PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

AN ARCTIC ICE MODEL BASIN - DESIGN, CONSTRUCTION, AND OPERATING EXPERIENCE

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The discovery of oil and other natural resources in the arctic regions has stimulated interest in development of efficient bulk transportation systems and of efficient offshore structures for exploiting these discoveries. Research programs involved in these developments must logically include model experiments since analytical techniques alone are inadequate to characterize the rather complicated interaction between ships, structures, and ice. Such model experiments require the use of a specialized test facility.

This paper documents the demand for a test facility in which the interaction between hydraulic structures and ice may be modeled. The various types of experiments which the authors feel are relevent to the increasing interest in cold regions technology are described in general terms. The authors describe a preliminary study of the feasibility of constructing an ice model basin using a liquid nitrogen refrigerating system. The feasibility study required the construction of a small model of the model basin. Ice sheets were formed in this small basin over a period of several months. The fact that ice sheets suitable for modeling sea ice could be formed using a liquid nitrogen system was established. Further, the fact that this technique provided a very economical alternative to fixed refrigeration system was also established. Based upon these findings, the authors embarked upon the construction of the ARCTEC ICE MODEL BASIN. The paper describes the design of this facility including the refrigeration system, choice of major dimensions, and design of the towing system. Operating experience in the ARCTEC ICE MODEL BASIN is related. Initial shakedown experiments with the refrigeration system are described. Ice resistance experiments involving an United States Coast Guard WIND Class icebreaker model are discussed. Preliminary experiments with an arctic drilling platform are described.

DEMAND FOR ICE MODEL TEST FACILITY

Economic development of the north requires good logistical links between the potential resource centers of the north and the points of consumption and distribution in the more temperate zones. The devices employed to transport raw materials from the north and tools and equipment to the north must be designed to withstand the environment of the Arctic Regions. The equipment required to extract oil and minerals from the Arctic Regions must also incorporate design features for Arctic service. Many vehicles and devices for Arctic service such as bulk carrying surface ships, offshore oil drilling rigs, offshore oil loading terminals, ship mooring systems, ore loading facilities, submarine bulk carriers, and air cushion vehicles must cope with a variety of design and operational problems which the presence of an ice cover causes. The majority of the interactions between transportation and extraction systems and ice cover are not readily treated analytically. Consequently, the use of physical modeling is necessary to obtain sufficient information to solve many of the problems which arise in the design and operation of Arctic equipment. A number of these problems are worth mentioning. They are characterized by vehicle type and listed below:

A. Marine Vehicles
  1. Selection of adequate power to maintain economical speeds of advance in
    a. uniform ice
    b. broken ice
    c. mush ice
    d. pressure ridges
  2. Determination of structural loads sustained during
    a. steady motion in continuous unbroken ice
    b. ramming operations
  3. Determination of dynamic loads on the propulsion system sustained during propeller
    a. impact with ice
    b. milling of ice
  4. Excessive vibratory response caused by
    a. broad band exciting force on the hull during icebreaking

B. Offshore Structures and Platforms
  1. Overturning forces caused by
    a. motion of unbroken ice sheets past the structure
    b. impact with large floating ice masses
    c. impingment of pressure ridges against the structure

2. Unacceptable vibration of the structure caused by
    a. resonance phenomenon (frequency of ice failure force coincides with primary frequency of structure)
    b. random vibration-ice crushing forces have sufficiently broad band to cause significant response in the structure
3. Oscillation of moored floating vehicles due to large unsteady ice forces
4. Forces on anchoring systems caused by
    a. ice forces on the hull
    b. ice impinging against the anchor cables

C. Submarine Tankers
1. Structural forces on the hull and appendages sustained during
    a. emergency surfacing through ice
    b. unavoidable collision with submerged keels of pressure ridges
2. Drag forces caused by motion of a submerged vehicle near a compliant boundary (ice cover)
3. Stability and control problems caused by complex flow around a submerged vheicle in the enighborhood of a compliant boundary (ice cover)

D. Surface Effect Vehicles
1. Drag caused by wave making in the ice cover
2. Instability caused by traveling at critical speed over the ice cover
3. Breakthrough while parking due to
    a. elastic short term response of the ice sheet
    b. long term visco-elastic response of the ice sheet

A good deal of these problem areas involve analytically intractable phenomena. Even physical modeling of the various phenomena does not provide a panacea. However, the following list of experiments can be performed in an adequate test facility and should produce helpful data for solving the problems we have described.

A. Model Ice Resistance Tests
1. Icebreaking resistance
2. Broken channel resistance
3. Mush ice resistance
4. Resistance caused by inducing waves in the ice sheet
    a. moving load on the surface
    b. moving vehicle just below the surface

B. Structural Load Tests
   1. Slow motion of the ice sheet past structures of various shapes
   2. Motion of pressure ridges past structures of various shapes
   3. Loads on mooring systems used to anchor the above structures
   4. Loads exerted on icebreaker hulls

C. Vehicle/Structure Dynamics Tests
   1. Response of a ramming icebreaker
   2. Dynamic response of structures to unsteady ice forces
   3. Dynamic response of SEV traversing an ice field
   4. Dynamic response of a submarine vehicle traveling near the underside of an ice sheet

D. Visco-Elastic Effects
   1. Creep of long term loads on ice sheets

DEVELOPMENT OF THE MODEL BASIN

The requirements for a facility in which the interactions between structures, ships, and the ice cover could be modeled seemed evident. The fact that such model experiments were technically feasible and produced useful results had been demonstrated by the United States Coast Guard (1) and by the Soviets in the facility of the Arctic and Antarctic Institute in Leningrad (2). With this information, the principals of ARCTEC, Incorporated decided to investigate the feasibility of constructing an ice model test facility and operating it on a commercial basis.

Preliminary Investigation

The most forbidding aspect of such an undertaking was the cost of acquiring a refrigeration system of sufficient capacity to produce model ice sheets at an acceptable rate. Estimates of the cost of a small facility ran as high as $250,000.00. Refrigeration alone was estimated to cost $2,000.00 per ton. The upkeep of a high performance, two stage refrigeration system was considered a major deterrent since there would be a requirement for at least one highly skilled refrigeration mechanic on duty at all times during operation of the system. During a series of brainstorming sessions with a potential contractor for the refrigeration equipment, the use of liquid nitrogen as a cheap refrigerant was suggested. ARCTEC engineers began investigating ways in which the refrigerant could be used to cool both the liquid in the model basin and the air above the basin. Personnel at the National Aeronautics and Space Administration (Goddard Space Flight Center) were approached for advice and were very helpful. However, the majority of their applications of LN_2 were not suitable, since 100 percent radiant heat transferwas used in their deep-space-simulating systems. Consequently, maximum predicted freezing rates using such systems were unsatisfactorily low. In addition such systems involved extremely expensive containment, circulation, and control systems.

A small model basin 8' x 4' x 4' was constructed of polyurethane foam, wood, and polyethelyne sheets. ARCTEC engineers designed a system for spraying liquid nitrogen into the air space above the water surface. A network of piping was installed in an insulated lid which could be placed on top of the basin. The cover was sealed using a typical refrigerator gasket. Liquid nitrogen was admitted to the spray header from a low pressure flask. The flow was controlled with a throttling valve. Temperature was monitored with a remote sensing indoor-outdoor thermometer. The basin was filled with a thirteen part per thousand NA Cl solution. Ice sheets were formed on the surface of this basin by closing the lid, admitting LN_2 to the closed system (gas at about 0°F escaped freely past the gasket) and maintaining the temperature in the basin by throttling the inlet valve. Experience with the system developed to the point that one could control the resulting ice thickness by controlling the number of freezing degree hours.

The first test run in the model basin was made May 2, 1970. The fluid temperature was reduced to 30°F by dissolving frozen CO^2 in the tank. At that point the nitrogen was admitted to the spray header. Inspection of the ice sheet revealed a layer of ice consisting of all vertical crystals. Following this first successful freeze, ARCTEC engineers decided that it was worthwhile to undertake a program to determine quantitatively the properties of the model ice as related to the capacity of the refrigeration system. In particular, it was important to relate freezing rate to liquid nitrogen consumption. In addition, we decided to measure the resistance of model ice to motion of a 1/100 scale model of the WIND Class icebreaker. After accumulating the necessary equipment, the model basin feasibility study started in earnest.

Ice sheets were produced in the small basin on a daily basis during the months of May, June and July. The growth rate, salinity, flexural strength, and elastic modulus of the ice sheets was measured and recorded. Figure 1 shows a typical temperature versus time plot for one of the tests performed in June. The observed strength was 0.120 kg/cm^2. The growth rate was 1.31×10^{-4} cm/sec. The average ice salinity was 8.8 parts per thousand. During the period of May 2 through June 16, sufficient evidence was accumulated to assure ARCTEC engineers that uniform ice sheets with predictable salinity could be grown using the liquid nitrogen process. The strength of the ice sheets correlated reasonably well with ice salinity. Figure 2 shows the relationship between strength and salinity. However, scatter must be expected since no method was available to maintain ice temperature after removal of the lid of the ice basin. In addition, our techniques for measuring the ice temperature were poor. Figure 3 shows the relationship between the growth rate and the ratio of average ice salinity to water salinity. This data agrees well with data presented by Weeks and Lofgren (5) in 1967.

