To the Graduate Council:

I am submitting herewith a thesis written by Ernest H. Hudgins entitled "Frost and Ice Formation in the Air Convection Pile Permafrost Protection Device." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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The Graduate School

FROST AND ICE FORMATION IN THE AIR CONVECTION PILE PERMAFROST PROTECTION DEVICE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ernest H. Hudgins

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ABSTRACT

The problem under investigation is the frost and ice formation in a permafrost protection device, the air convection pile. The air convection pile is an open system device which utilizes the bouyant force of warm air to subcool and refreeze the permafrost. Permafrost is a moist, unconsolidated soil in which a portion of the soil thaws during the summer and refreezes during winter. The air convection pile is composed of two tubes and a head. The outer tube is embedded in the permafrost and can serve as part of the support of the structure. The inner tube is mounted concentrically with the outer tube and is shorter than the outer tube to provide a flow path. The head provides support for the inner tube and prevents animals and the elements from entering the pile. In the winter the air in the annulus existing between the two tubes is warmer than the ambient air and rises up the annulus. The cold ambient air is drawn in through the inner tube to be heated in the annulus. This flow of cold air refreezes and subcools the permafrost. In the summer the pile should remain inactive. However, frost and ice can form on the outer pile wall surfaces. This research was an experimental study to determine: (1) the severity and cause of the ice, (2) its effects on the winter operation of the pile, and (3) a method of stopping the ice from forming.

Tests indicated that a significant moisture concentration gradient existed in the annulus of the pile. This gradient indicated that the ice was forming by diffusion.

Profiles taken of ice established that the ice accumulation present in the annulus would not be sufficient to block the annulus. However, if wind induced flow proves to be a problem, a sufficient ice mass to cause blockage of the annulus could form. Tests showed that if a large ice mass forms, as long as it did not completely close the annulus, the ice would not stop the start up of the pile. Calculations showed that a large ice mass would sublimate out of the pile.

Test results showed that the amount of ice formed was independent of humidity ratio but did depend on the geometry of the pile; as the distance from the annulus outlet to the permafrost is increased the rate of ice formation is decreased. Test results established that the ice formation could be stopped by installing a bladder containing a low boiling point fluid in the annulus of the pile.

The air convection pile is for a number of reasons an attractive alternative as a permafrost protection device. However, wind induced flow could result in failure of the pile due to the increases in ice formation.

Future studies should address the development of an analytical model of the ice formation to verify the experimental results.

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NOMENCLATURE

A	Surface Area of Ice
Area	Area of Element
C	Mass Concentration
Cp	Specific Heat at Constant Pressure
D	Diffusion Coefficient
Dh	Hydraulic Diameter
Gr	Grashof Number
H	Height of Element
h	Convective Heat Transfer Coefficient
hD	Convective Mass Transfer Coefficient
K	Thermal Conductivity
L	Neck Length
l	Length of Ice Mass
M	Number of Trapezoidal Elements
m	Mass
m	Mass Flow Rate
Nu	Nusselt Number
P	Pressure
Pr	Prandtl Number
Q	Heat Transfer Rate
R	Gas Constant for Water Vapor
Re	Reynolds Number
RH	Percent Relative Humidity
Ri	Radius of the Outer Surface of Ice Mass
S	Sum of the Volume of Each Trapezoidal Elements

Sc	Schmidt Number
Sum	Sum of the Areas of Each Trapezoidal Elements
T	Ice Thickness
Tmax	Annulus Thickness
U	Velocity of Air Stream Across Ice
VOL	Volume of Element
W	Width of Element
X	Distance from Support Wall
X(M)	Axial Coordinate of Trapezoidal Element
Y	Distance from Annulus Outlet
YBAR	Centroid of Element
Y(M)	Vertical Coordinate of Trapezoidal Element
Yment	Moment of Inertia of Element

GREEK SYMBOLS

β	Coefficient of Thermal Expansion
θ	Temperature
μ	Viscosity
ρ	Density of Air
τ	Time Required for Ice Mass to Completely Sublimate out of the Pile
ω	Humidity Ratio
$\bar{\omega}$	Average Humidity Ratio

SUBSCRIPTS

A	Annular
D	Based on Diameter
f	Average Film Conditions
i	Ice
S	Sublimation
Sat	Saturation Conditions
W	Ice Surface Water Vapor Conditions
∞	Air Stream Water Vapor Conditions

CHAPTER I

INTRODUCTION

Today few regions are as challenging to man as the arctic. Not only is this region plagued with extreme cold, but the terrain itself is unyielding. A large portion of this terrain is composed of a soil known as permafrost, which has been in a delicate thermal balance for thousands of years. The permafrost may extend to depths of several hundred feet. It is composed of a top layer that melts in summer and refreezes during winter. The depth of the active layer varies from a few inches to several feet. During the summer, the permafrost is covered by vegetation which provides a natural thermal insulation for the permafrost.

Heavy equipment associated with construction projects disturbs this vegetation and compacts the soil. This destruction causes the depth of the active layer to increase from year to year, and after a period of time may not completely refreeze creating a thawed zone. This leads to unacceptable weakening of foundations and deterioration of roads. This problem must be taken into account to insure the reliability and safety of construction projects.

An example where permafrost deterioration must be considered is in the construction of roads, buildings, and pipelines in parts of Alaska. A recent example of where the permafrost protection was important was the Trans-Alaska Pipeline. The pipeline had to be elevated over about one half its length due to the permafrost. The anticipated vegetation destruction associated with the construction of the pipeline and the building of the parallel roadway forced the use of permafrost protection devices.

To protect the permafrost either an active or passive system can be used. In an active system a coolant is circulated through piping in the permafrost. However, such systems are expensive to install, operate, and maintain. Passive systems (thermosyphons) utilize the effects of natural convection or phase change produced during the winter when the permafrost is warmer than ambient to cause circulation in a vertical pipe. There are three primary types of permafrost thermosyphons. These are (1) heat pipes, (2) liquid circulation tubes, and (3) the air convection pile. Studies conducted on these devices have shown that they will provide the necessary permafrost protection (1).

The heat pipe consists of a tube extending into the ground with a vertical fin radiator attached. The tube is filled with a low boiling point fluid which is charged to a pressure such that it boils in the range of 20 to 25°F. Heat from the permafrost causes the fluid in the below ground section to boil; the vapor rises in the tube and condenses in the above-ground radiator section where the heat is then rejected to the atmosphere. The heat pipe itself is capable of transporting large amounts of heat. However, in an installed pipe, the flow of heat is controlled by the thermal resistance associated with the permafrost and the rejection of heat to the atmosphere. Therefore, the permafrost cooling with the installed heat pipe is only marginally greater than of the other devices (2). There is also a concern that the life of the heat pipes would be less than that of the structure (3).

Liquid circulation tubes are somewhat similar to the heat pipe, except that they are larger in diameter, and the fluid remains a liquid (4).

The air convection pile, which is the topic of this thesis, is a passive, open system which utilizes the buoyant force of warm air at the base of the pile to circulate cold ambient air through the pile. The resultant heat transfer causes the permafrost to refreeze and subcool during the winter to stabilize and add extra heat absorbing capacity for the summer. This extra capacity for absorbing heat will tend to offset any additional melting caused by a surface disturbance. The air convection pile has several advantages over the other permafrost protection devices. These are: the piles are not susceptible to vandalism, they are cheaper, easier to construct and install, and provide a direct exchange of heat with the surroundings.

The basic parts of the air convection pile (Figure 1) are the head, the inner tube, and the support pile. The support pile provides the support for the above-ground structure. It is usually 45.75 cm (18 in) in diameter and is installed in the permafrost to a depth of 3 to 18 meters (10 to 60 ft). Inside the support pile, a thin 25.4 cm (10 in) diameter tube is suspended concentric with the support pile. This tube is usually 15 to 30 cm (6 to 12 in) from the bottom of the pile to provide a passage for flow. The head provides the support for the tube

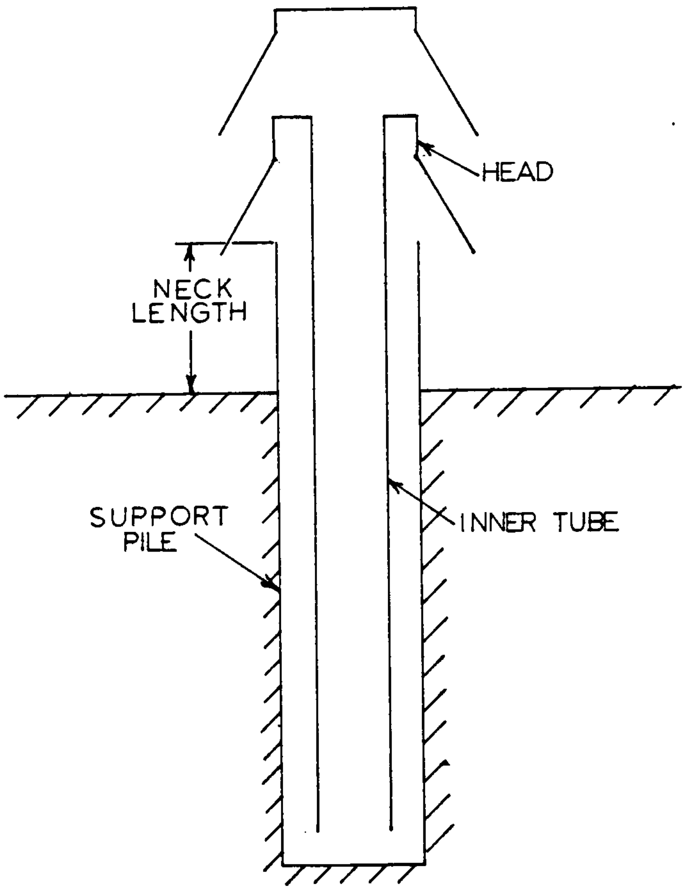

Figure 1. The Air Convection Pile

and separates the inlet of the tube from the outlet of the annulus and keeps the elements and animals out of the pile.

In the winter, as shown in Figure 2, the air in the pile is warmer than the outside air. This air tends to flow up the annulus while the colder ambient air enters through the tube inlet. This flow of air and resultant heat transfer refreezes and subcools the permafrost. The overall heat removal rates have been reported by Jahns, et al. (5). The flow of air through the pile will continue as long as the ambient temperature is lower than the permafrost temperature of -1 to -4°C (30 to 26°F) (3). Therefore, in the summer the air in the pile is no longer warmer than the outside air and the pile shuts itself off. During this period of time the pile is filled with cold dormant air (Figure 3). A concern with the air convection pile has been that the moisture in the dormant air mass would freeze out on to the inside of the support pile. It was postulated that the ice could bridge the annulus of the pile, as shown in Figure 4, and prevent or delay the start-up of the pile the next winter (5). Therefore, this study was undertaken to determine the degree of frost and ice formation in the annulus of the pile under arctic conditions and to obtain a method or methods to reduce or stop the ice formation.

Another potential problem with the air convection pile during the summer is that surface winds might create small pressure disturbances in the vicinity of the head and cause warm air to flow through the pile (6). This wind effect is being investigated in another experimental pile where the fluid dynamics and heat transfer characteristics of the

