

- Permeability of the in situ concrete (e.g., by testing cores).

- Ice abrasion resistance of the in situ concrete with or without coatings.

- Concrete cover measurement in relation to that specified.

- Effectiveness of prestressing steel grouting, and the freeze-thaw resistance of the in situ grout.

2. Procedures need to be developed to record the actual location of reinforcement, prestressing ducts, and other embedments in the structure, to aid later identification in service where damage has occurred.

3. Further study is necessary to produce practical specifications for field usage, covering relevant testing and control procedures.

Structure Integrity Monitoring

1. It is essential to develop an integrated systems approach to the task of strucutre integrity monitoring. All components of the structure must be accorded the appropriate significance, e.g., foundations, marine response characteristics (both static and dynamic), subsurface structure, and the superstructure.

2. Evaluation is required of equipment, installation procedures and data handling, to produce meaningful results to the operator and the statutory

authority, and to avoid failure in service or difficulty in interpretation of results.

3. Back-up testing of the systems, under simulated operating environments of moisture and cold, is essential to minimize the risk of failure, hopefully over the life of the structure.

4. Careful estimation of the magnitude and variation of possible data output from sensing devices is essential, whether they be strain or stress gauges, accelerometers, ice pressure transducers, seabed piezometers etc., to ensure that the results are meaningful. For example, a low strain gauge result can mean either a low strain or a high stress under restraint.

5. Back-up testing of the devices related to the materials in the structure is essential to avoid errors in the conversion of strain gauge outputs into corresponding stress values and to aid interpretation. Strain gauge results for concrete need to be supplemented with data on the shrinkage, elastic properties, creep, and thermal expansion of the in situ concrete, if stress is to be determined. Alternatively, stress gauges, although less accurate, can give a direct reading without the substantial errors of conversion of strain values to stresses.

6. Study is required of the optimum approach for system design, installation and monitoring, in association with the inspection requirements. Preferably the same organization should be responsible for supervising and interpreting the results as was involved during equipment selection, its installation and the subsequent monitoring phases. There may well be an advantage to link their responsibility with the regular inspection organization to maximize the value from both.

Inspection Procedures

1. In view of the large surface areas of concrete involved, a scheme for systematic recording needs development. The desired scheme should:

- be practical for inspectors to carry out;
- enable easy reference later onshore to evaluate possible defect situations; and
- be capable of being readily updated in subsequent inspections, to highlight significant changes relative to previous inspections.

2. A practical system of coding visual defects such as cracks, staining, and honeycoming needs urgent consideration, as visual inspection is the primary method for global scanning of the structure.

Inspection Techniques

1. Existing techniques (such as visual and photographic defect recording, common NDT methods, and core sampling for subsequent analysis) need to be investigated for their use:

   - above and below water;
   - with and without freezing environments.

2. It may be necessary to modify the existing techniques and develop equipment to operate underwater and at low temperatures. Equipment components may not function reliably without modification, for example, electrical components may need to be sealed against water vapor or be thermally protected against extreme cold.

3. Novel techniques for inspecting the structure require detailed investigation, since they may potentially provide greater information, or increase the scanning rate of the structure. Such techniques might include:

   - Tomography
   - Vibrational and ultrasound scanning
   - Time domain reflectometry, for scanning prestressing tendons for damage along their length using end anchorage access

- Magnetic and other electrical responses to galvanic and local steel corrosion, for example, as used for pipe line inspection
- Thermography, benefitting from the stable temperature conditions, to identify local cold spots

Specialists in the specific technologies involved in the effective development of such techniques need to work closely with inspection agencies to ensure the practicality of the results.

4. For underwater inspection, design of equipment is required for operation by divers or RCV's, preferably for recording at the surface.

5. Inspection from within structures with external walls, while having obvious advantages, requires:

   - study of suitable techniques, and

   - consideration <u>at the design stage</u> for providing access under either wet or dry conditions, preferably the latter. Many of the internal inspection operating problems due to the cold and ice environment would be avoided if internal inspection were made feasible.

<u>Repair Procedures</u>

Prior study is required to consider the total process involved in undertaking a repair, particularly if major damage has occurred. Topics needing to be assessed include:

- Methods for rapid early analysis of the damage from initial observations, such as, for example, the size and construction details of a structure and the ship where a collision has occurred, the velocity and shape of the ship and extent of the cracked area.