Figure 1

PLOT OF TEMPERATURE

VS

TIME (MINUTES)

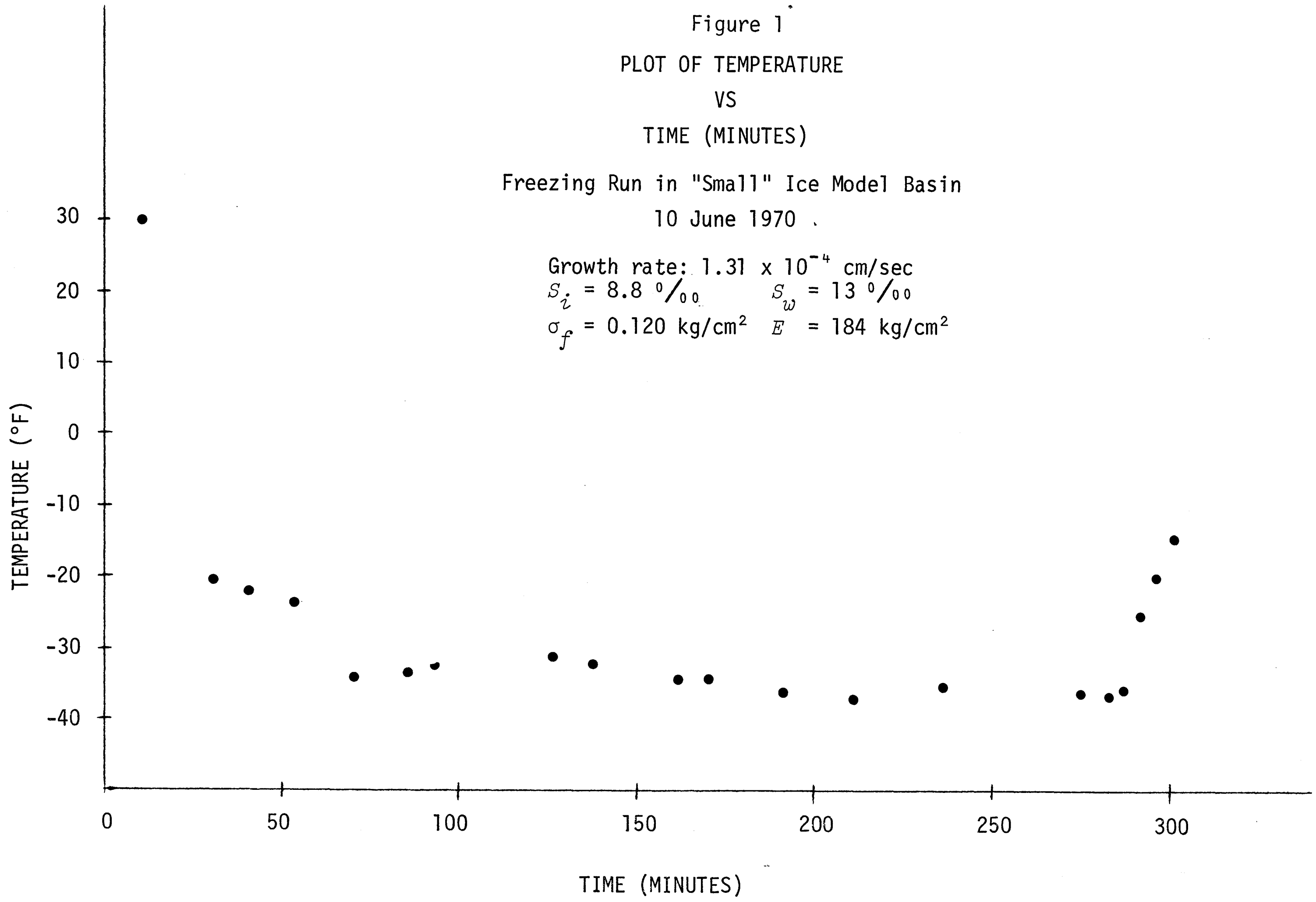
Freezing Run in "Small" Ice Model Basin

10 June 1970

Growth rate: 1.31 x 10^{-4} cm/sec

S_i = 8.8 ‰ S_w = 13 ‰

σ_f = 0.120 kg/cm² E = 184 kg/cm²



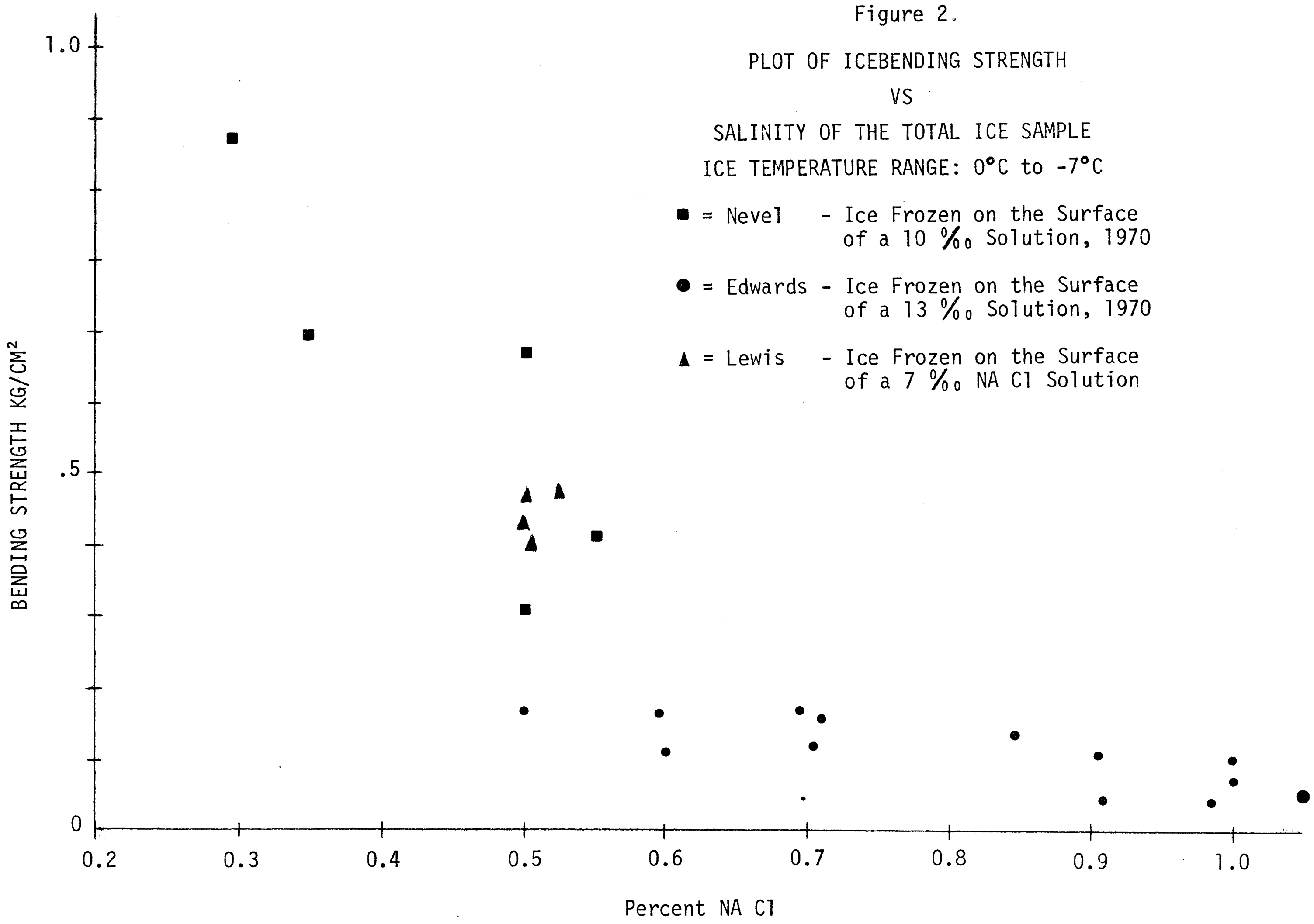


Figure 2.