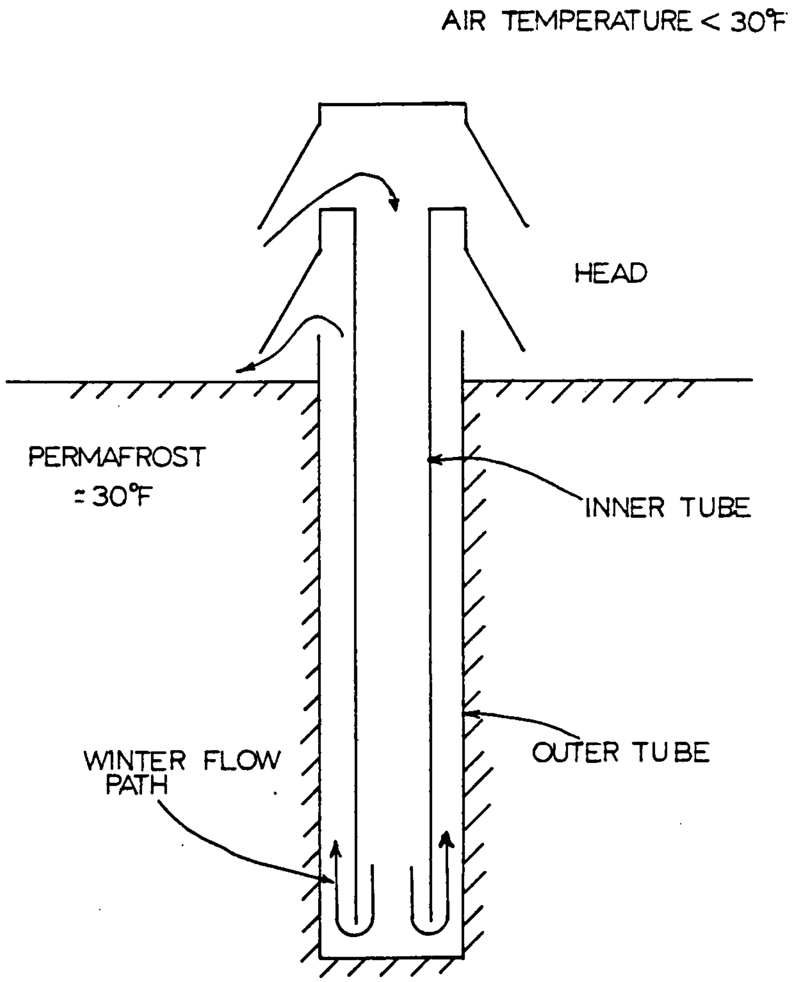

Figure 2. Air Convection Pile During Winter and Winter Flow Path

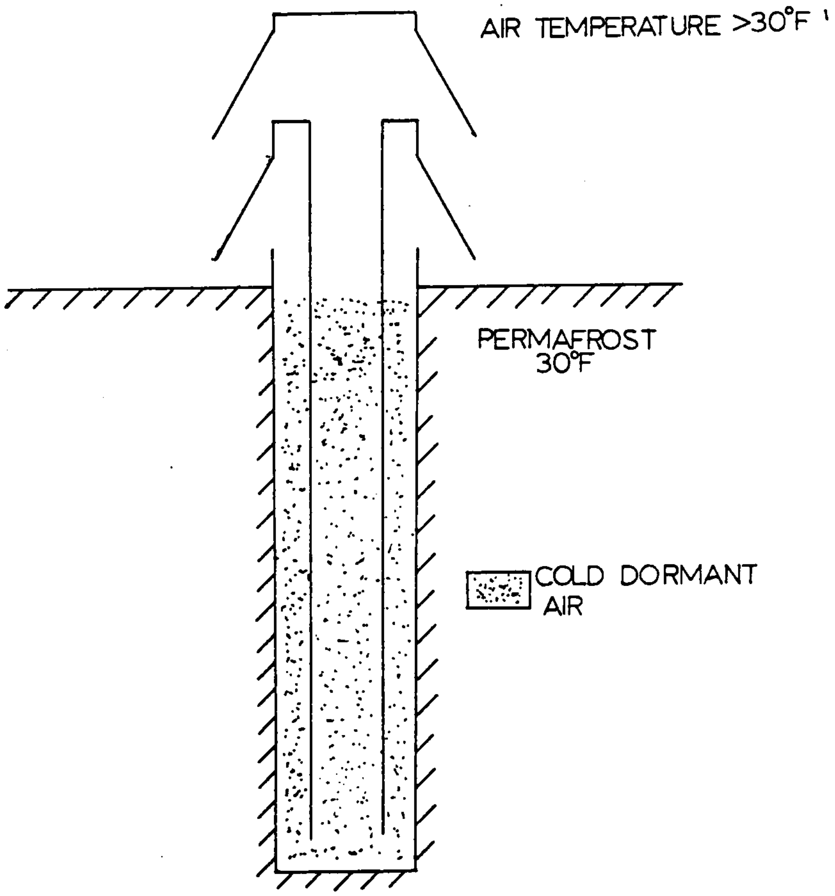

Figure 3. Air Convection Pile During Summer

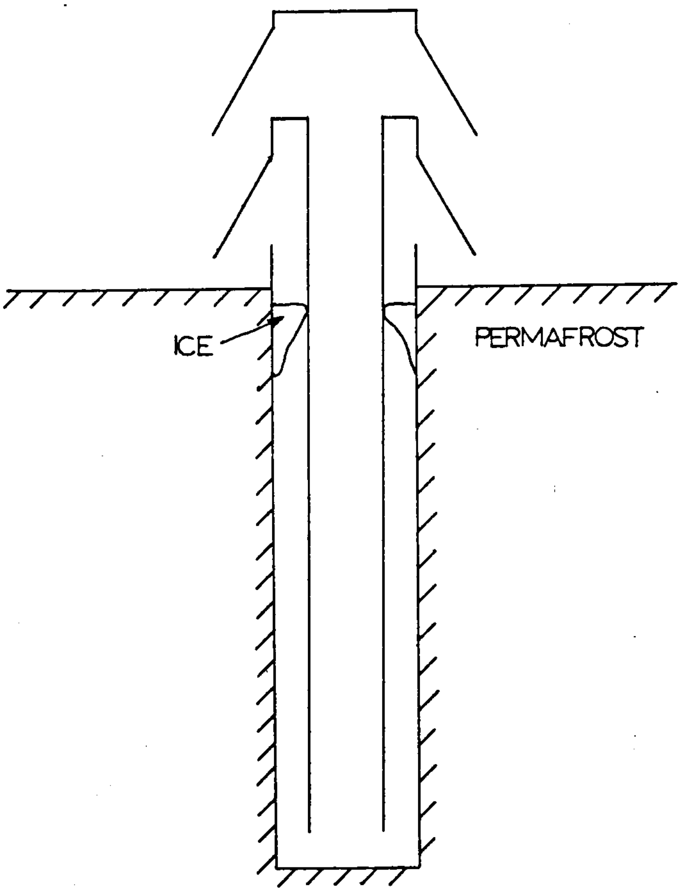

Figure 4. Failure of Air Convection Pile Due to Ice Blockage

device during winter operation. This study is being conducted by Evans (7).

Purpose and Objectives

The purpose of this thesis was to accurately experimentally investigate the frost and ice formation in an air convection pile for various arctic environmental conductions and for various pile geometries.

The preliminary objectives of the study were to determine:

- Degree of ice formation
- Cause of the ice formations
- Effects of arctic environment and pile geometry on ice formation
- Effects of the ice on pile operation
- Methods of preventing ice build-up.

CHAPTER II

REVIEW OF PREVIOUS WORK

A review of previous work yielded only one paper in the area of frost and ice formation in an air convection pile (8). However, the study was primarily concerned with the design of test equipment to test the air convection during its winter operation. Results of a ten day test on the rate of ice formation are also given, but the validity of these results are questioned. The reasons for questioning the results are discussed in Chapter III, Equipment Modifications.

Literature indicated that attempts to analytically model the frost and ice formation would be extremely difficult since the properties of the frost and ice, thermal conductivity, density, and specific heat vary with the stage of formation of the frost and ice (9). To correctly solve such a problem is difficult and involves a similarity solution (10).

A model of frost and ice formation under natural convection could not be found. However, models do exist for frost formation under free stream conditions, e.g., frost formation on a heat exchanger surface. Typically, the accuracy of these models is no better than 20 percent (4, 11).

A literature search was conducted to obtain literature related to frost and ice formation by condensation and by diffusion. Several articles were found on the effects of frost and ice formation on heat transfer rates. However, few papers could be found on the cause of frost and ice formation. The literature on condensation indicated that condensation occurs at specific nucleation sites and that it may be promoted on certain surfaces such as Teflon (1, 12). Literature indicated that large temperature differences between the ambient air and the frosting surface and a high humidity ratio are conducive to heavy frost formation (13, 14, 15).

A literature review of papers yielded several interesting papers on sublimation of ice. However, all of the papers dealt with the freeze drying of foods under a vacuum. No papers on the sublimation of ice under atmospheric conditions could be found. However, several text books were found dealing with sublimation (16, 17).

CHAPTER III

TEST EQUIPMENT

Data were taken on a 3.05 m (10 ft) air convection pile with a 45.7 cm (18 in) ice support pile and a 25.4 cm (10 in) diameter inner tube. These tube sizes created a concentric 10.2 cm (4 in) annulus. The pile and an environmental chamber were designed and constructed by Onufer (18). The pile is constructed of galvanized ducting and sheets. The simulated below ground section is wrapped with 1.25 cm (0.5 in) diameter copper tubing soldered at a 3.08 cm (2 in) core spacing. The below ground section is insulated by a box made of 3.08 cm (2 in) thick polystyrene and is supported by a frame made of 2.54 X 2.54 cm (1 X 1 in) angle iron. The environmental chamber is made of 1.6 cm (5/8 in) exterior plywood and insulated with layers of 3.08 cm (2 in) thick polystyrene. The heating load to the chamber is supplied by flood lights and which also simulates some of the day time solar radiation. The cooling to the pile and chamber was furnished by a 5.3 kw (1.5 ton) chiller.

The chamber temperature and humidity were controlled by two sets of thermostats and humidistats and a series of relays. This configuration allows both the chamber temperature and humidity to be controlled as a function of time.

A detailed description of the initial design of the pile and test chamber may be found in Reference 8. Although much of the necessary equipment was already present, several modifications were made to the test equipment.

Equipment Modifications

A visual inspection and test of the system raised some questions on the validity of the results of a preliminary test done by Onufer. The inspection of the test equipment showed numerous air leaks into the simulated below ground section of the pile. A temperature difference of +6°C between the top and bottom of the pile wall was causing a natural convection flow inside the pile. The combination of the air leaks and the temperature gradient would increase the rate of ice formation due to the constant circulation of moist air across the ice.

These problems were rectified by seating the joints of ducting with a silicone caulk and by reversing the coolant outlet and inlet to the below ground section. By doing so, the lower sections of the pile were now colder than the sections above creating a stable air mass inside the pile.

A system of valves were added to allow the simulation of different neck lengths. As shown in Figure 5, the neck length is the distance from the annulus outlet to the permafrost. The neck length is an important parameter to consider since it depends on the application of the pile. Long neck lengths would be encountered in the building of overhead pipelines or roadways and over uneven terrain. Shorter neck length piles would be used in construction of buildings or surface roadways.

A view-port was added in the head of pile to allow photographs of the ice growth to be taken without disturbing air in the area of the ice.

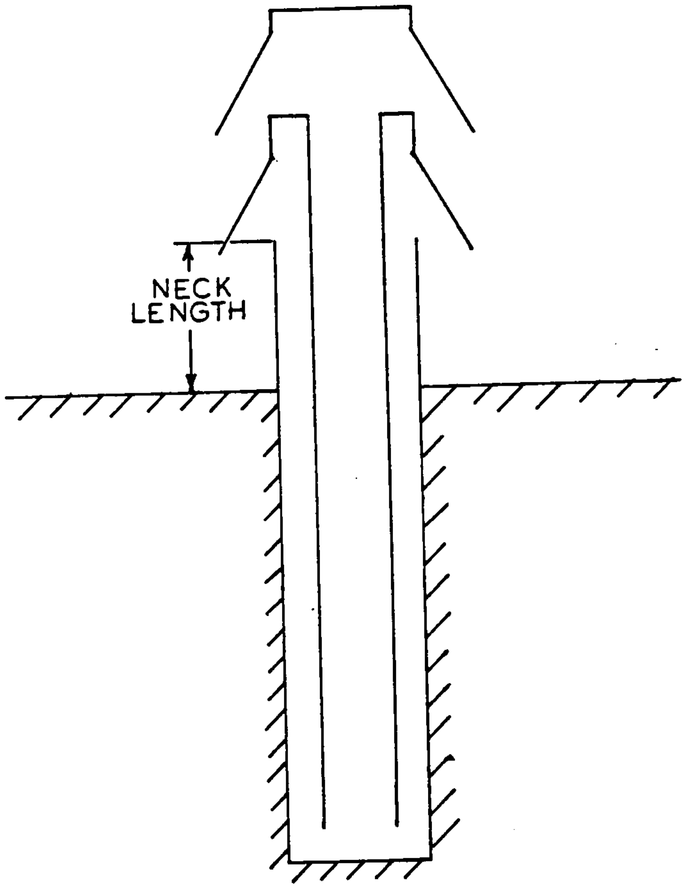

Figure 5. Pile Neck Length

The humidity trays were replaced with a small room vaporizer (Figure 6). The vaporizer provided safe trouble-free operation during all tests. The humidity trays failed quite often and created an electrical hazard.

Several additional pieces of equipment were installed to provide additional and more accurate data.

The humidity sensor was replaced with a hygrosensor and hygrometer indicator (Figure 7). The previous sensor was basically a wet and dry thermocouple with a small fan to pull air across two thermocouples. It was replaced due to erroneous and erratic readings when checked against a Bendix Psychrometer. The temperature difference between the two devices would result in a percent difference of 0 to 100 percent for the resulting relative humidities. A reason for such a wide range of error can be attributed to minor displacements of the wick and thermocouple bead (18).

The 12 channel Westronic strip chart recorder was replaced with a Leed and Northrup Trendscan 1000 data acquisition system (Figure 8). The Trendscan provided direct time of day readings of all thermocouples and milivolt output devices. The Trendscan also provided extra capacity for thermocouples and devices with mV outputs.