- The availability of repair materials and equipment to undertake either a temporary or long term repair.

- Repair methods and procedures to restore leak tightness or strength to the structure. The former is of particular importance where oil pollution from damaged storage tanks is important.

- Inspection procedures and techniques for assessing the effectiveness of the repair afterwards.

<u>Repair Techniques for Types of Damge</u>

Various levels and types of damage have been identified which will require different methods for inspection and repair where immersed and cold conditions exist.

1. <u>Abrasion</u>

   a. <u>Inspection</u> - methods of recording the nature and rate of abrasion need investigation.

   b. <u>Repair</u> -

      - coatings - methods of repair need to be developed.

      - concrete - thin overlay materials with adequate bond to existing concrete need assessment and testing under simulated structural conditions.

2. <u>Spalling</u> (due to impact from ice, vessels, or equipment)

   a. <u>Inspection</u> - visual inspection may be sufficient

b. Repair - suitable cementitious/resin based products need evaluating under simulated structural conditions.

3. Puncture (major damage due to impact from vessels or equipment)

a. Inspection - NDT methods need to be assessed to support visual observation.

b. Repair - techniques to restore the structure need development. Restorations of the rebar, the prestress and the concrete need to be considered as well as alternative restoration systems by, for example, external patching or steel plating within or outside the structure.

4. Cracking

a. Inspection - NDT methods need to be evaluated to assess extent and nature of cracking.

b. Repair - suitable cementitious/resin based materials are required to penetrate cracks under simulated site conditions.

5. Freezing and Thawing

a. Inspection - visual inspection may be sufficient.

b. Repair - the same requirements as for repairs of concrete damaged by abrasion.

6. Corrosion

Corrosion of rebar may result in spalling, cracking, lamination of the concrete cover, or loss of section of the bar. For prestressing steel, corrosion may result eventually in tendon failure.

a. Inspection -

i. dry - techniques are already available which need modification for on-site usage.

ii. wet - techniques need to be developed.

b. Repair - treatments of the steel need evaluation and simulation testing.

Consideration of further prevention techniques (e.g., cathodic protection, surface coatings) may be necessary for avoiding similar damage to other critical areas.

7. Frozen Concrete

a. Inspection - existing techniques to inspect for concrete and steel damage may not work for frozen concrete. Simulation testing is a priority need in this area.

b. Repair - materials and equipment need evaluation and testing to identify their suitability for placing and in service performance. For example, injection equipment may block due to low temperature although the resins may be suitable as regards, e.g., their bond to the frozen concrete. Heating locally may be necessary and needs investigation.

8. Thermal Overload

Where a severe temperature difference occurs between oil in storage tanks and the frozen external environment, damage to the relatively thin concrete walls was not considered to be particularly onerous, so that neither inspection nor repair problems were identified.

9. Leakage (including seepage)

Leakage due to hydrostatic pressure may occur at poor construction joints, porous concrete in the walls and local honeycombing, as well as at cracks. Leakage paths along prestressing tendons have occurred in North Sea structures and there has been great difficulty in identifying their source.

In other structures, leakage induced by hydrostatic pressure has resulted from flow along embedments, due to settlement of fresh concrete below the rebar, formwork ties, and other penetrations.

a. Inspection - novel techniques, such as radioactive tracer methods, need development to track down the extent and source of leakage.

b. Repairs - sealing materials and techniques need development to withstand the possible further build-up of hydrostatic pressure. Simulation testing is essential.

Summary

With the likely large usage of concrete structures for Arctic oil and gas exploration and production, it is considered essential to implement the recommendations to ensure that inspeciton, monitoring, and repair proceduress are developed to meet the special and demanding conditions likely in the Arctic operating environment. Lack of suitable rapid and sound inspection and repair techniques could well result in substantial increases in cost and production time loss, subsequent deterioration of the structure in service or cessation of platform operations after damage. The research requirements identified by the Inspection/Repair Working Group are summarized in table 1.