PLOT OF ICEBENDING STRENGTH

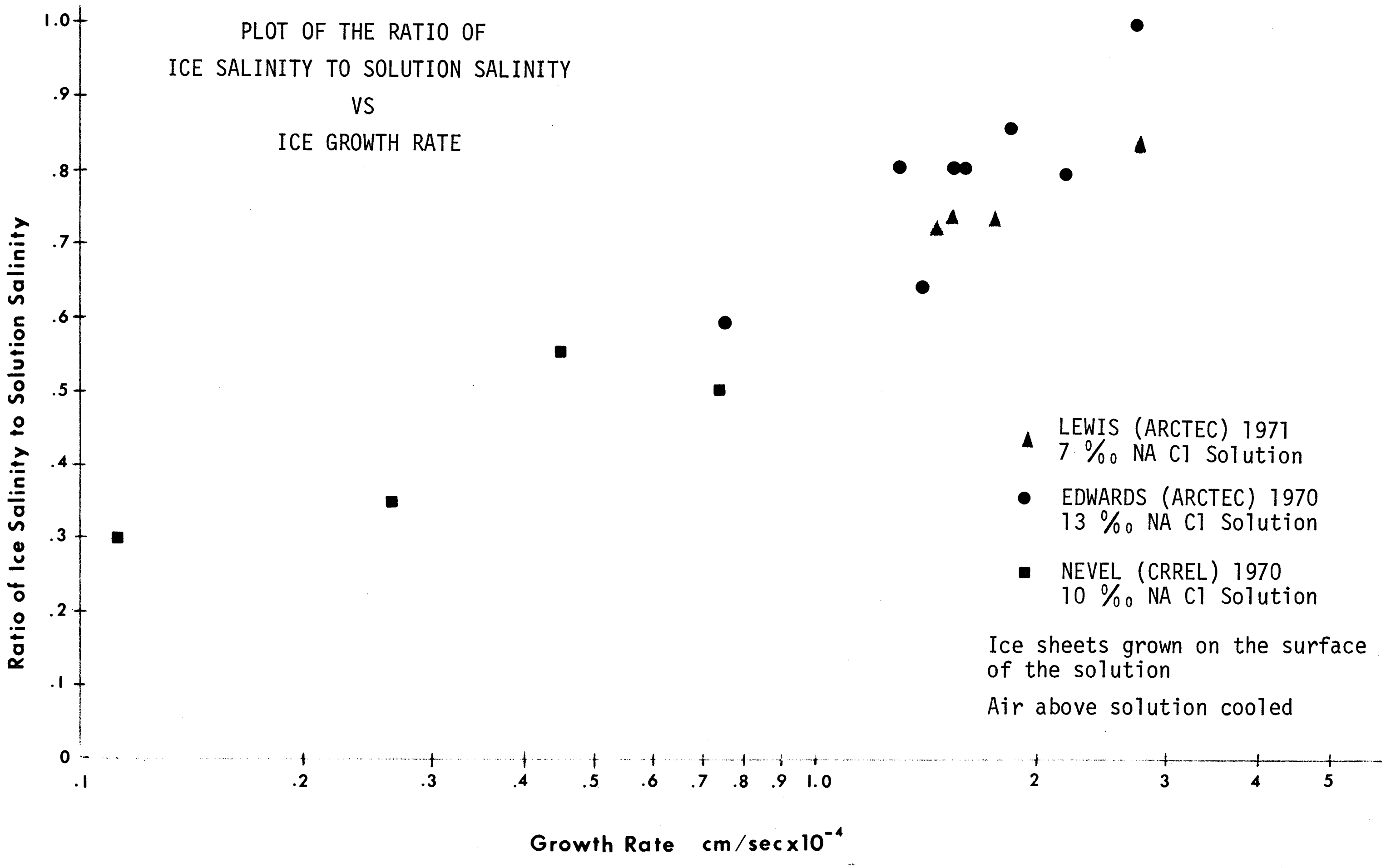
VS

SALINITY OF THE TOTAL ICE SAMPLE

ICE TEMPERATURE RANGE: 0°C to -7°C

Figure 3

PLOT OF THE RATIO OF
ICE SALINITY TO SOLUTION SALINITY
VS
ICE GROWTH RATE



Ship Model Tests

A 1/100 scale model of the WIND Class Icebreaker was constructed and towed at constant speed through the basin. The results of the tests are shown in Table I and Figure 4. Despite the scatter, the tests demonstrated the feasibility of performing meaningful model tests in ice formed using liquid nitrogen. The tests were completed on July 30, 1970. During that period, the nitrogen consumption was monitored carefully. The average ice thickness in the basin was used to compute the average quantity of useful ice produced. From June 11 to July 30, 3,677 pounds of liquid nitrogen at standard temperature and pressure were consumed and 1,940 pounds of model ice produced. The conclusions were that one pound of liquid nitrogen produced an average of 0.53 pounds of useful model ice. At the bulk rate cost of liquid nitrogen, it was determined that ice sheets suitable for model tests could be produced economically.

Conclusions Drawn from Experiments in the Small Model Basin

The tests performed in the small model basin proved that, with some refinement, a refrigeration system consisting of an apparatus to spray liquid nitrogen into the air above a water surface will produce an ice sheet sufficiently uniform to permit meaningful ice resistance experiments. Such experiments are probably the most dependent upon uniform ice thickness of any mentioned earlier in this paper. It was further determined that the average salinity of the ice sheet could be varied by alternating either freezing rate or tank water salinity or both, thus permitting good control over one of the primary variables which determines the value of flexural ice strength. The other variable is ice temperature. No attempt was made to control ice temperature in the small basin. Once the lid was removed from the basin, the ice was exposed to summer air temperatures of 70°F to 90°F. Nonetheless, reasonable values of flexural strength and elastic modulus were obtained from the ice sheet. Table I shows a range of elastic modulus from 50 to 90 kg/cm^2 and flexural strength from .035 to .233 kg/cm^2. The most meaningful result of the tests was the establishment of the economic feasibility of using the liquid nitrogen refrigeration system.

Designing the Large Model Basin

The design process for the large model basin consisted of the following steps:

a. Selection of the gross parameters of the basin
b. Design of the refrigeration system
c. Design of the model towing system
d. Design of temperature control and instrumentation system

The selection of the size of the model basin itself influenced the acquisition cost of the facility very strongly. Since the size of the basin influenced the quantity of ice cover which must be produced during each freeze, the operating costs of the facility will also be strongly dependent upon the size of the model basin. The width of the model basin limits the size of the model and ice

TABLE I

RESULTS OF WIND CLASS MODEL TESTS IN ARCTEC'S "SMALL" MODEL BASIN (λ = 100)

DATE	S_i ($^0/_{00}$)	R (Kg)	V (ft/sec)	h (cm)	E (Kg/cm²)	σ_f(Kg/cm²)
06-29-70	13.3	.212	.220	1.23	5.7	.078
06-29-70		.095	.371	1.00	5.7	.078
06-29-70		.092	.336	1.65	5.7	.078
06-29-70		.185	.320	1.56	5.7	.078
06-29-70		.125	.352	1.48	5.7	.078
06-30-70	--	.400	.348	1.65	16.2	.111
06-30-70		.224	.538	1.57	16.2	.111
06-30-70		.095	.600	1.72	16.2	.111
06-30-70		.156	.576	1.90	16.2	.111
07-07-70	9.8	.023	.368	.60	17.1	.035
07-07-70		.048	.417	.70	17.1	.035
07-07-70		.043	.410	.80	17.1	.035
07-07-70	10.0	.165	.460	1.35	11.1	.094
07-07-70		.115	.482	1.25	11.1	.094
07-07-70		.190	.462	1.60	11.1	.094
07-07-70		.310	.463	1.68	11.1	.094
07-07-70		.160	.408	1.60	11.1	.094
07-08-70	--	.219	.454	1.72	15.4	.062
07-08-70		.330	.413	1.85	15.4	.062
07-08-70		.207	.480	1.73	15.4	.062
07-09-70	8.0	.050	.213	1.10	29.7	.233
07-09-70		.050	.360	.98	29.7	.233
07-09-70		.050	.333	.98	29.7	.233

DATE	S_i ($\frac{0}{00}$)	R (Kg)	V (ft/sec)	h (cm)	E (Kg/cm^2)	σ_f(Kg/cm^2)
07-10-70	--	.115	.470	1.10	23.6	.118
07-10-70		.096	.497	1.38	23.6	.118
07-10-70		.058	.464	1.15	23.6	.118
07-11-70	--	.129	.708	1.31	6.0	.100
07-11-70		.195	.575	1.57	6.0	.100
07-11-70		.099	.588	1.30	6.0	.100
07-14-70	--	.070	.370	.82	4.7	--
07-14-70		.069	.367	.90	4.7	
07-14-70		.073	.340	.90	4.7	
07-14-70		.083	.448	.85	4.7	
07-14-70		.099	.431	.90	4.7	
07-14-70		.096	.413	.90	4.7	
07-15-70	--	.145	.359	1.20	63.3	.172
07-15-70		.261	.360	1.30	63.3	.172
07-15-70		.310	.220	1.40	63.3	.172
07-15-70		.049	.257	1.00	63.3	.172
07-15-70		.091	.236	1.20	63.3	.172
07-15-70		.170	.171	1.35	63.3	.172
07-15-70		.186	.105	1.40	63.3	.172
07-15-70		.302	.127	1.50	63.3	.172
07-16-70	--	.031	.245	.90	35.1	.109
07-16-70		.031	.226	.75	35.1	.109
07-16-70		.021	.245	.60	35.1	.109
07-16-70		.049	.363	.90	35.1	.109
07-16-70		.028	.360	.70	35.1	.109
07-22-70	5.0	.241	.650	1.20	90.4	.153
07-22-70		.184	.524	1.30	90.4	.153
07-22-70		.095	.520	.90	90.4	.153
07-23-70	--	.090	.492	1.10	19.0	.147
07-23-70		.135	.437	1.20	19.0	.147
07-23-70		.145	.430	1.20	19.0	.147
07-23-70		.145	.690	1.12	19.0	.147
07-23-70		.182	.632	1.20	19.0	.147