The profilometer was modified to improve its accuracy. The profilometer was attached to a track mounted on the inner tube wall as shown in Figure 9. Initially, the profilometer was held to the inner tube by magnetic shoes on the profilometer. Each time a profile of the ice was taken the profilometer could follow a different path over the

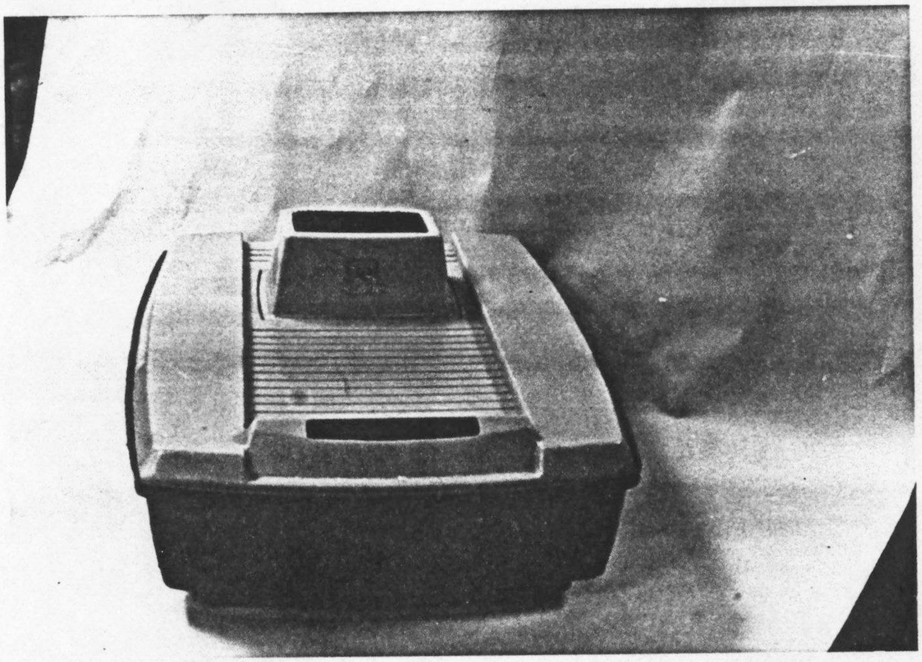

Figure 6. Vaporizer

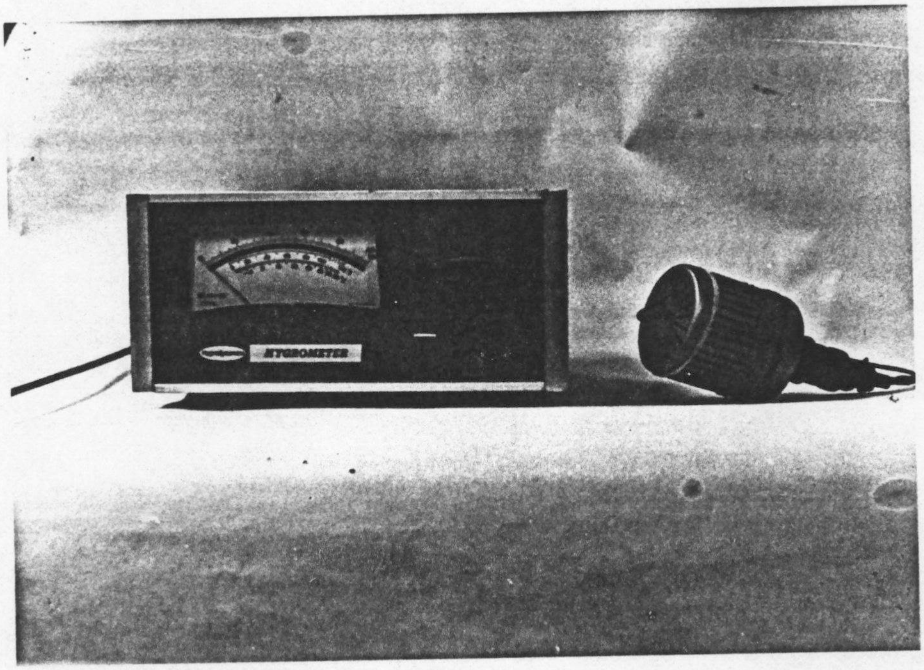

Figure 7. Hygrometer and Hygrosensor

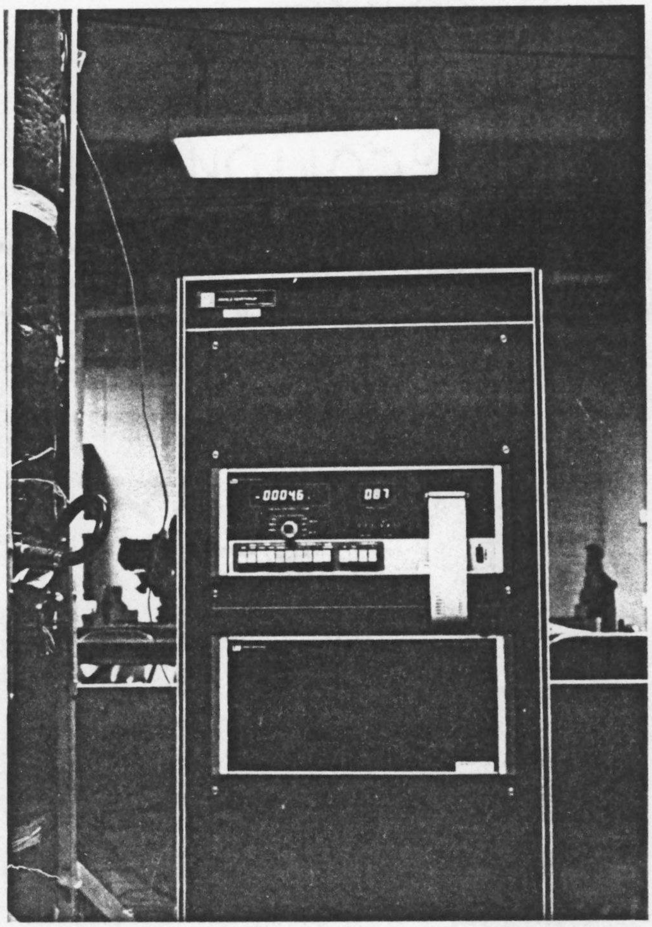

Figure 8. Trendscan Data Acquisition System

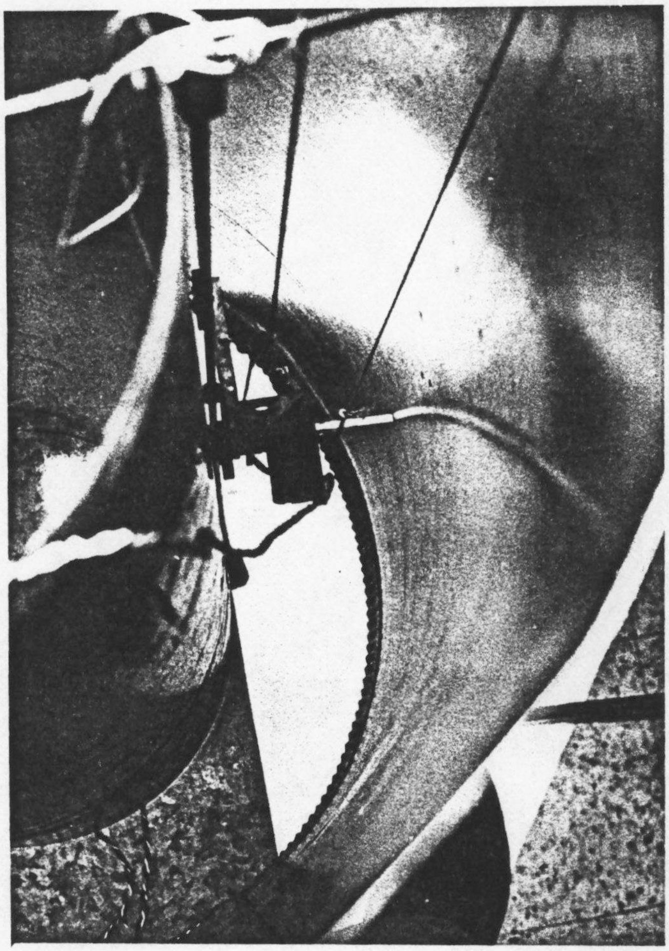

Figure 9. Profilometer

ice. The magnetic shoes were soon not strong enough to hold the device to the inner wall and would allow the profilometer to pull away from the inner tube wall. By placing the profilometer on a track allowed it to follow the same path each time a profile was taken and prevented the profilometer from pulling away from the inner tube. The track also proved a definite reference point for use in reducing ice profiles for input to a computer program to calculate the ice volume. The resistors on the profilometer were waterproofed to prevent them from shorting out and producing erratic readings. However, this modification was not made until the end of the first test, Test 1. A battery which was used to power the profilometer was replaced with a regulated power supply to ensure accurate profiles.

The modified test chamber is shown in Figure 10.

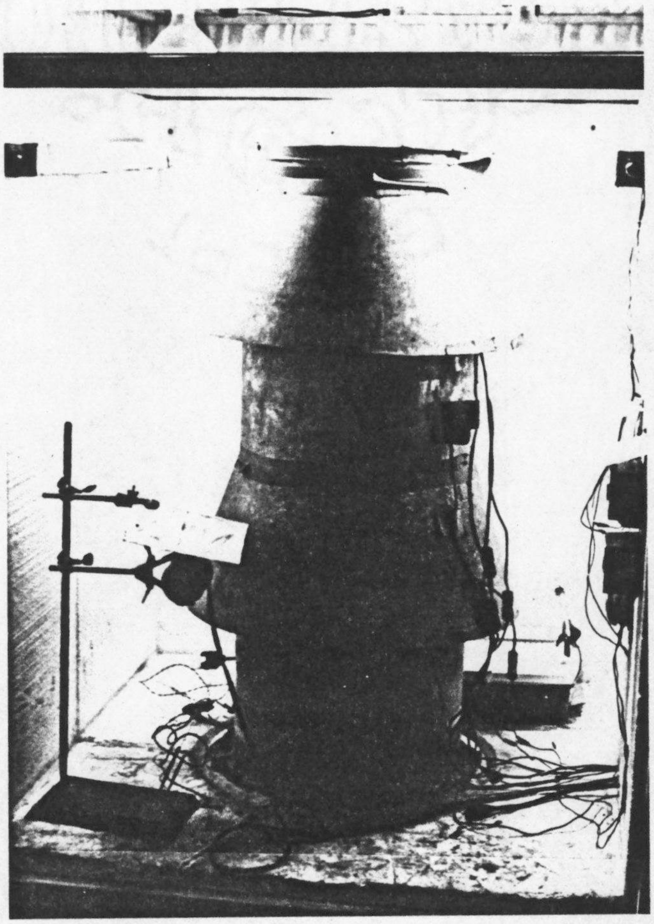

Figure 10. Modified Test Chamber

CHAPTER IV

DESCRIPTION OF TESTS

Tests were conducted on the air convection pile with the objective of determining the answers to the following questions:

- By what mechanism is the ice forming?
- How is the rate of ice formation affected by the arctic environment?
- How does the pile geometry affect the ice formation rate?
- How will an ice mass affect the winter operation of the pile?
- How can the formation of the ice be stopped or slowed?

Preliminary Tests

Preliminary tests were performed to determine how the ice was forming. Two mechanisms for the ice formation were postulated. The ice could form by moisture condensing on the inside surfaces of the head, and the run off freezing when reaching the simulated below ground section. The alternate mechanism is by mass diffusion. That is, water vapor will diffuse due to a concentration gradient established by different humidity ratios in the head of the pile and in the vicinity of the ice.

To investigate the first mechanism, small troughs were made from plastic freezer bags (Figure 11) and were installed in the annulus of the pile at different levels as shown in Figure 12 to collect any condensate run off. If the ice was forming by condensate run off, water would collect in the troughs at levels above that of the ice

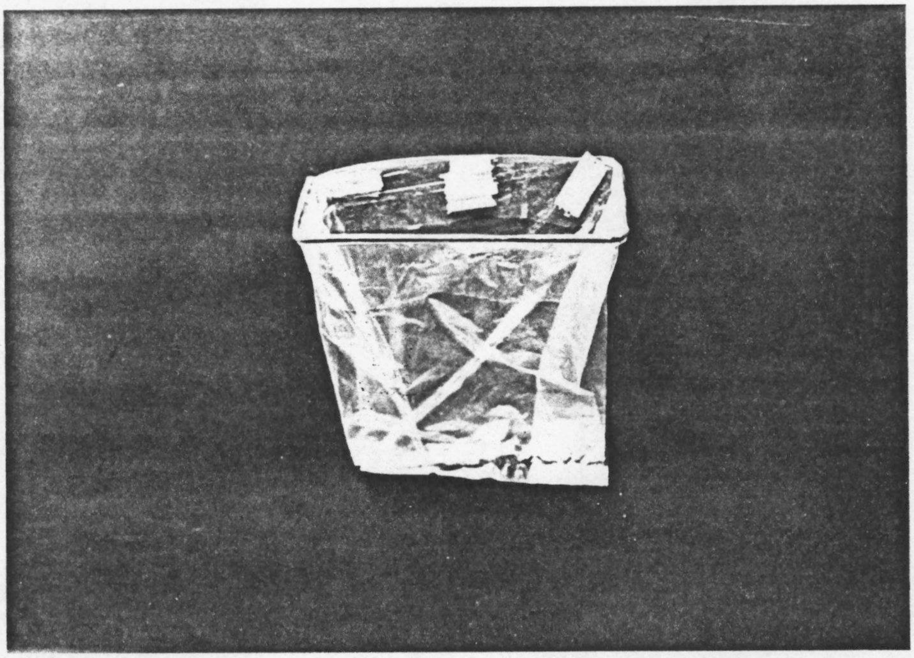

Figure 11. Condensation Troughs

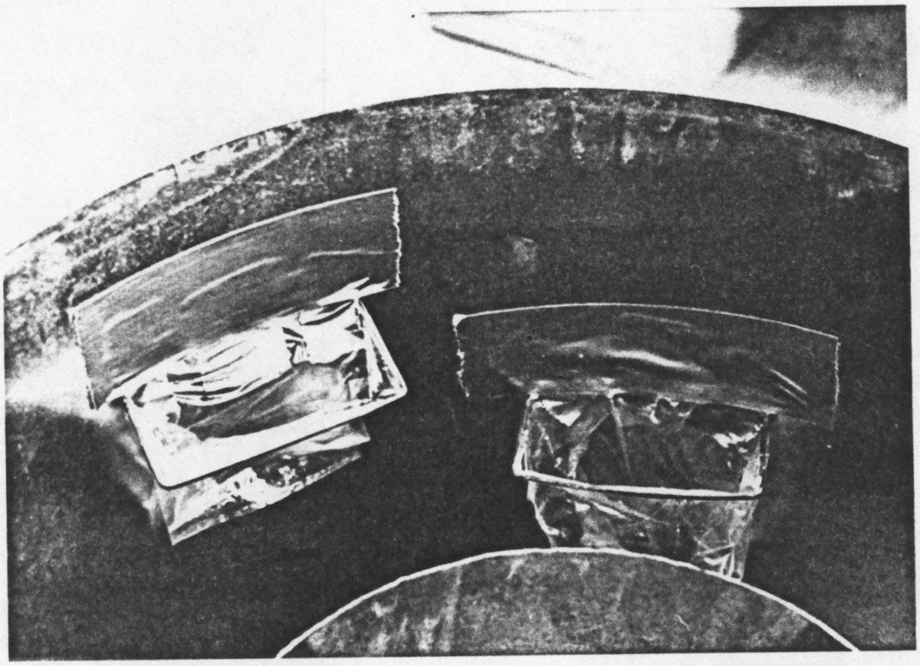

Figure 12. Condensation Troughs Installed in Pile

formation. If there were not any water present in the troughs, this would indicate that the ice was not forming by condensation and that the ice formation could not be controlled by the installation of drains in the head and support pile.