Table 1. Research Needs Relative to Inspection and Repair

CATEGORY	NEEDS
1. INSPECTION DURING CONSTRUCTION	1. Test methods for assessing in situ material performance.
	2. Procedures for recording structural detailing.
	3. Practical specifications for testing and control procedures.
2. STRUCTURE INTEGRITY MONITORING	1. Evaluation of equipment and sensors performance regarding in-service vulnerability.
	2. Data processing for assuring the relevance of results.
	3. Optimization of control organization for equipment design, installation, and monitoring in relation to inspection needs.
3. INSPECTION PROCEDURES	1. Observation recording systems.
	2. Visual defect classification system.
4. INSPECTION TECHNIQUES	1. Suitability of existing techniques for usage underwater and/or in cold environments.
	2. Development of novel alternative techniques for faster and clearer scanning for possible defects.
	3. Assessment of inspection methods for RCV or diver usage.
	4. Internal inspection techniques and needs for structural design to facilitate their usage.
5. REPAIR PROCEDURES	Evaluation and development of procedures for damage analysis, repair, and after-repair inspection.
6. REPAIR TECHNIQUES	Evaluation of the suitability of existing repair materials and equipment used offshore to deal with different potential types of damage (abra-

NOTES

i. Most of the above research must be dominantly related to underwater usage, as well as in low temperature, cold water environments and in frozen concrete.

ii. It is realized that in certain cases considerable development effort will be required to make the technqiues effective under such field conditions.

iii. No order of priority has been given as each aspect is of equal significance.

6. ACKNOWLEDGMENT

The planning committee wishes to express its thanks to the workshop participants for giving their time to attend and actively participate in the workshop. Special gratitude is extended to the Group Chairmen who volunteered so much of their time to prepare their position papers and group reports. Appreciation is extended also to Ms. Carol McKenzie for her extraordinary efforts in the planning and execution of the workshop. Finally, we wish to thank Mrs. Sara R. Torrence for handling arrangements for the workshop, and Ms. Mary L. Ramsburg and Ms. Ulesia B. Gray for typing the draft reports. It was the cooperation of all these individuals that produced a successful workshop.

APPENDIX

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III. WORKSHOP AGENDA

Tuesday, March 1, 1983

9:00 - 9:25 a.m. Introduction and Welcome

Nicholas Carino, Chairman
Workshop Planning Committee
National Bureau of Standards

Samuel Kramer, Deputy Director for Programs
National Engineering Laboratory
National Bureau of Standards

Winston Revie, Assistant Director
Materials Research Program Office
Canada Centre for Mineral and Energy Technology

Charles Smith, Inspection Enforcement Division
Minerals Management Service
U.S. Department of Interior

9:25 - 10:00 a.m. Presentation of Position Papers (Plenary Session)

Introduction - Edward O. Pfrang
Chief, Structures Division
National Bureau of Standards

Ben Gerwick - Chairman, Design Working Group
Robert Philleo - Chairman, Materials Working Group
Peter Pullar-Strecker - Chairman, Construction Working Group
Roger Browne - Chairman, Inspection/Repair Working Group

10:30 - 1:00 p.m. Working Group Meetings - Morning Sessions

2:00 - 3:30 p.m. Working Group Meetings - Afternoon Sessions

4:00 - 5:00 p.m. Working Group Meetings - Afternoon Sessions

<u>Wednesday, March 2, 1983</u>

9:00 - 10:00 a.m. Working Group Meetings - Final Sessions

10:30 - 1:00 p.m. Presentation of Group Reports (Plenary Session)

DESIGN - Ben Gerwick

MATERIALS - Robert Philleo

CONSTRUCTION - Peter Pullar-Strecker

2:00 - 3:00 p.m. Presentation of Group Reports and General Discussions (Continued)

INSPECTION/REPAIR - Roger Browne

3:00 - 3:30 p.m. Concluding Remarks and Adjournment

Mohan Malhotra

Canada Centre for Mineral and Energy Technology

Nicholas J. Carino

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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 workshop was held March 1 and 2, 1983 at the U.S. National Bureau of Standards. The objective was to bring together an international group of experts for the purpose of information exchange on the subject of the performance of Arctic offshore concrete structures. The workshop participants were divided into four working groups to discuss the following subjects related to Arctic offshore concrete structures: 1) design; 2) materials; 3) construction; and 4) inspection and repair. Each working group addressed the following topics within their subject: past experiences, current projects, and recommended research areas. The chairmen of each group prepared reports summarizing their group's deliberations. These reports are incorporated into this workshop summary.

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

Arctic; concrete; construction; design; inspection; offshore structures; repair; research; structural engineering; technology assessment; workshop.

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