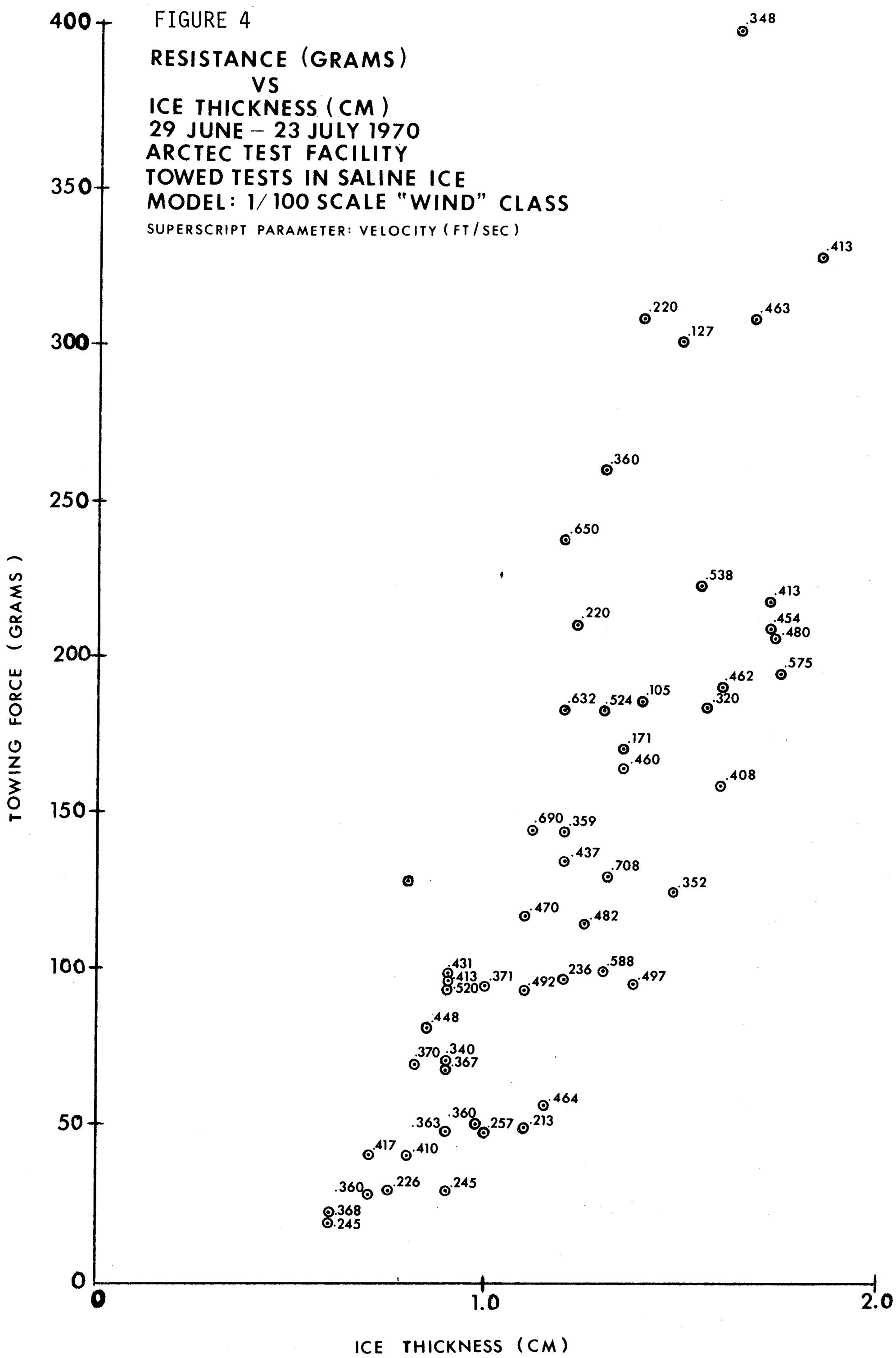


FIGURE 4
RESISTANCE (GRAMS)
VS
ICE THICKNESS (CM)
29 JUNE – 23 JULY 1970
ARCTEC TEST FACILITY
TOWED TESTS IN SALINE ICE
MODEL: 1/100 SCALE "WIND" CLASS
SUPERSCRIPT PARAMETER: VELOCITY (FT/SEC)
TOWING FORCE (GRAMS)
ICE THICKNESS (CM)
0
50
100
150
200
250
300
350
400
0
1.0
2.0

thickness in which tests may be performed since the basin walls will affect the behavior of the ice sheet under load. Meyerhof (4) has stated that the edges of an ice sheet must be at least three times the characteristic length of ice sheet from the load boundaries before the behavior of the sheet approaches that of an infinite plate. The Soviets, however, indicate that for ship tests the ice failure around the vehicle occurs very close to the load (ship) and the boundaries of the ice sheet can be significantly closer to the model sides before interfering with the ship resistance measurements. Another consideration was the ability to gain access to the basin surface. If the breadth of the basin exceeds eight feet, a person walking along the side will not be able to take samples from the middle. A basin width of eight feet was selected on the grounds that accessibility of the tank surface was kept high while a capability to test a 1/100 scale model of a large tanker with 200 foot beam in a model of twelve foot arctic pack ice was maintained. The length of the model basin is determined by the expected number of ship lengths required to obtain an acceptable amount of steady state resistance data. Previous experience with self-propelled model tests in ice and full scale tests of ships in ice indicated that about six ship lengths were required to obtain an useful record of ice resistance data. This suggested a basin length of 72 feet. However, physical limitations on available floor space dictated a reduction in length to 60 feet. It turned out that such a length was acceptable for towed model tests because steady state could be reached quite rapidly and good data was obtained in two to three ship lengths. The depth of the basin was determined by consideration of blockage effect of a moving model. This is essentially a requirement to maintain the ratio of the expected model immersed cross-section to basin cross-section below .05. The largest ship model which we expected to test had a cross-section of one square foot. A four foot depth provided the proper value of this ratio and also maintained an aspect ratio of the basin of two to one which is acceptable hydraulically. Nominal basin dimensions which were selected are:

length	60 feet
breadth	8 feet
depth of water	4 feet

Design of the Refrigeration System

The basin dimensions determine the size of the insulated room surrounding the model basin. A two and one-half foot wide walkway around the basin was considered necessary to provide adequate working space. The ends of the cold room were specified at eight feet from the ends of the basin to provide room for handling the models. Once the surface area of the water in the basin was established, and the volume and surface area of the walls and roof of the cold room determined, it was possible to determine the loads on the refrigeration system.

The primary load on the refrigeration system is provided by the heat released due to formation of ice in the basin. Calculations indicated that using three inch slabs of foamthane insulation to insulate the walls and roof of the basin, the losses to the outside of the cold room ranged from 27 to 15.7 percent of the ice forming load at cold room temperatures between +20°F and -100°F. The configuration of the refrigeration system may be seen in Figure 5. The liquid nitrogen is admitted through the spray headers at the overhead of the model basin. The basin overhead was a dull black painted surface which when cooled to temperatures near -320°F absorbed heat from the basin due to radiant transfer. The atomized liquid nitrogen expands violently to a gas and causes a turbulent region above the ice sheet. Hence, heat is also transferred across the basin surface due to turbulent heat transfer. The gas escapes to the cold room at the bottom of flexible transparent flaps. This escaping gas cools the cold room and finally is extracted from the cold room through ducting under the floor of the cold room. An estimate of the required flow rate of liquid nitrogen was obtained by relating the ice growth rate to the air temperature above the ice. This is accomplished by writing the equations describing the heat flux at the air-ice water interface

$$q_{\text{fusion}} = q_{\text{rad}} + q_{\text{conv}} \qquad [1]$$

The assumption is made that the ice layer is thin and the conduction through the ice layer is very large with respect to convection. Then

$$\frac{dx}{dt} = \frac{h_{\text{ice}}\,(\theta_{\text{water}} - \theta_{\text{room}}) + q_{\text{rad}}}{\rho_i g\, H_{\text{fus}}} \qquad [2]$$

where

$\frac{dx}{dt}$ = ice growth rate

h_{ice} = film heat transfer coefficient

ρ_i = density of ice

g = gravitational constant

H_{fus} = latent heat of fusion of ice

θ = temperature

q_{rad} = radiant heat flux estimated from Stefan Boltzman equations

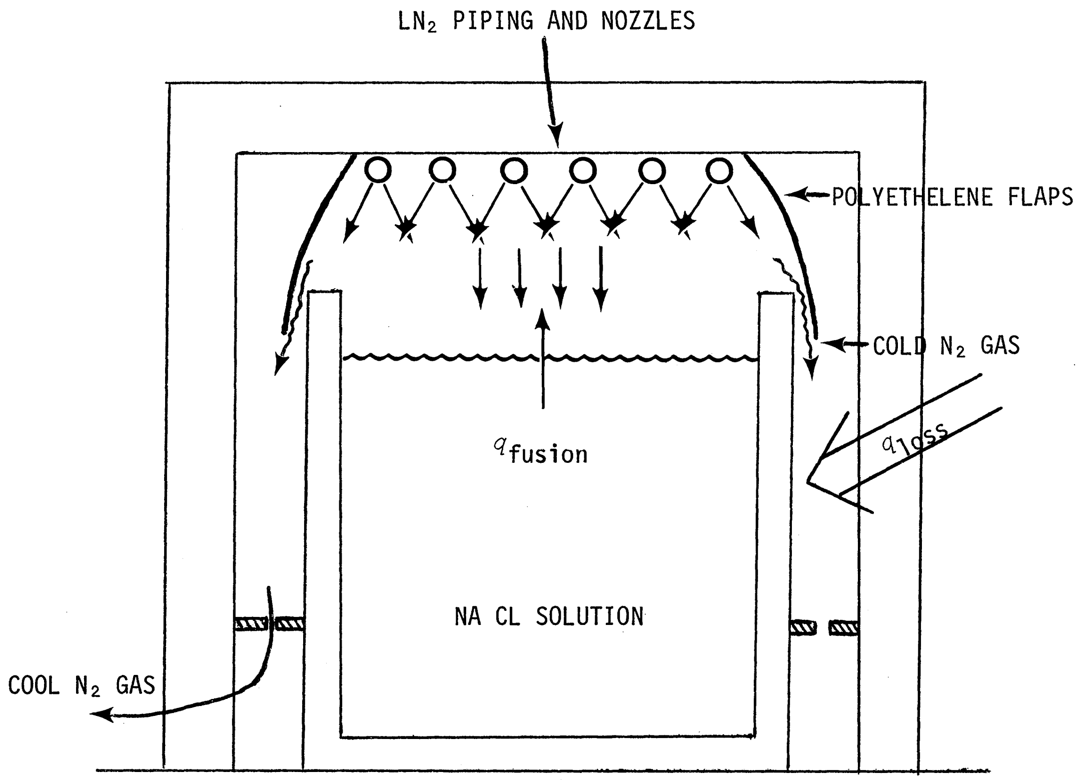
The liquid nitrogen flow rate was estimated by equating the ice formation load and various other heat losses all of which are functions of temperature in the room to the enthalpy of the incoming liquid nitrogen.

$$\dot{w}\,(H_{\text{vap}} + Cp\,\theta_{\text{liq}}) = \dot{w}\,Cp\,\theta_{\text{room}} + q_{\text{losses}} + q_{\text{freezing}} \qquad [3]$$

The results of these calculations are shown in Figure 6. With their required flow rates known, the overhead piping and spray system could be sized. This part of the design was perhaps the most important one. The proper choice of nozzles, the spacing of the nozzles and the arrangement of the supply piping was critical. The uniformity of the ice sheet depends upon the proper spray system design. Because