To investigate the second possible mechanism for ice formation, humidity traverses along the length of the annulus were made using the hygrosensor. If the ice were forming by diffusion, these tests would show a concentration gradient in the annulus of the pile.

Effects of Arctic Environment

The effects of arctic conditions on the rate of ice formation was investigated by operating a pile with an Omnidirectional Head and a 0.153 m (6 in) neck, as shown in Figure 13, under various simulated arctic conditions in the test chamber. Fairbanks, Alaska summer weather was selected as the typical arctic site. During the three months of summer weather temperature extremes range from highs in the nineties to lows in the thirties. The relative humidity can vary from 90 to 30 percent during a 24 hour period (19).

During the tests, the chamber temperature and humidity were the parameters which were controlled and the data were presented as a function of the time averaged chamber humidity ratio. Profiles of the ice were taken with the profilometer and the ice thickness and volume were calculated from these profiles. During a test, the pile wall, head, inner tube, annulus temperature, and humidity gradients were monitored and recorded. At the end of a test, photographs of the ice formation were made and its mass was determined by weighing the

Figure 13. Omnidirectional Head with 0.153m (0.5 ft) Neck

resulting water after the pile was thawed. A schematic of the test system is shown in Figure 14.

The effects of a wind induced flow on the rate of ice formation was investigated by placing a small fan in the head of the pile with 0.153 m (6 in) neck as shown in Figure 15. The fan circulated air down the inner tube and up the annulus. This flow path was chosen strictly due to the ease in mounting the fan. A speed controller was used to set the speed of the fan to obtain a velocity in the annulus of 22.8 meters per minute (75 ft/min), a velocity equivalent to that caused by a wind in excess of 32 kilometers per hour (20 mph). More information on the effects of wind induced circulation may be obtained from Reference 7.

Tests on the effects of the environment were somewhat limited due to the test equipment. The chiller's capacity was not large enough to maintain both the pile wall at -6°C and the chamber temperature below 14°C, which limited the range of conditions which could be modeled. Only certain humidity ratios could be duplicated since there was no practical and economical method of dehumidifying the test chamber. Therefore, the lower humidity ratio tests could be run only during the less humid winter months. During the tests on the effects of wind induced flow the chiller was unable to maintain a pile wall temperature below freezing due to the added load of the air circulating through the pile.

Effects of Ice on Pile Operation

It was of interest to determine what effects a large ice mass would have on the winter start up and steady state operation of the

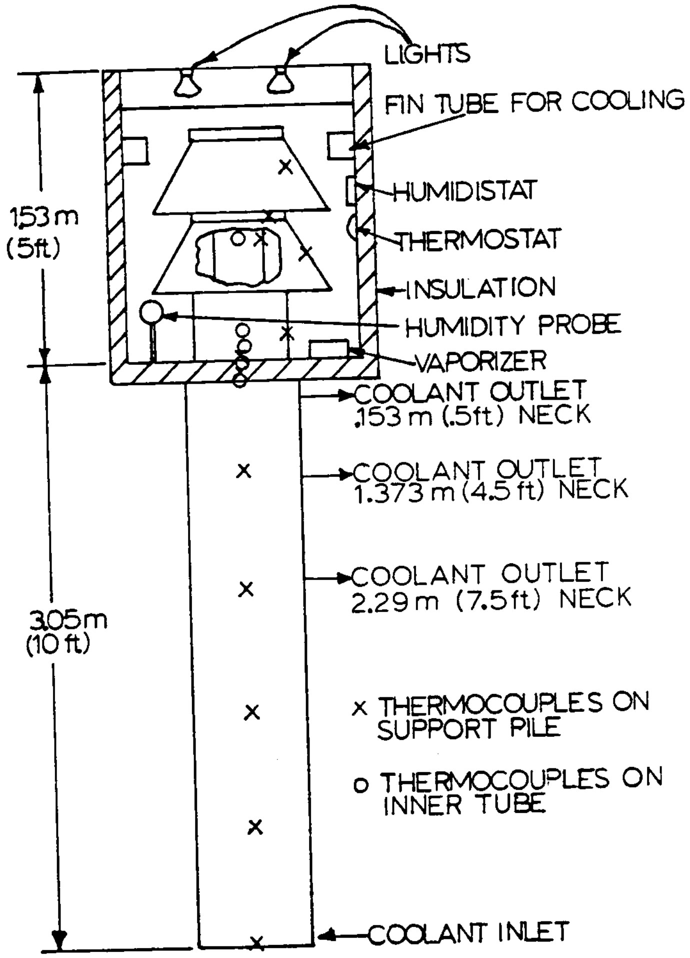

Figure 14. Experimental System

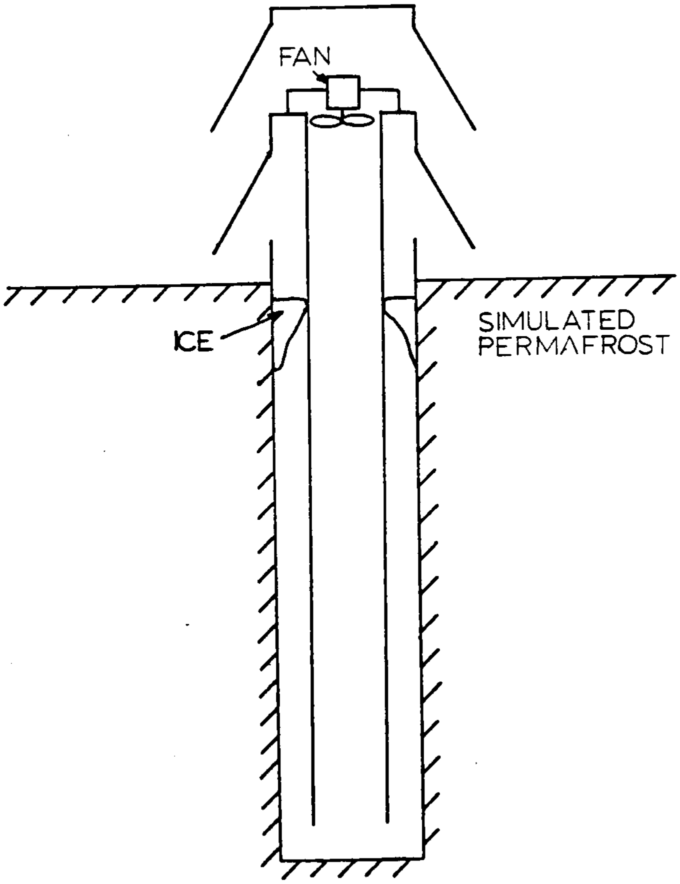

Figure 15. Summer Wind Induced Flow Test Set Up

device. For this test an inflatable torus was made (Figure 16) such that when inflated would simulate a mass of ice 9.5 cm (3.76 in) thick and extending 15 cm (6 in) into the pile. Such an ice mass would reduce the area for flow from 1100 cm^2 (175 in^2) to 52 cm^2 (8 in^2). The bag was installed in the upper annulus region of another test pile used to simulate winter operating conditions (7). A specially designed, low interference hot film anemometer probe and anemometer was used to measure the velocity of the air stream in the annulus below the ice. The center line velocity of the annulus was measured during start-up and after steady-state operation was reached, a velocity traverse of the annulus was made.

Effects of Pile Geometry

The effects of uncooled neck length on the rate of ice formation was determined by operating the pile under one set of arctic conditions for three different neck lengths. The same types of data were taken during these tests as with the tests on the effects of environmental conditions, except that ice profiles and photographs could not be made. A day-by-day set of ice profiles could not be made since the profilometer track was not designed for the longer neck lengths. Photographs of the ice were not made because of lighting problems and a telephoto lens was not available.

Test of the Vapor Bag

One possible solution to the ice problem is to seal the annulus of the pile during summer. A method which was developed was to install a

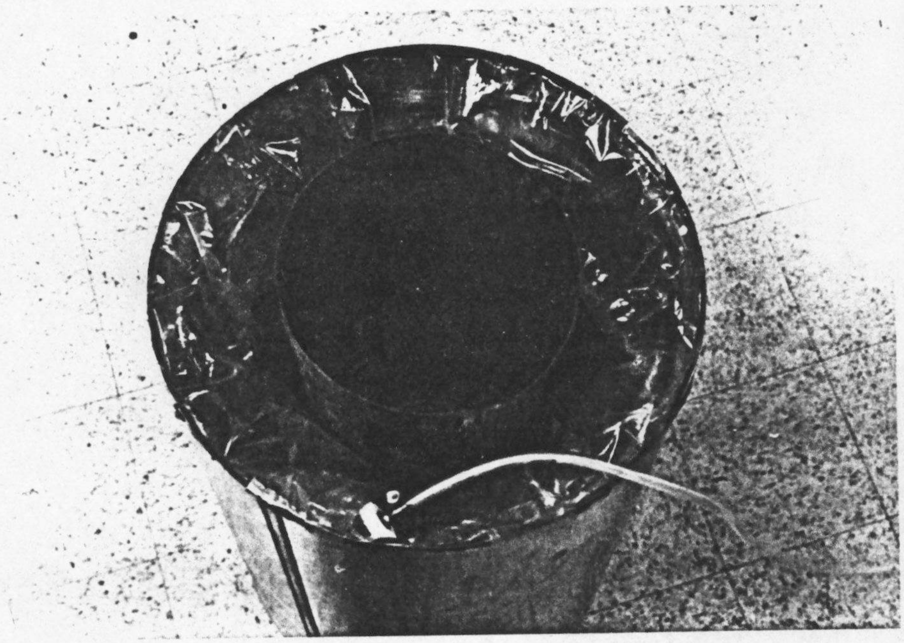

Figure 16. Simulated Ice Blockage

vapor inflated bag at the top of the annulus. A schematic of the system is shown in Figure 17. The bladder would be filled with a refrigerant, such as Refrigerant No. 114 or 21, which have boiling points of 3.5°C (38.4°F) and 8.9°C (48.1°F), respectively (20).

The vapor bag would operate as follows: As the summer temperatures approach the boiling point of the refrigerant, the refrigerant contained in the canister outside the pile would start to boil. As it boils, the bladder would be inflated, as shown in Figure 18. As long as the outside temperature remains above the boiling point of the refrigerant, the annulus will be sealed by the bladder, as shown in Figure 19. During the winter as the ambient temperature drops below the boiling point of the refrigerant, the refrigerant in the bladder will condense and drain back into the canister and the bladder will collapse to the side of the pile as in Figure 20.

To test the system, a vapor bag was made by heat sealing two plastic sheets together. The bag was attached to the outer pile wall with duct tape. Due to the expense of the refrigerants and the method of heat sealing of the bag, compressed air was used to inflate the bag during the test.

The effectiveness of the vapor bag was judged by observing the amount of ice forming on the pile wall through a view port below the vapor bag.

Due to the method of heat sealing used, it was impossible to test an vapor bag for more than 10 days before a leak developed in the bag.

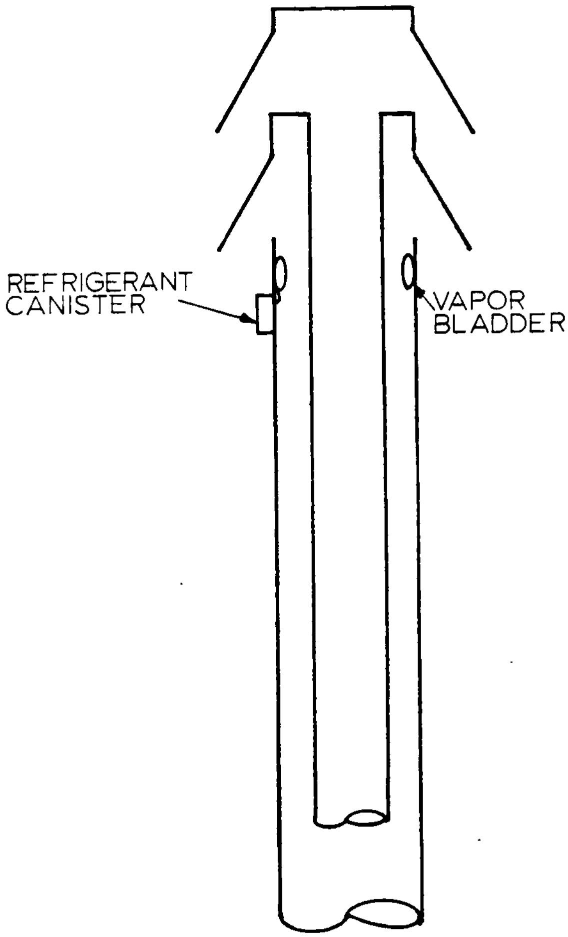

Figure 17. Schematic of Vapor Bag System

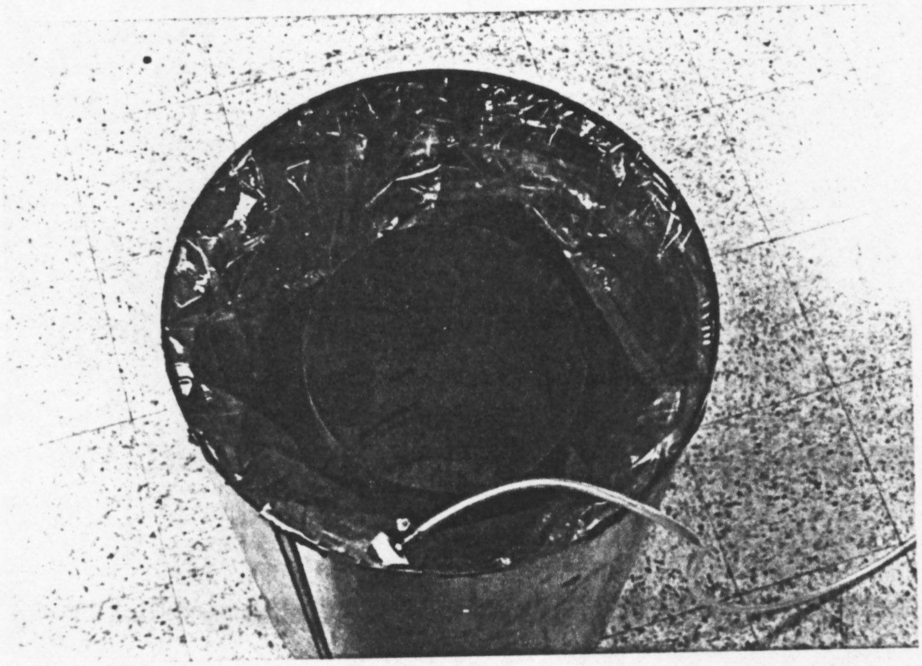

Figure 18. Vapor Bag as it Starts to Inflate

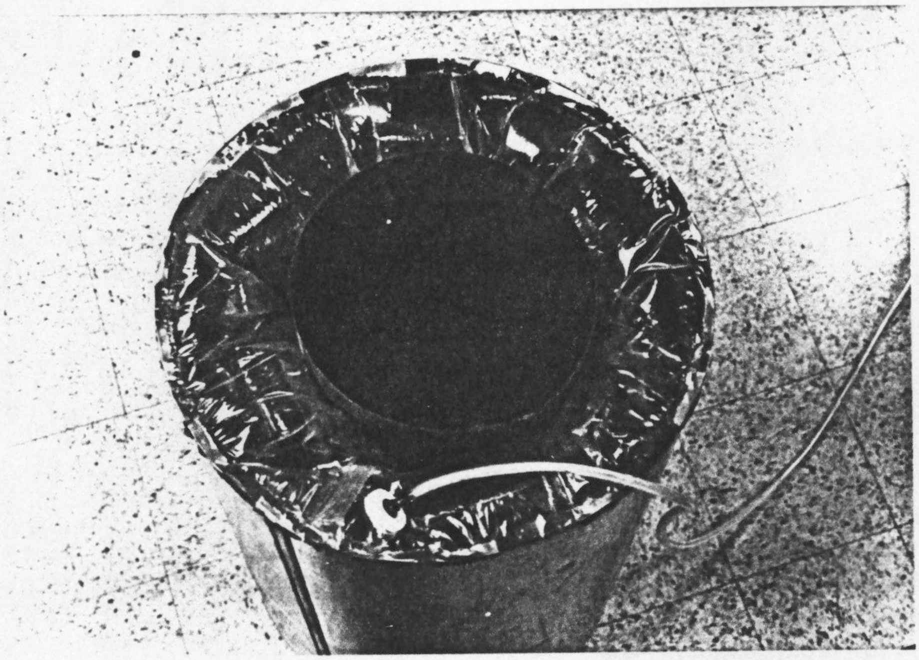

Figure 19. Fully Inflated Vapor Bag

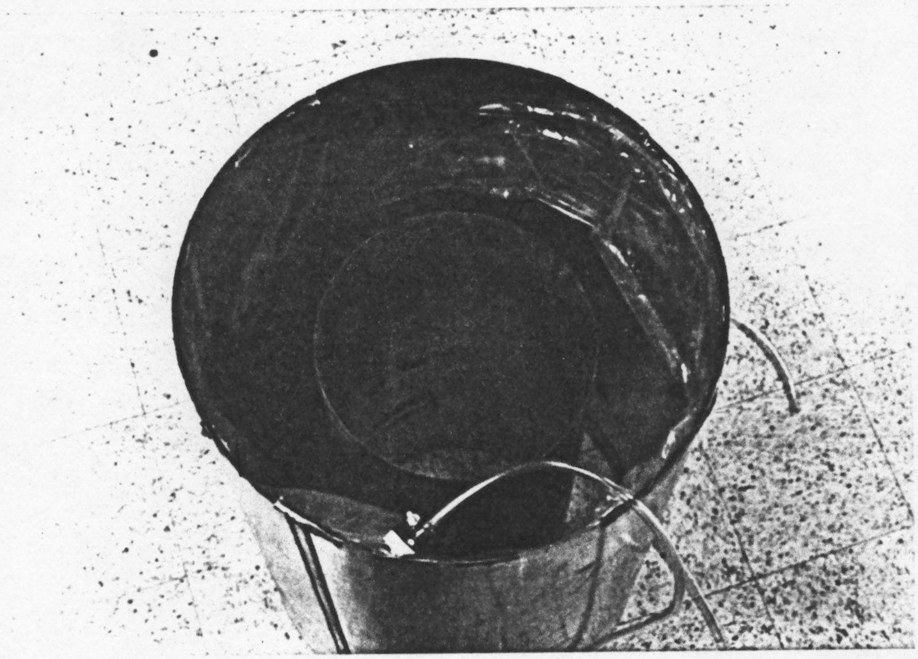

Figure 20. Uninflated Vapor Bag Installed in the Air Convection Pile

CHAPTER V

DATA ANALYSIS

During the testing of the air convection pile, data were taken in the following forms:

- Ice profiles
- Humidity traverses
- Chamber humidity profiles
- Chamber temperature profiles
- Pile wall temperature profiles
- Final ice mass
- Annulus velocity profiles
- Ice photographs

Ice profiles were taken of the outer pile wall at 24-hour intervals corresponding to the end of the cold periods in the environmental chamber. One ice profile every 24 hours proved to be sufficient since the ice was forming slowly. Taking only one ice profile daily also prevented unnecessary damage to the frost and ice surfaces.

Ice profiles were reduced to evaluate three different areas of interest: (1) to predict pile failure by the formation of an ice bridge which would block the annulus, (2) to parameterize the effects of various environmental conditions, and (3) to determine what effects pile geometry has on ice formation.

To predict pile failure, ice profiles were evaluated in terms of the maximum thickness of the ice. When the ice reaches a thickness of 10.16 cm (4 in), winter operation will not begin due to the flow path being blocked, as shown in Figure 4 (p. 8). The maximum height of the ice profiles at each time interval was plotted versus hours from start-up to predict if a failure would occur. Partial blockage of the pile was not considered a failure since sublimation during the winter will clear the annulus (see Appendix B).

To evaluate the effects of pile geometry and environmental conditions, ice profiles were evaluated on the basis of maximum ice thickness and ice volume. The ice volume was computed by using the ice profiles to generate a solid of revolution around the center line of the pile and integrating the resulting solid to obtain a volume. In actual practice the profiles were evaluated to a depth of 30 cm (12 in) from a reference point, in this case the top of the profilometer track. The integration was performed by first reducing the ice profiles to height versus distance measurements and then using a computer to perform a trapazoid integration of the data (21). A listing of the program is contained in Appendix A. The ice volume was plotted versus hours from start-up for each test.

Ice profiles could only be successfully taken for the shorter neck lengths due to length of the profilometer track. Two data points were obtained for the test of a 1.373 meter neck (4.5 ft) and no ice thickness data could be taken for test of a 2.283 m (7 ft) neck.

Humidity traverses of the annulus were used in determining what the effects of varying pile geometry and environmental conditions have on the rate of ice formation and by what mechanism the ice was forming. Traverses were made from the top of the annulus to depth of 60 cm (24 in) below the level of ice formation. Measurements were taken at 10 cm (4 in) intervals.

In determining the mechanism by which the ice was forming, a traverse was made with the humidity sensor after the profilometer indicated the frost and ice was forming on the outer wall of the pile. Humidity traverses were initially taken on 48 hour intervals. However, it was found that the existing gradients remained constant during a test and only two traverses were made during a test on later tests. Two traverses were made to ensure that a representative gradient was obtained. Making only two traverses allowed the test chamber to remain undisturbed for longer periods of time. If different environmental conditions or neck lengths have an effect on the rate of ice formation, the resulting concentration gradient would be different. The concentration gradient was computed by first reducing the percent of relative humidity obtained from the hygrosensor to a corrected percent relative humidity using a conversion table supplied with the sensor and the dry bulb temperature of air surrounding the sensor. A psychrometric chart was used to determine the humidity ratio from the corrected percent of relative humidity and dry bulb temperature. The humidity ratios were plotted versus neck position to obtain the concentration gradients.

A sample temperature and humidity profile of the chamber and a temperature profile of the pile wall were taken at one hour intervals during a test. During the 15 hour day and the 9 hour night period the controls would control the chamber temperature to within ±3°C (5.4°F) and the chamber humidity ratio to within ± 3 percent for the two different set points. The pile wall temperature would vary ±7°C (4°F) over a 24 hour cycle. The chamber and pile profiles were used as indicators of how the test equipment was performing and determining test conditions. A sample of the chamber humidity profiles is shown in Figure 21 and a sample of the temperature profile is shown in Figure 22.

The final ice mass was also used as an indicator on the rate and amount of ice formation. The mass of the ice formed during a test was determined by weighing the water contained in the pile after it was thawed at the end of a test. The final ice mass was used to obtain an average daily rate of ice formation by dividing the weight of the ice by the length of the test.

Velocity and temperature profiles were taken in the annulus of another air convection pile used to simulate the winter operation of the pile. In order to determine if a partial ice blockage of the annulus would result in the failure of the air convection due to it failing to start up in the winter or if the heat transfer rate would be reduced such that the permafrost would not be refrozen or subcooled. The velocity in the annulus is determined by converting the milivolt output from the anemometer with a calibration curve for the anemometer. The heat transfer and mass flow rates were