FIGURE 5

CROSS-SECTION OF BASIN DURING FREEZING PROCESS



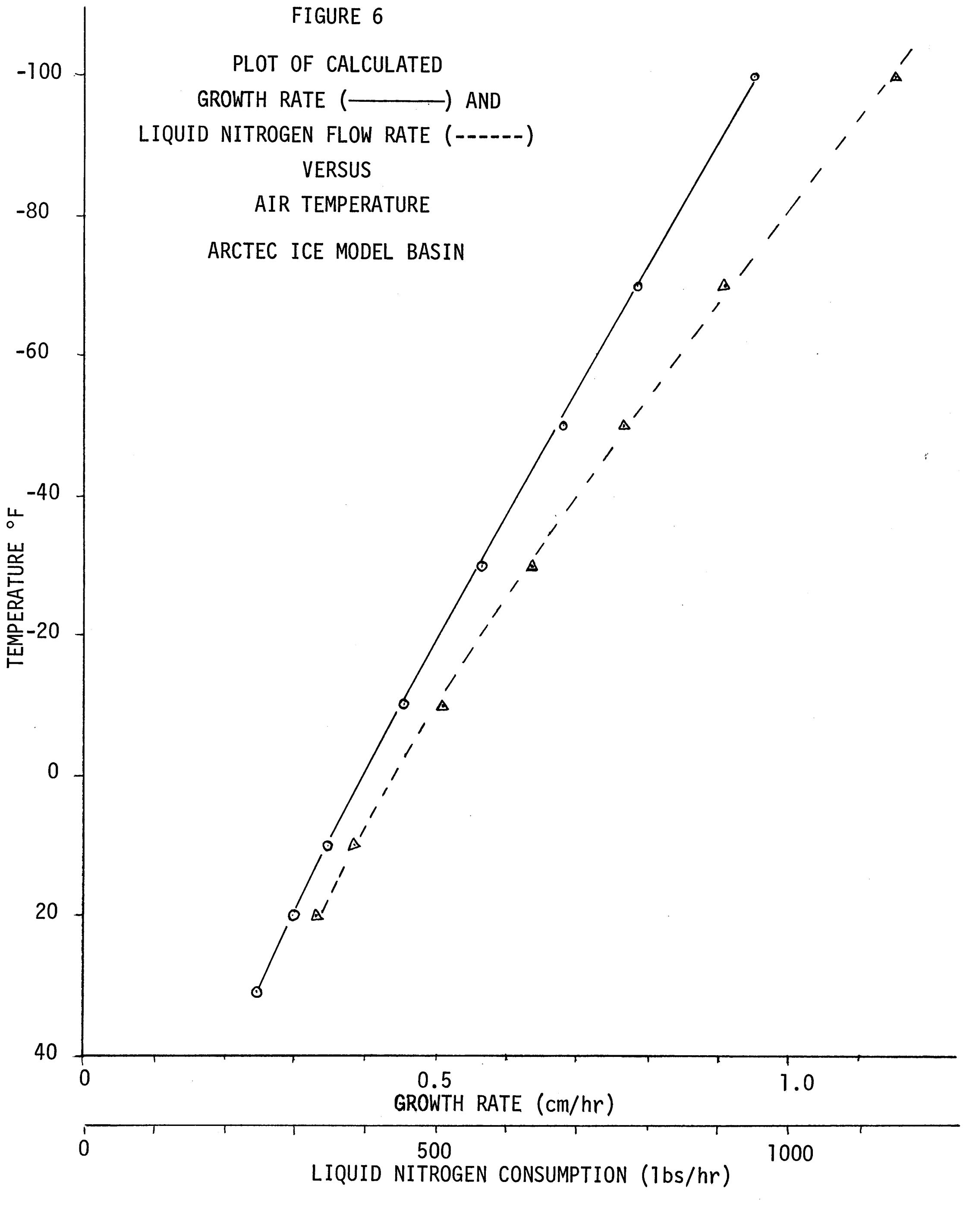


FIGURE 6
PLOT OF CALCULATED
GROWTH RATE (————) AND
LIQUID NITROGEN FLOW RATE (------)
VERSUS
AIR TEMPERATURE
ARCTEC ICE MODEL BASIN
-100
-80
-60
-40
-20
0
20
40
TEMPERATURE °F
0
0.5
1.0
GROWTH RATE (cm/hr)
0
500
1000
LIQUID NITROGEN CONSUMPTION (lbs/hr)

of the peculiarities of cryogenic fluids, improper choice of the number and size of nozzles will result in excessive flow of liquid and subsequent spills and a distorted ice sheet surface. Selection of too few nozzles or undersize orifices will result in inability of the system to get past the initial transient with the result that liquid will never appear at the nozzle outlets. The design of the system involves an estimation of the quantity of liquid flowing in the pipes which is converted to gas by absorption of heat from the cold room and through exterior piping runs. The total liquid and gas flow determines the nozzle size and number. The resulting system operates well between 25 and 50 psig supply pressure. The flow rates are adequate to reduce the temperature from ambient to -50°F in fifteen minutes and maintain freezing rates shown in Figure 6. The spray pattern of the nozzles has been successfully selected and the nozzles so arranged that the variation in the thickness of the ice surface produced rarely reaches ten percent of the thickness.

Design of the Model Towing System

The operational requirements of the towing system were:

a. Capability to exert towing forces (for tests of structures in thick ice) as high as 1000 pounds
b. A wide speed range (.1 ft/sec - 10 ft/sec)
c. Freedom from vibration
d. Capable of supporting mechanisms to permit realistic motions of models

The falling weight towing system was rejected because of the restraint on maximum towing force. The constant speed overhead monorail system used so often in small towing tanks was rejected because of the blockage effect it would have upon the liquid nitrogen distribution system. The tracking system by itself was rejected because self-propelled model tests in ice are inefficient and restrictive. The capability to track was considered necessary, however, in the carriage design. The final decision was to employ a carriage spanning the ice tank towed by an endless wire which was driven by an eddy current clutch drive motor. The carriage rides on articulated roller bearings which in turn ride on the surface of two case-hardened steel round rails on either side of the basin. The towing wire extends along either side of the basin around fairleads on the forward and after end of the carriage. The wire proceeds down at either end of the basin under the basin floor. The drive motor and reduction gearing is situated outside the cold room. Speed is controlled by controlling the current to an eddy current clutch which connects a constant speed five horsepower motor running at 1,780 rpm to a four speed gear box which in turn drives a timing belt seven to one reduction system. The speed range is from 0.2 ft/sec to 10 ft/sec. At the low speed end, the carriage has a capability of exerting 1,300 pounds of force in the direction of motion. The carriage drive is equipped with a feed back system which permits the towing system to act in a tracking mode. Figure 7 shows the carriage during a

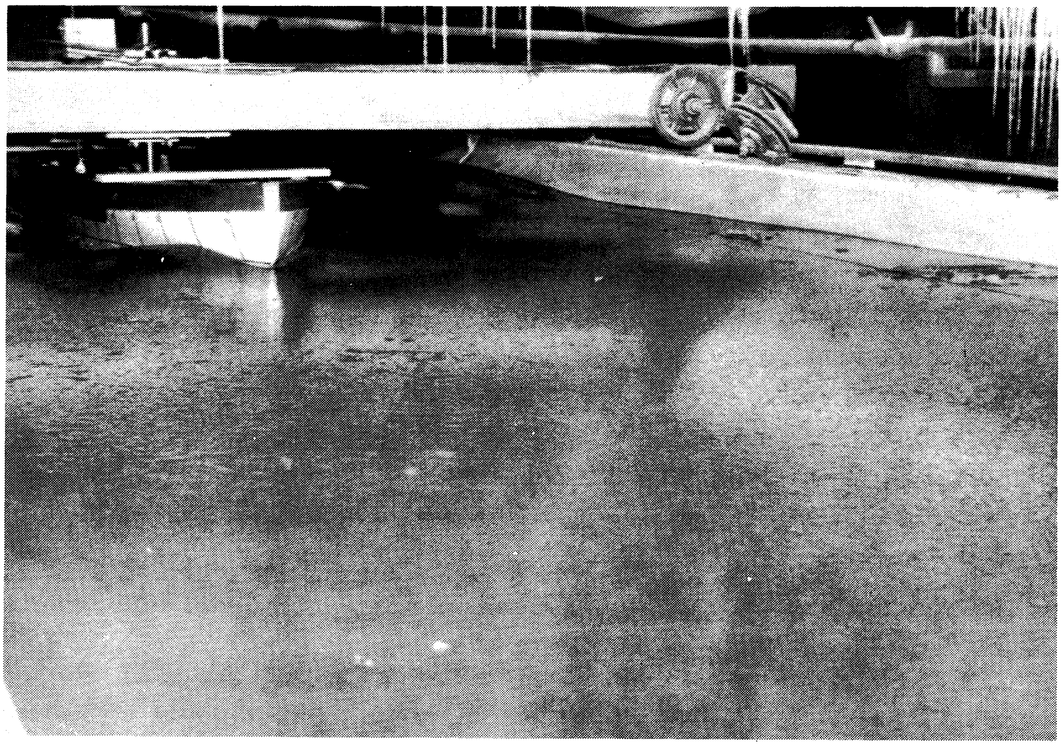


Figure 7. Photograph taken during a high speed ice resistance test in thin ice (vehicle is a 1/36 th scale model of the WIND Class Icebreaker).

high speed test run in thin ice. The WIND Class model is suspended below the carriage in a four degree of freedom mechanism.