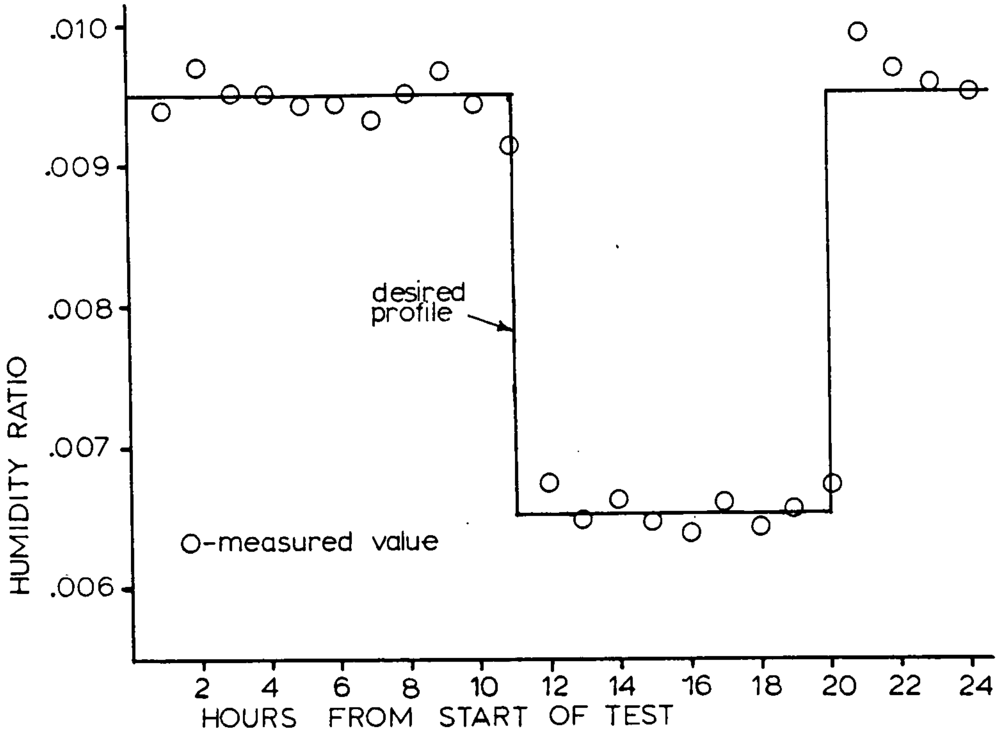

Figure 21. Sample Chamber Humidity Profile

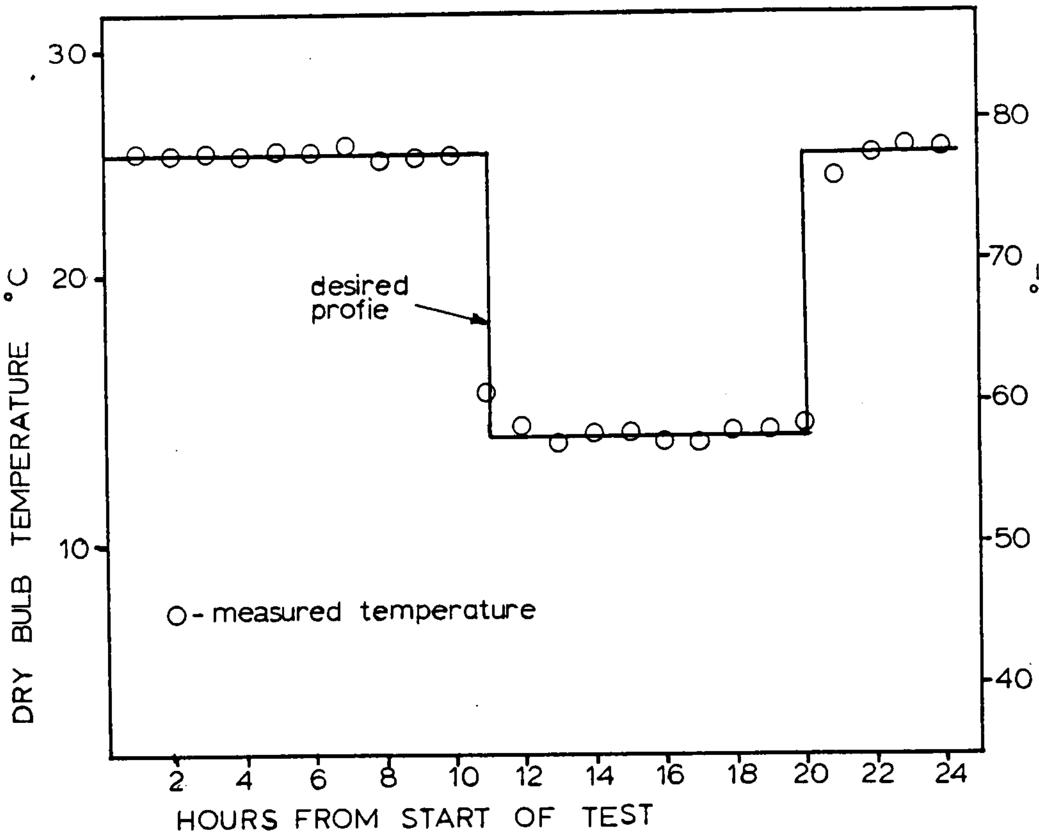

Figure 22. Sample Chamber Temperature Profile

calculated using a pocket calculator program. The program and calibration curve were developed by Evans (7).

Photographs of the ice and frost formation were made with a 35mm Canon single lense reflex camera. Photographs were taken from a view point in the top of the pile. A high speed black and white film was used since low light level proved to be a problem. The only problem which was encountered was with reflections off of the glass plate covering the view. This problem was solved by changing the lighting arrangements. A typical photograph of the ice formation is shown in Figure 23.

Error Analysis

The major discrepancy in the results lies in the calculated ice volume. The error in the ice volume is due to error in the profilometer, the method used to calculate the ice volume, and that the ice is not a uniform solid.

The error introduced by profilometer was found to be small, $\pm$ 3 percent, when compared to the other sources of errors. The profilometer accuracy was determined by measuring several blocks of known thickness.

The error in the method used to calculate the volume was determined by comparing the area calculated by the computer program with that from a planimeter for a set of ice profiles. The calculated area was approximately 20 percent less than the area obtained using the planimeter. This same percent difference was assumed to be true for the calculation of the ice volume.

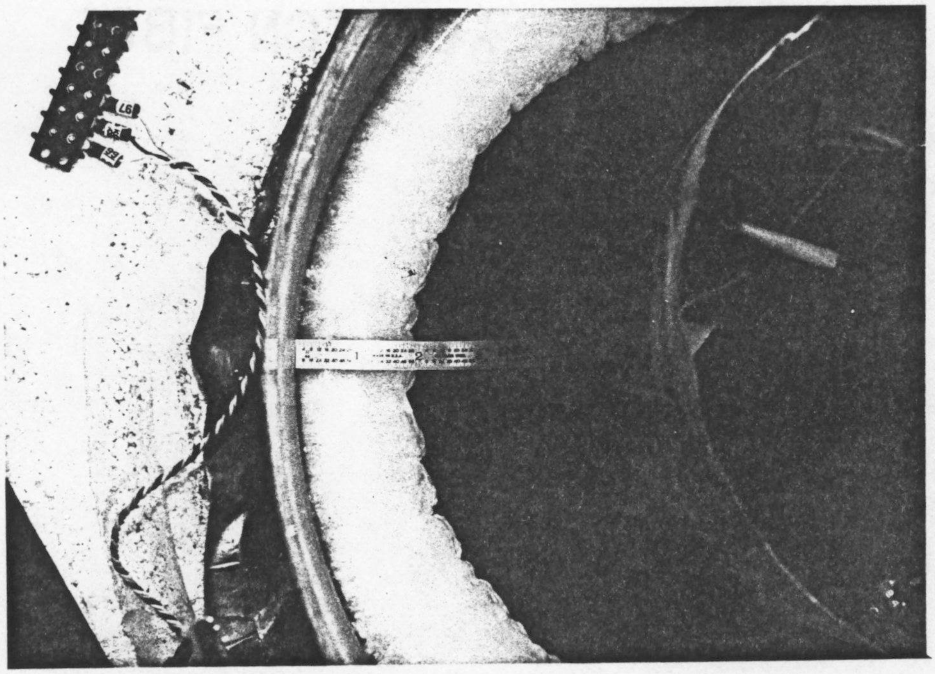

Figure 23. Ice Formation in the Pile

The major source of error in the volume calculations is the assumption of a uniform solid of revolution around the center line of the pile. As can be seen in Figure 23, the ice surface is not uniform. Several ridges and valleys are present in the surfaces of the ice. Many of the valleys are at least 6.8 cm (.25 in) deep. If a profile is taken along a ridge or valley it can result in an error of ± 25 percent in the calculated ice volume. Together with the truncation error and the error introduced by assumption of a uniform solid of revolution resulted in a total root mean square error of 30 percent in the calculated ice volume.

The accuracy of the humidity and temperature measurement was determined from manufacturers' data. The accuracy of the humidity profiles are determined as ± 3 percent between -6°C and 35°C (21°F and 95°F). Temperature measurements were found to be accurate to ± 1.3°C (± 2.3°F).

CHAPTER VI

RESULTS AND DISCUSSION

Experimental Results

In order to characterize the ice formation in the pile, an experimental program was undertaken to simulate conditions that might occur in arctic applications. Preliminary tests of the pile showed a substantial concentration gradient was present in the annulus of the pile. This concentration gradient and the absence of condensate in the troughs indicated that the ice was forming by diffusion.

The variables chosen to study were the ambient conditions and the height of the above ground section. Tests were run for chamber humidity ratios of 0.0085 to 0.0186 and temperatures of 14 to 27°C (58 to 79°F), respectively. The height of the above ground section was set at 0.153, 1.373, and 2.288 m (.5, 4.5, and 7.5 ft). The pile wall temperature was maintained at -6°C (21.2°F) with a 2 to 4°C (3.6 to 7.2°F) variation in temperature over a twenty-four hour cycle.

Table 1 gives the conditions for the tests: humidity ratios, neck length, and total time of the test. The final ice mass and the average rate of ice formation during the test is also given in Table 1. Tests 1 and 6 correspond to Fairbanks minimum and maximum temperature and percent relative humidity condition respectively.

A plot of the maximum ice thickness versus time for tests 1, 2, and 3 are shown in Figures 24, 25, and 26, respectively. As can be seen by the plots, the ice forms at the same rate, during its early

Table 1

Test Conditions and Results

Test No.	Humidity Ratio Day	Humidity Ratio Average	Humidity Ratio Night	Length of Test (days)	Neck Length (meters)	Final Mass (kilograms)	Temperature Day °C	Temperature Night °C	$\dot{m}$ $(\frac{kg}{Day})$
1	0.010	0.0085	0.0065	27	0.153	2.06	32	14	0.076
2	0.0120	0.0100	0.0088	18	0.153	1.50	23	15	0.080
3	0.0132	0.0123	0.0098	50	0.153	5.34	24	14	0.107
4	.0164	0.0146	0.0134	30	1.373	1.29	25	17	0.043
5*	0.0164	0.0146	0.0134	18	2.288	0.45	25	17	0.025
6*	.0186	0.0166	0.0134	10	0.153	1.0	27	21	0.10

*No ice profiles taken during test.

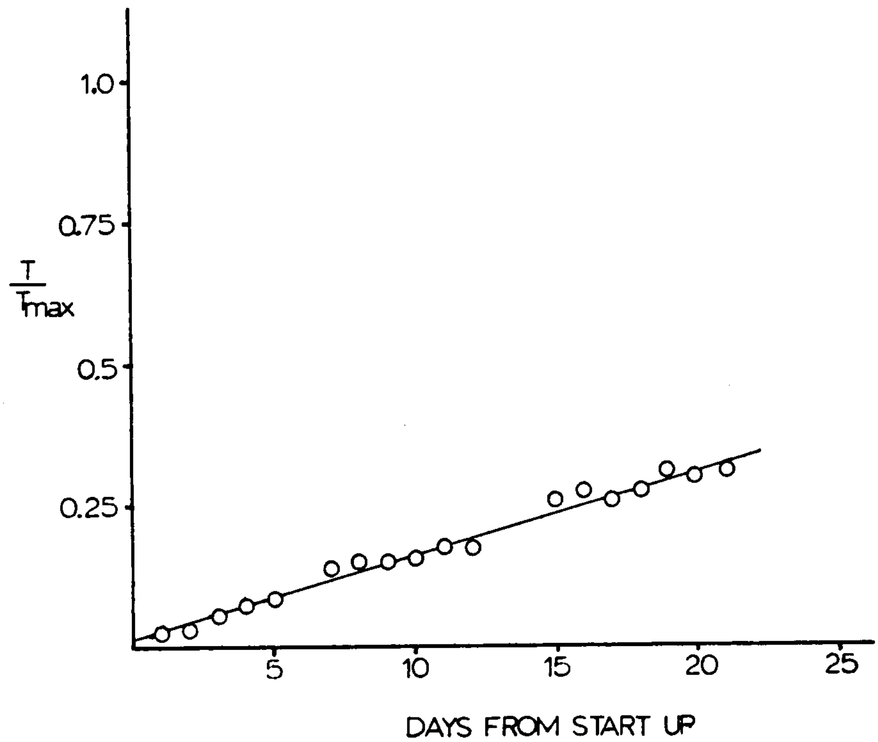

Figure 24. Dimensionless Ice Thickness Versus Days from Start Up for $\overline{\omega}$ = 0.0085 and a Neck Length of 0.153 Meters (Test 1)

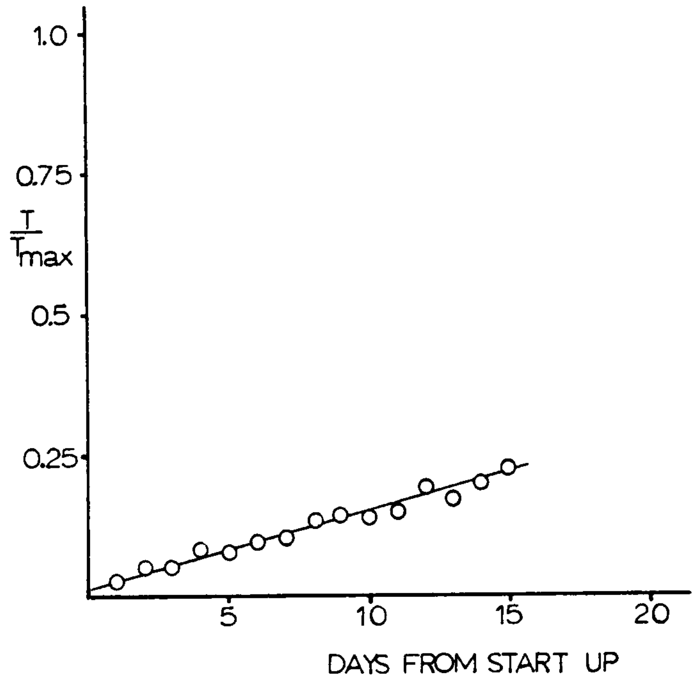

Figure 25. Dimensionless Ice Thickness Versus Days from Start Up for $\overline{\omega}$ = 0.010 and a Neck Length of 0.153 Meters (Test 2)