Design of the Refrigeration Control System

A simplified mathematical model of the ice freezing system was developed. Figure 8 shows this model. Analysis of this model shows that the system is quite stable and that if the mass rate of flow of liquid nitrogen set and was held constant (valve opened and left in position), the temperature in the basin would fall rapidly to a steady value and level off. As the ice grows to several centimeters in thickness, the ratio of ice thickness to thermal conductivity of ice becomes large with respect to the inverse of the film heat transfer coefficient. The temperature then would gradually fall. Reference to the block diagram in Figure 8 shows that there are other stabilizing characteristics in the system. As the room temperature falls slightly the losses increase, the available refrigerating capacity of the liquid nitrogen falls and the growth rate increases, further increasing the load on the system. All of these factors lead to an inherently stable system. Hence, no automatic control was necessary. Figure 9 shows a temperature versus time plot for a freezing run in the ARCTEC Ice Model Basin. Control of spatial temperature gradients was obtained by splitting the spray system into discrete subsystems, the nitrogen flow to which is controlled by adjusting separate values for each subsystem. The temperature is sensed at up to sixteen locations with copper constantan thermocouples. The temperature readings are all sampled by a precision selector switch and a very accurate digital voltmeter. Observation of the spatial distribution of temperature in the basin permits fine adjustments to the nitrogen flow rate in the subsystems to insure uniform ice growth along the pool.

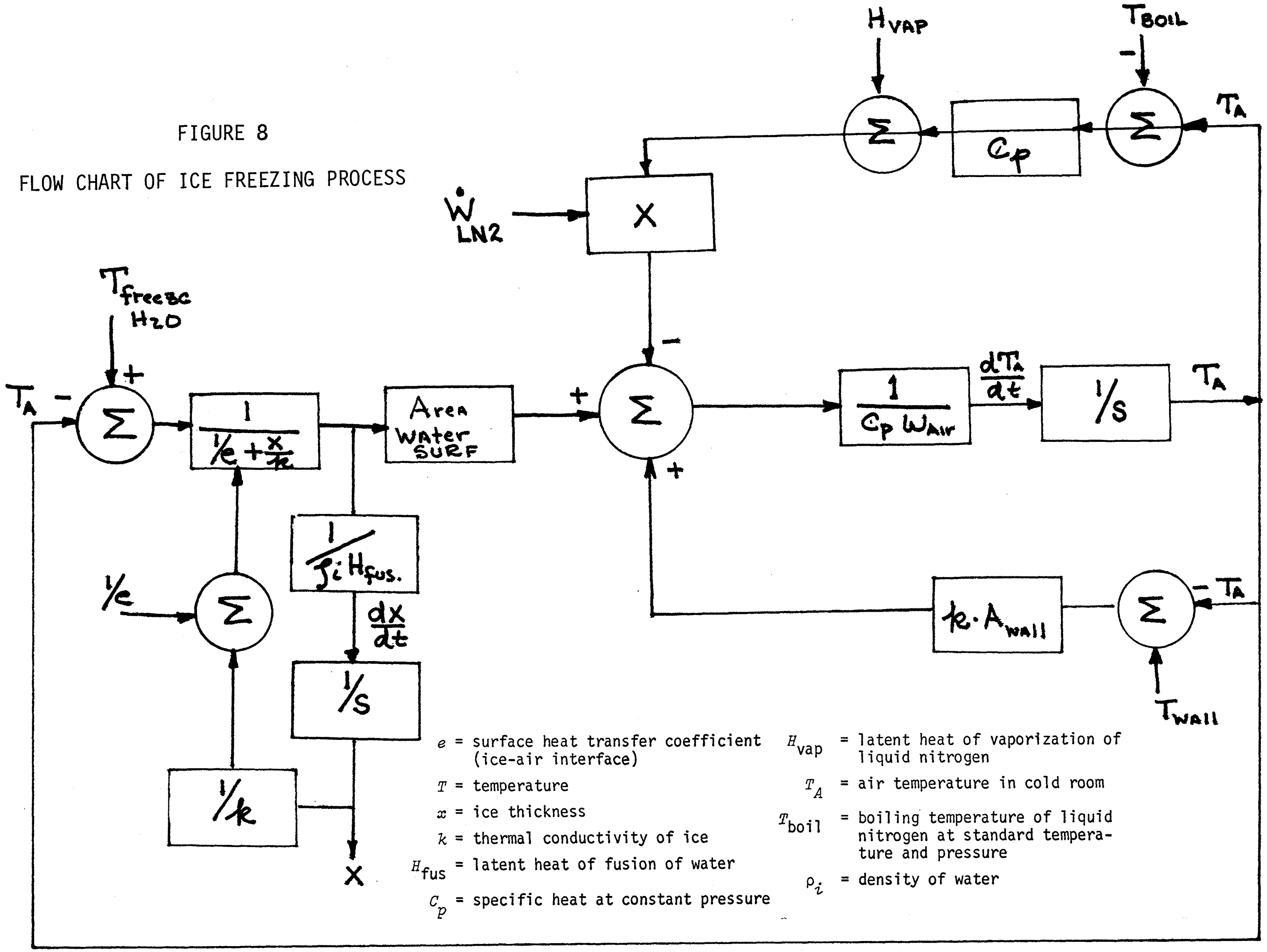
OPERATION OF THE MODEL BASIN

Shakedown Tests

The first few weeks in January, 1971 were spent in debugging the refrigeration system. This process consisted of becoming familiar with the characteristics of the spray system. Adjustments were made to nozzle orientation and orifice size. At the completion of the shakedown tests, the system was producing uniform ice sheets at rates quite close to those calculated. Figure 10 shows an ice thickness versus time plot for a typical ice growth test. A prediction line obtained from the calculated growth rates shown in Figure 6 is superimposed on the data for the temperature of the test. The ice strength, elastic modulus, and ice salinity were measured during all experiments. Satisfactory values of strength and elastic modulus were obtained. Figure 11 shows ice thickness plotted as a function of basin length. The variation is approximately 12.5 percent. The actual growth process was not the reason for this variation. The thickness measurements were made on the edges of a broken channel through which a model ship had passed. As a result, intermittant flooding of the ice sheet has introduced error in measuring ice thickness by adding thickness in the areas where the ice

FIGURE 8

FLOW CHART OF ICE FREEZING PROCESS



e = surface heat transfer coefficient (ice-air interface)

T = temperature

x = ice thickness

k = thermal conductivity of ice

H_{fus} = latent heat of fusion of water

C_p = specific heat at constant pressure

H_{vap} = latent heat of vaporization of liquid nitrogen

T_A = air temperature in cold room

T_{boil} = boiling temperature of liquid nitrogen at standard temperature and pressure