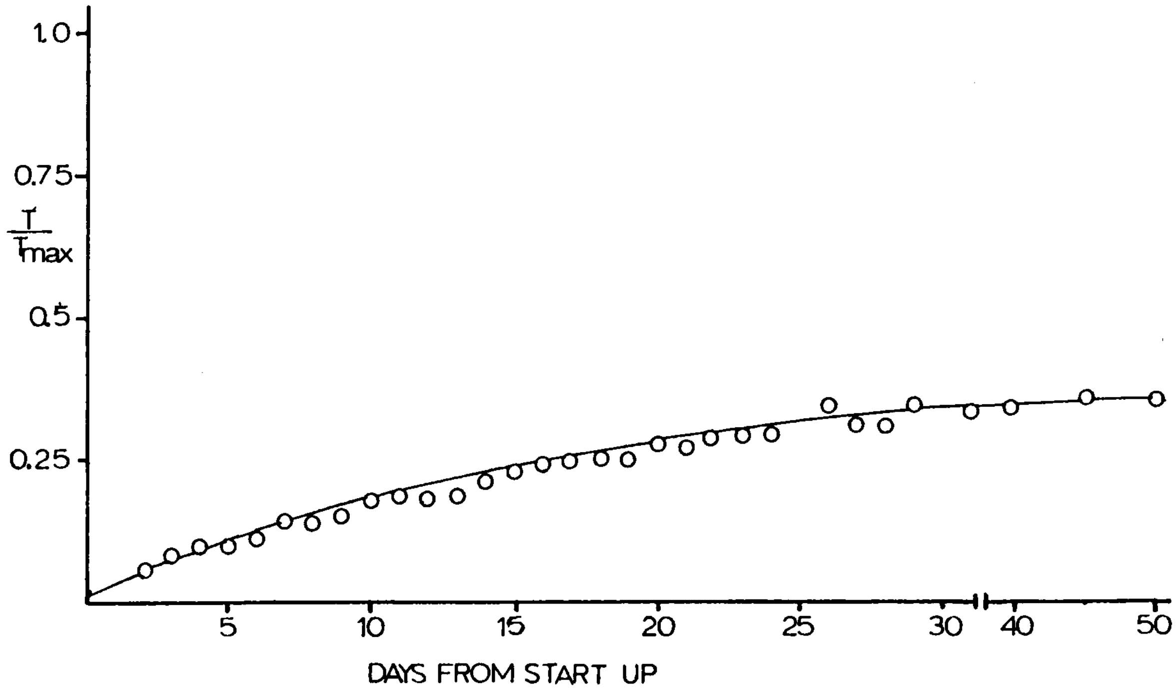

Figure 26. Dimensionless Ice Thickness Versus Days from Start Up for $\bar{\omega}$ = 0.0123 and a 0.153 Meter Neck (Test 3)

life, for the three different chamber humidity ratios. Figure 27, which is a plot of ice volume versus time for the three tests, also shows the result that the ice growth is independent of the chamber humidity ratios. This surprising result can be explained by considering Figures 28 and 29, Tests 1 and 6 respectively, where the measured humidity ratio traverses are shown as a function of dimensionless neck position. In the vicinity of the ice formation, the slopes of the curves are identical. This was also the case for the other tests performed at different chamber humidity ratios, although only the results of two tests are shown. By considering the basic Ficks law of diffusion (17).

$$\frac{\dot{m}}{A} = -D\,\frac{\partial C}{\partial y} \tag{1}$$

Since $C = \frac{\omega}{\rho}$, and assuming constant properties, the equation can be rewritten as:

$$\frac{\dot{m}}{A} = \frac{-D}{\rho}\,\frac{\partial \omega}{\partial y} \tag{2}$$

When the length is made non dimensional with $\overline{y} = y/L$, the equation becomes:

$$\frac{\dot{m}}{A} = \frac{-D}{\rho L}\,\frac{\partial \omega}{\partial \overline{y}} \tag{3}$$

By considering Equation 3 the same mass flow rate, and hence the same ice formation rate, would occur if the slopes of the curves, ω / $\overline{y}$ are the same in the vicinity of the ice. The reason for these same slopes for the different chamber humidity ratios cannot be explained.

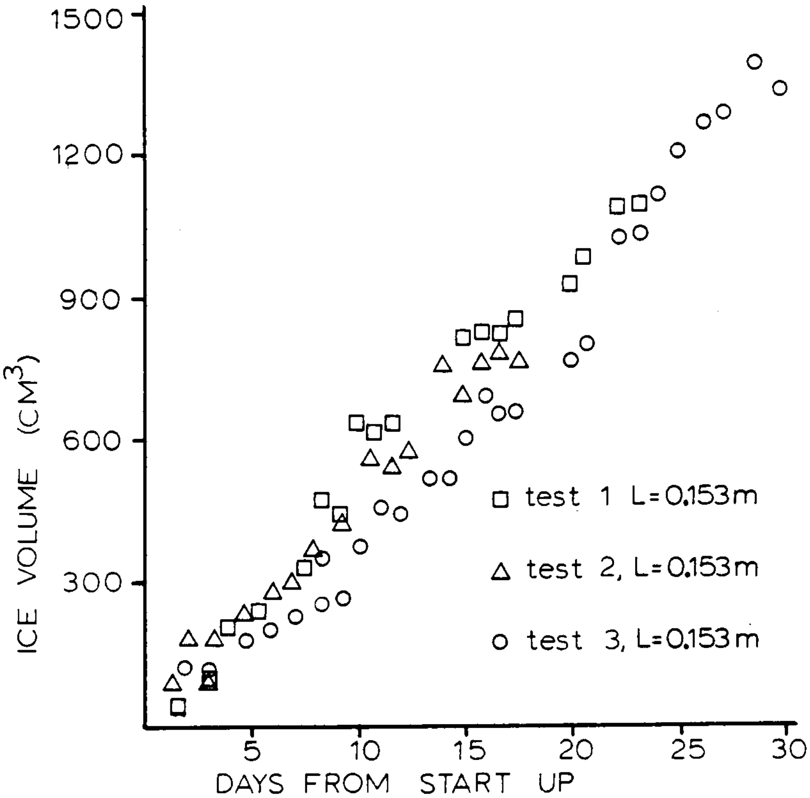

Figure 27. Calculated Ice Volume Versus Days from Start Up

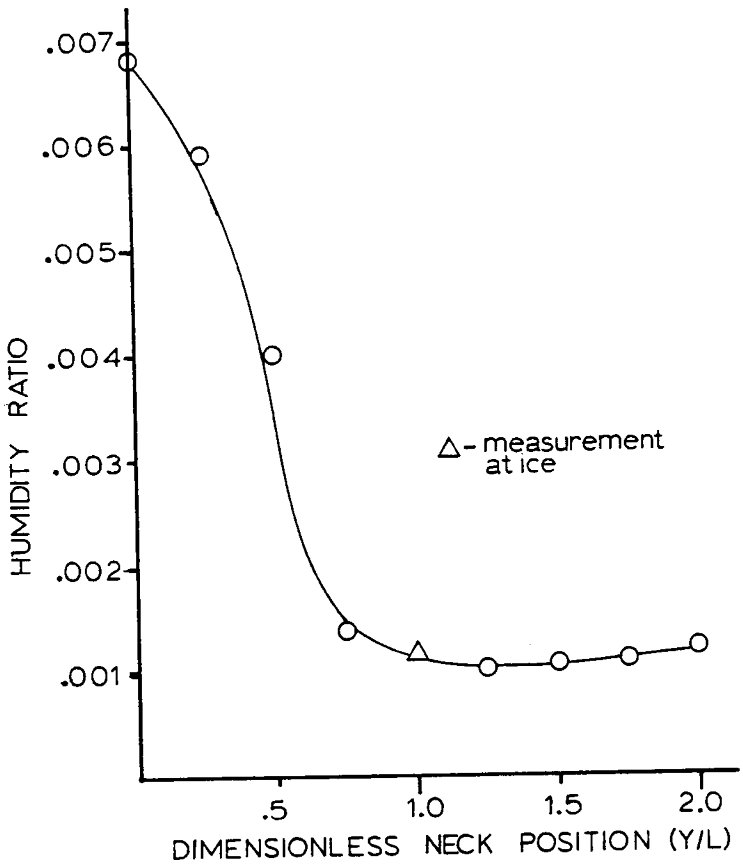

Figure 28. Humidity Ratio Versus Dimensionless Neck Position for $\overline{\omega}$ = 0.0086 (Test 1)

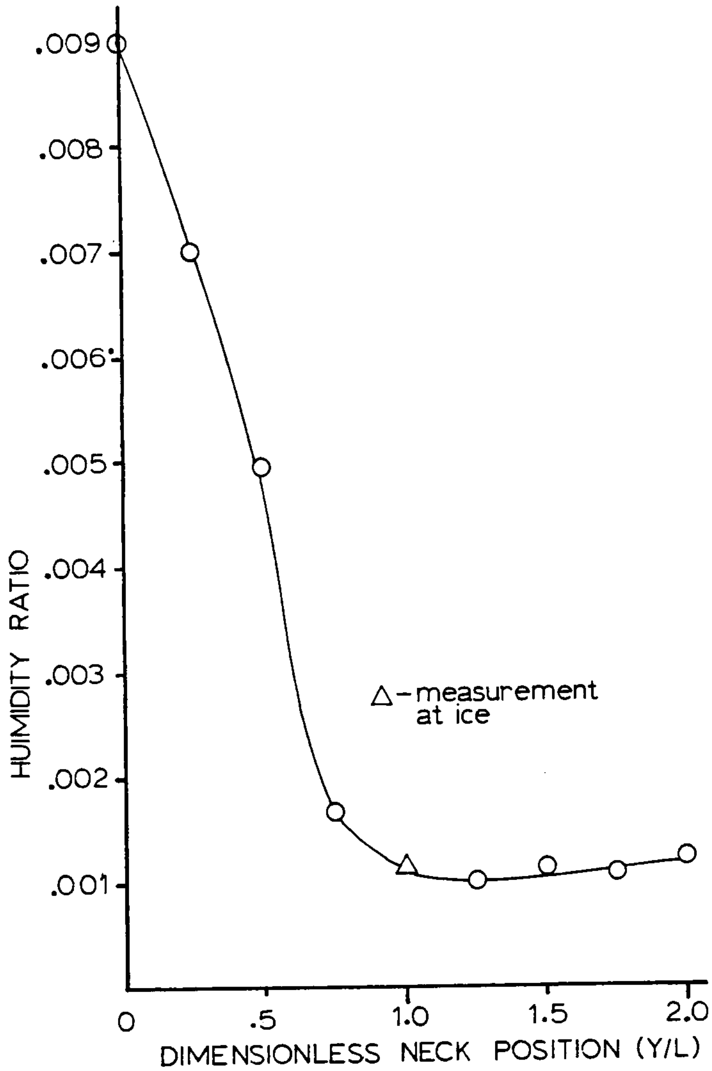

Figure 29. Humidity Ratio Versus Dimensionless Neck Position for $\overline{\omega}$ = 0.0186 (Test 6)

One possible explanation for this result could be the pile head geometry. Attempts to investigate this possible solution by removing the head of the pile were unsuccessful due to a lack of cooling capabilities.

Another important observation which was made is that the maximum ice thickness levels off at 3.8 cm (1.5 in) after 25-30 days of operation (See Figure 26). It is postulated that the maximum ice thickness is governed by a balance between conduction, convection, and radiation heat transfer at the ice formation front. In other words, after the ice reaches a certain thickness, no further increase in thickness is possible because the surface temperature of the ice is not subcooled enough for any moisture to freeze out of the air onto the ice. However, the ice will continue to increase in thickness on levels where the thickness of the ice is less than the maximum possible ice thickness. This is shown in Figures 27 and 30. In Figure 27, the volume of the ice mass is still increasing after 25 days and does not appear to start to level off. In Figure 30, profiles of the ice at 2, 6, 11, 16, 20, 26, and 32 days are replotted for test 3. As can be seen, the ice is increasing in thickness at lower levels in the pile.

Another important finding concerns the effect of uncooled neck length, (height of air convection pile which is above ground). From Table 1 and Figures 31 and 32, it can be seen that the ice formation rate is considerably smaller with a longer neck length, 1.373 meters (4.5 ft) as opposed to a 0.153 meter (0.5 ft) neck. This result can be understood by again considering Equation 3. The humidity ratios from tests 3 and 4 are plotted versus dimensionless length, (y/L) in Figure 33.