ρ_i = density of water

FIGURE 9

PLOT OF COLD ROOM TEMPERATURE

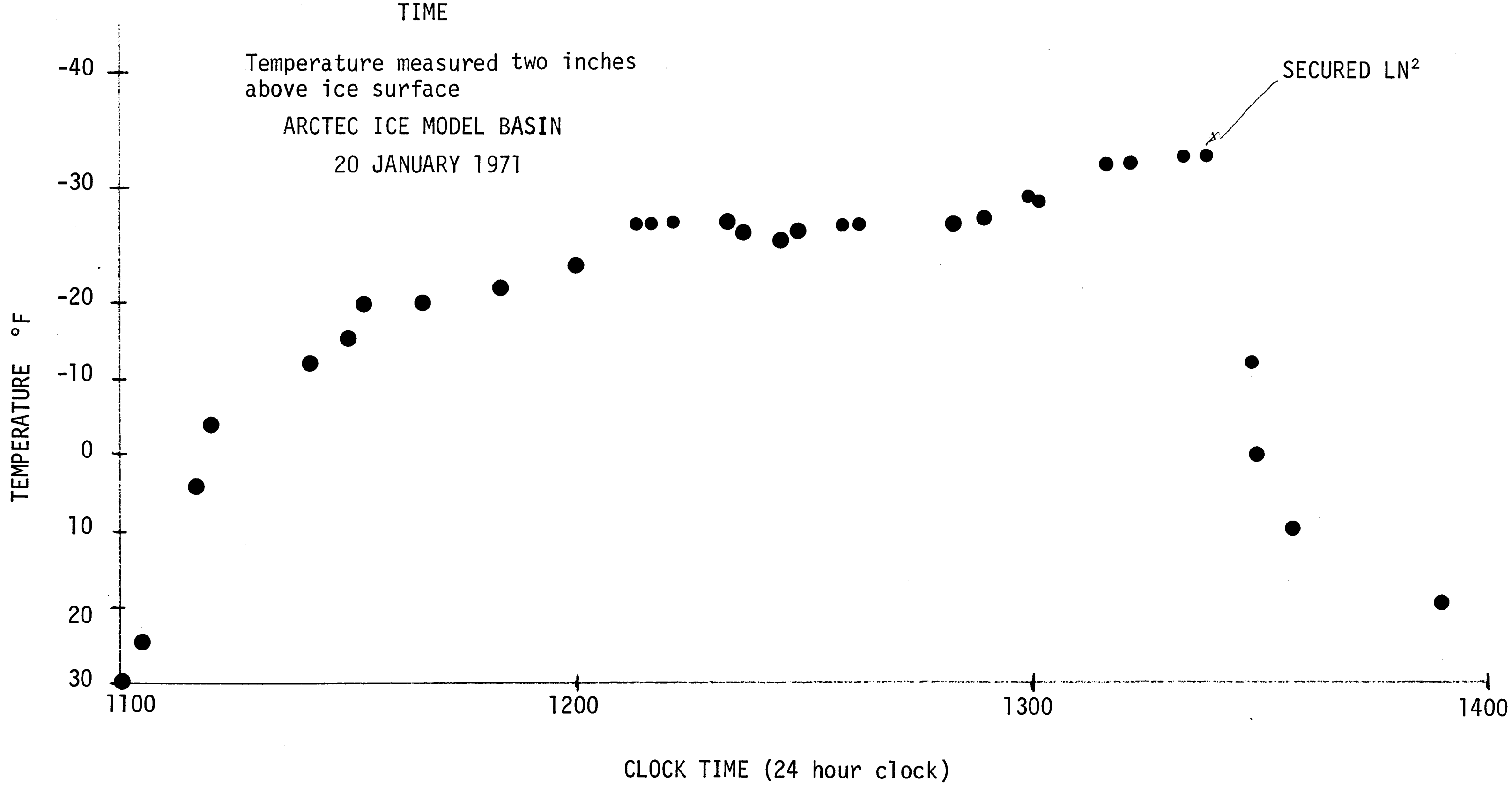
VS

TIME

Temperature measured two inches above ice surface

ARCTEC ICE MODEL BASIN

20 JANUARY 1971



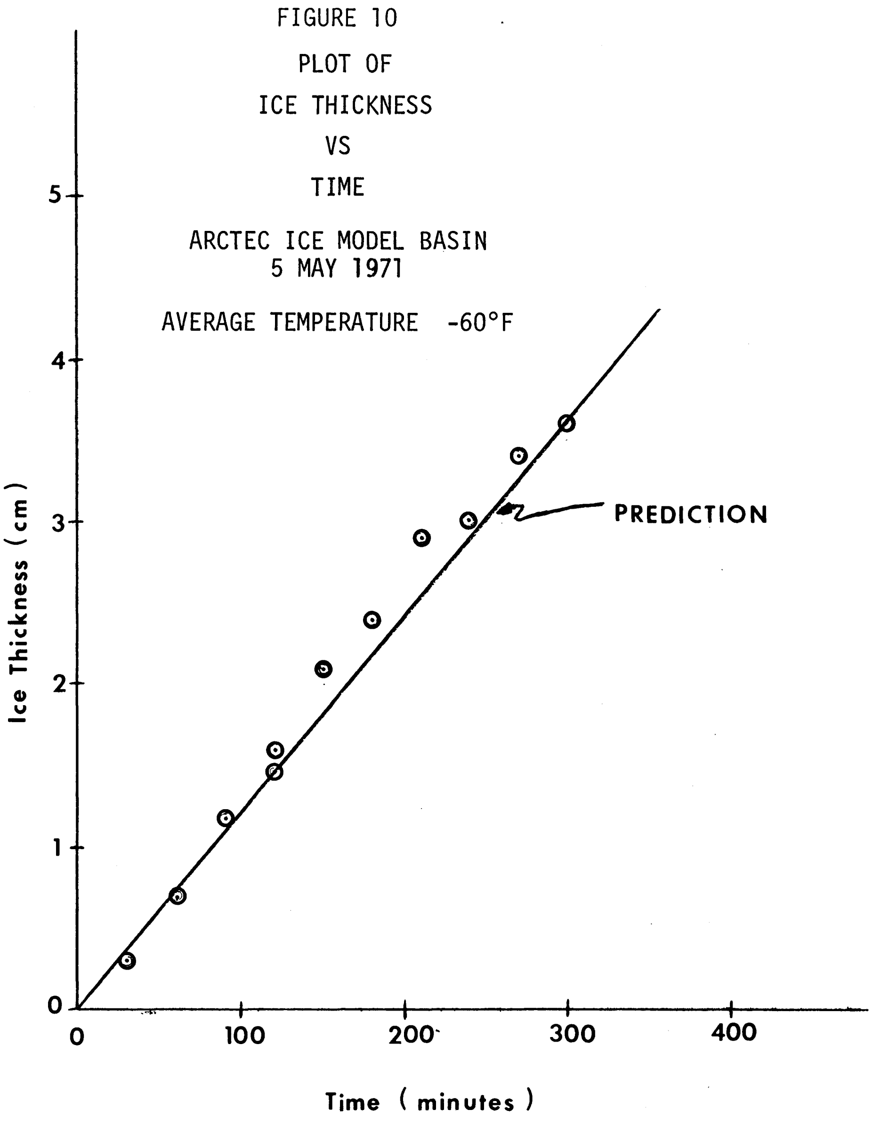


FIGURE 10
PLOT OF
ICE THICKNESS
VS
TIME
ARCTEC ICE MODEL BASIN
5 MAY 1971
AVERAGE TEMPERATURE -60°F
PREDICTION
Ice Thickness (cm)
0
1
2
3
4
5
0
100
200
300
400
Time (minutes)

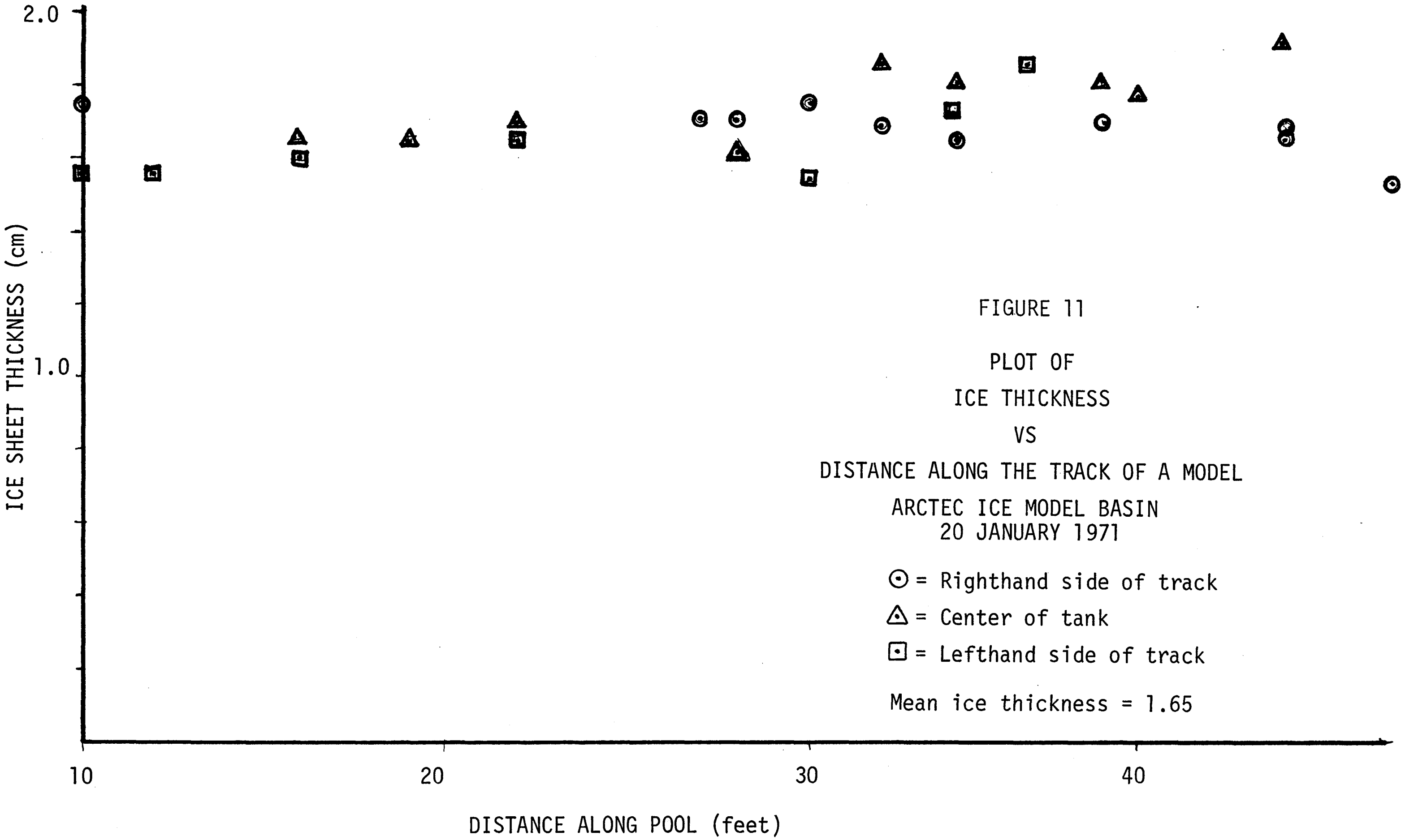


FIGURE 11

PLOT OF
ICE THICKNESS
VS
DISTANCE ALONG THE TRACK OF A MODEL
ARCTEC ICE MODEL BASIN
20 JANUARY 1971

was flooded. In any case, tests to date indicate that resistance to ship motion is dependent upon mean ice thickness. Small thickness variations within the length do not affect mean towing force.

Tests of the WIND Class Model

A 1/36 scale model of the United States Coast Guard's WIND Class Icebreaker was tested in the ARCTEC Ice Model Basin. Figure 8 shows one of the tests in progress. The results indicated that the model experiments could be used to predict the icebreaking capability of the full scale ship with acceptable accuracy. Figure 12 shows the ARCTEC data superimposed on a plot of data obtained at the Naval Undersea Research and Development Center during experiments conducted by the authors for the United States Coast Guard in 1969. The regression line shown in Figure 12 is the result of exhaustive full scale tests of a WIND Class icebreaker (1) and (3). Agreement between ARCTEC model test results and full scale results is relatively good.

Arctic Drilling Rig

Following the tests of the WIND Class, a model of an arctic drilling rig was tested in the model basin. The purpose of these tests was to determine the feasibility of obtaining meaningful data for the design of buoyant offshore drilling rigs. The principal tests which were run were:

a. Towing the platform behind an icebreaker with a beam narrower than the beam of the drilling rig
b. Towing the rig in unbroken ice to simulate movement of the ice filed against the rig
c. Towing the rig in its own broken channel

Figure 13 shows ice resistance tests of the drill hull underway in the ARCTEC Ice Model Basin.

Tests of a Thermal Positioned Air Cushioned Transporter

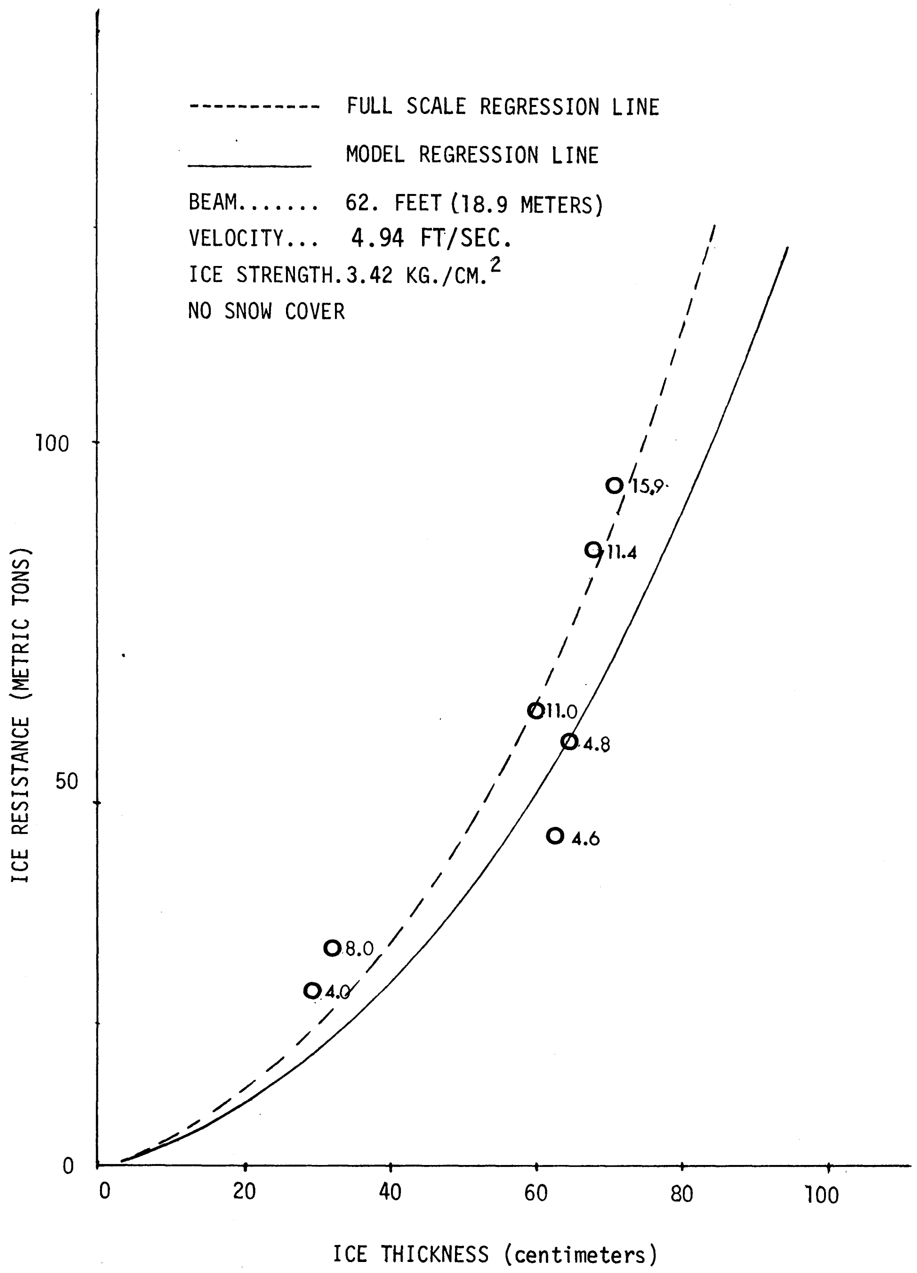
In May 1971, ARCTEC completed a series of model tests of Arctic Engineers and Constructors' unique Air Cushioned Transporter (ACT). The vehicle was designed to provide drilling and construction services in the Arctic on a year round basis. The model test program, which consisted of mathematical as well as experimental modeling, was primarily aimed at evaluating thermal positioning systems for maintaining the drill version of the ACT on station during movement of the ice fields. Figure 14 shows the ACT being prepared for tests in the ARCTEC Ice Model Basin.

CONCLUSION

The preliminary research prior to construction of the ARCTEC Ice Model Basin and the eight months of operating experience since the basin's completion suggest that it is technically and economically feasible to model the interaction between ships, structures, and ice cover. The implementation of the liquid nitrogen Ice Formation System, which was conceived of and developed by the authors is the most significant step in providing economical model testing in ice. We

FIGURE 12

PLOT OF WIND CLASS MODEL AND FULL SCALE DIMENSIONLESS REGRESSION EQUATIONS IN FULL SCALE UNITS WITH AIMB MODEL DATA SUPERIMPOSED (VELOCITY SUBSCRIPT)



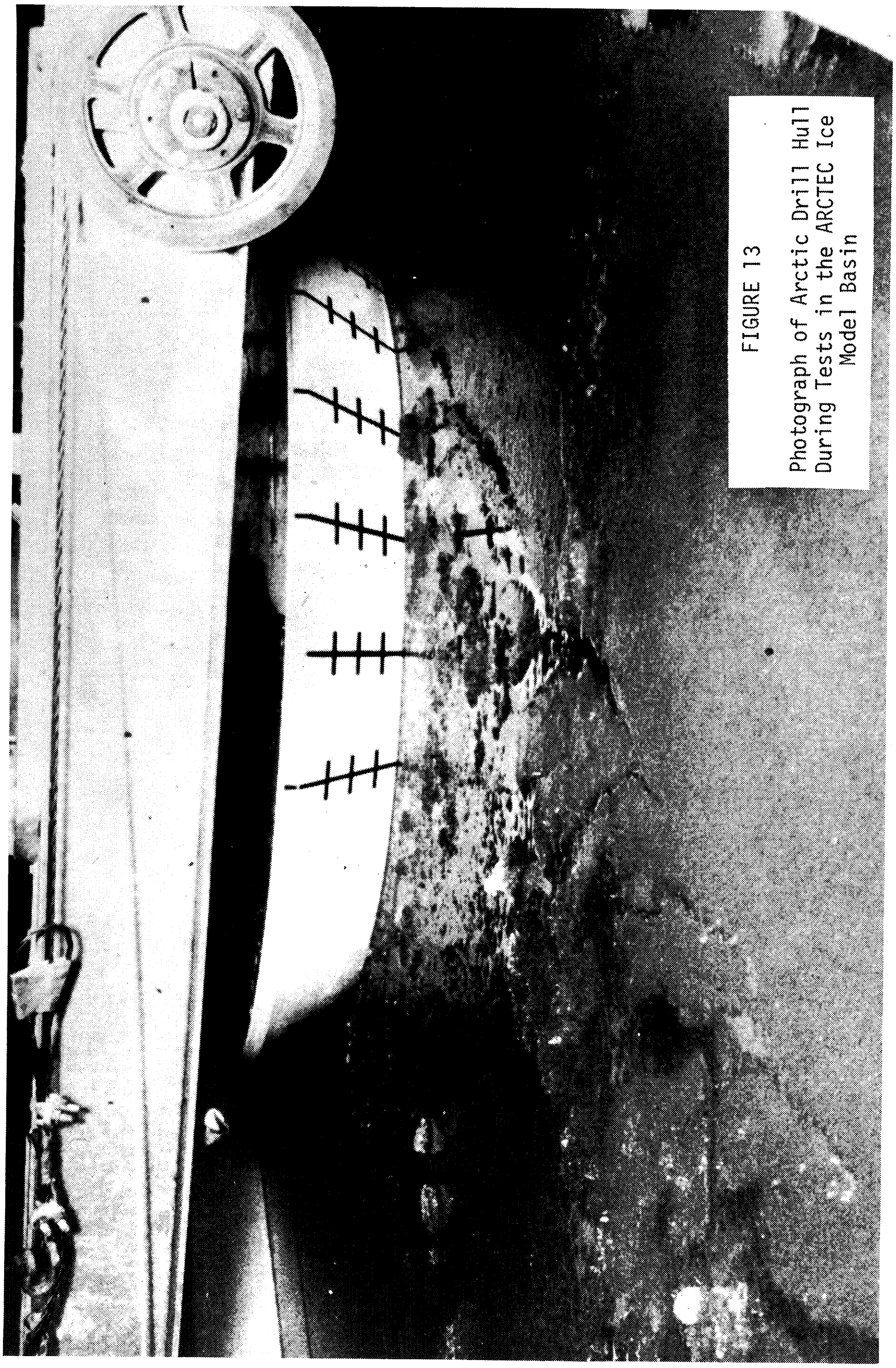


FIGURE 13

Photograph of Arctic Drill Hull During Tests in the ARCTEC Ice Model Basin

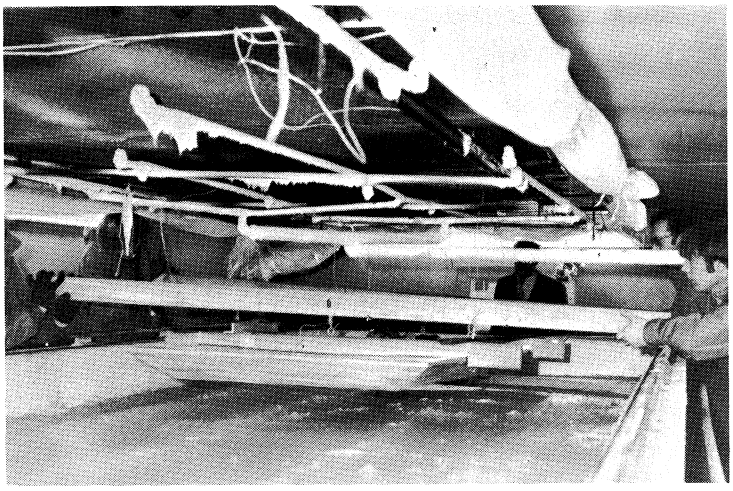


FIGURE 14

Model of ACT Being Lowered Into
the Ice Model Basin.

have found in the past few months that up to three ice sheets per day can be produced which are suitable for model tests with a 1/36 scale model. Not only does the high ice growth rate provided by this system permit rapid acquisition of data, it also causes the formation of the extremely fine grained, high salinity ice necessary for model tests.

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