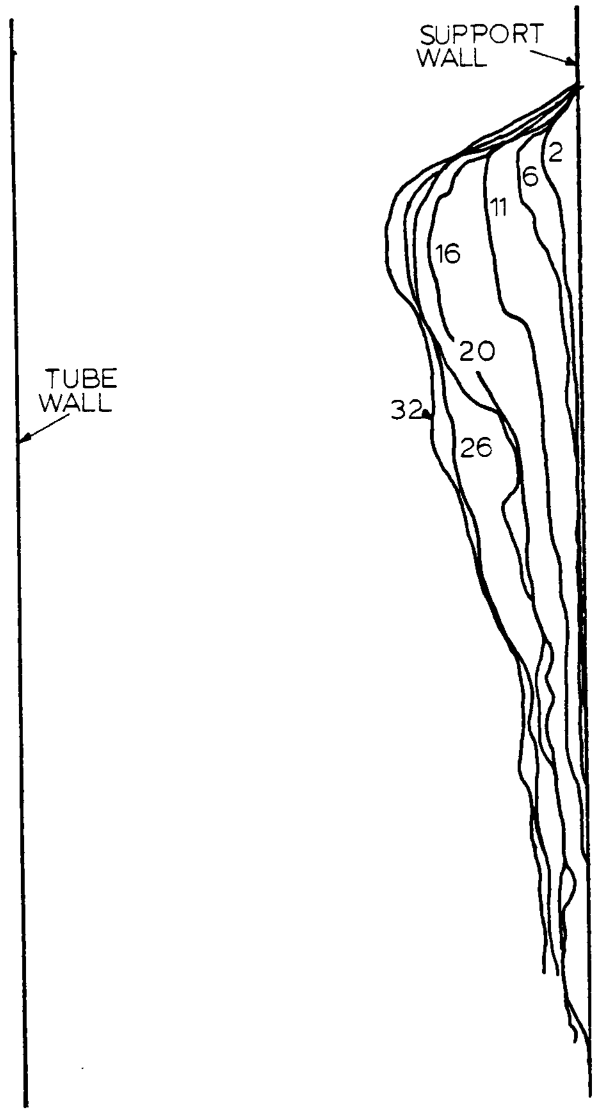

Figure 30. Ice Profiles for Test 3 at 2, 6, 11, 16, 20, 26, and 32 Days After Start of the Test

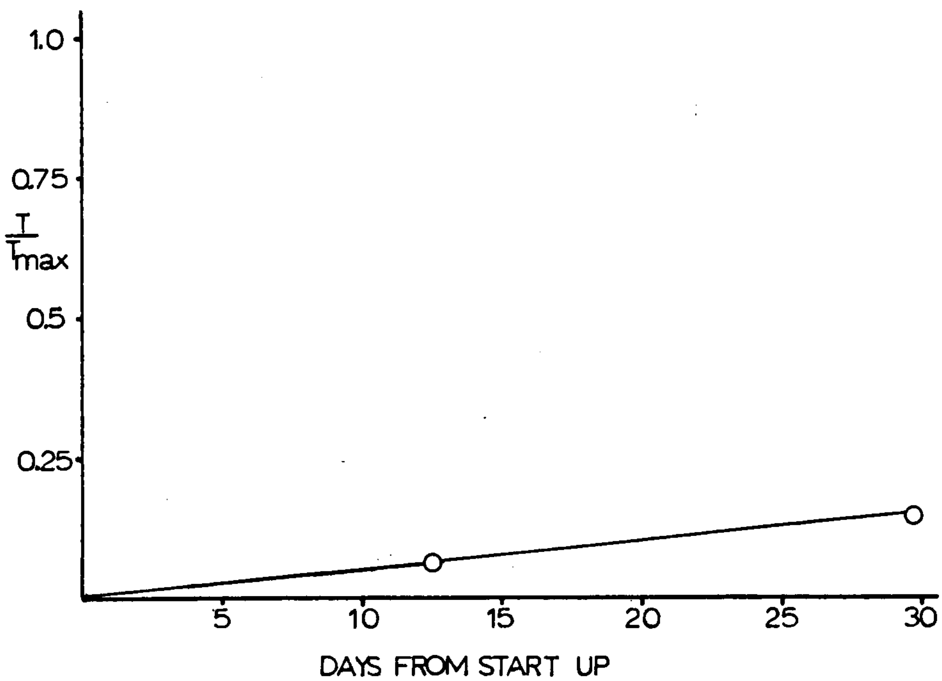

Figure 31. Dimensionless Ice Thickness Versus Days from Start Up for $\overline{\omega}$ = 0.0146 and a 1.373 Meter Neck

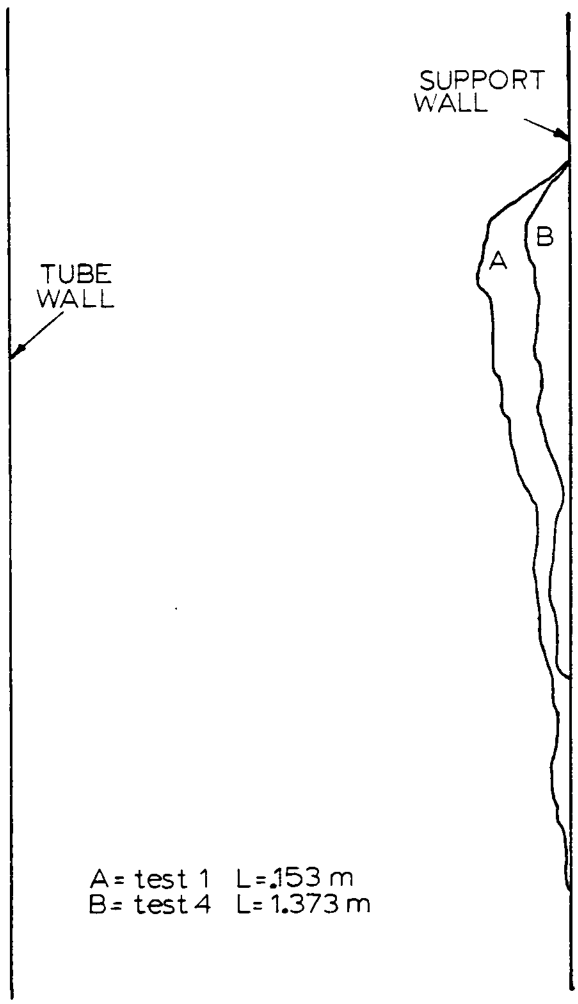

Figure 32. Comparison of Ice Profiles for Different Neck Lengths After 13 Days

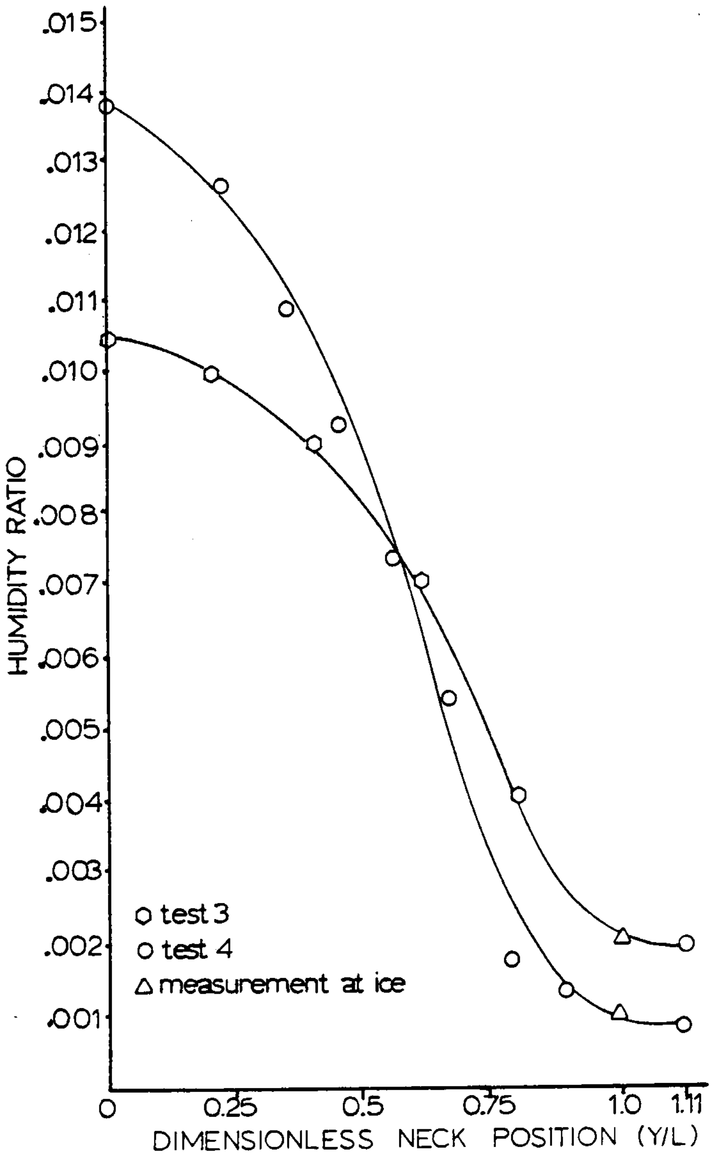

Figure 33. Humidity Ratio Versus Dimensionless Neck Position for Test 3 and Test 4

The slopes of the curves, $\partial\omega/\partial\bar{y}$ are approximately equal, within experimental accuracy, in the vicinity of the ice formation. From Equation 3, the rate of ice formation will be inversely proportional to the neck length L. Thus, the ice formation rate will be reduced by increasing the neck length of the pile.

The results from a test conducted on the effects of a wind induced flow in the annulus of the pile were limited due to problems with test equipment. Due to the circulation of warm air through the pile, the chiller was unable to maintain a wall temperature sufficient to cause ice to form. However, the temperature was low enough to cause condensation. At the end of 48 hours 2.86 kilograms (6.3 lb) of water were present in the pile. It is assumed that if a wall temperature sufficient to cause the moisture to freeze could have been maintained, ice of an equivalent mass would have formed. Such an ice mass could be equivalent of an ice mass with a maximum thickness of 2.5 to 3.8 centimeters (1 to 1.5 in). If a wind induced flow occurred in the field for several days, total blockage of the annulus could occur.

Results of the test on the effects of a partial ice blockage on the operation of the pile are shown in Figures 34 and 35. Figure 34 shows that the ice would not prevent the pile from starting up in the winter for the case of 52 cm^2 (8.0 in^2) remaining open area for flow. Figure 35 shows the effects of the blockage on the velocity profile. The mass flow rate was 1.130 kg/hr (4.34 lb/hr), approximately one half that of a cleared pile. The temperature of the exit air stream was 4 °C (7.2 °F) hotter with the blockage. The heat transfer rates were the same for both cases at 158 watts (540 Btu/hr) (7).

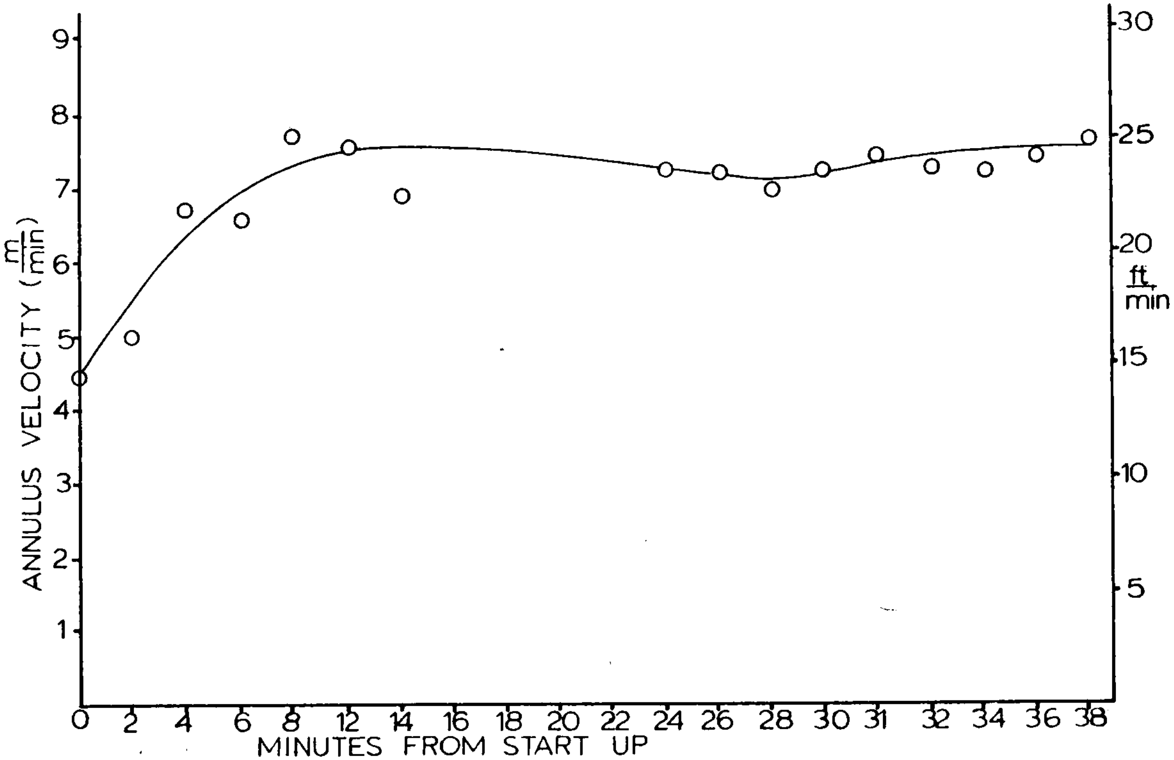

Figure 34. Annulus Velocity Versus Start Up Time for Partial Ice Blockage

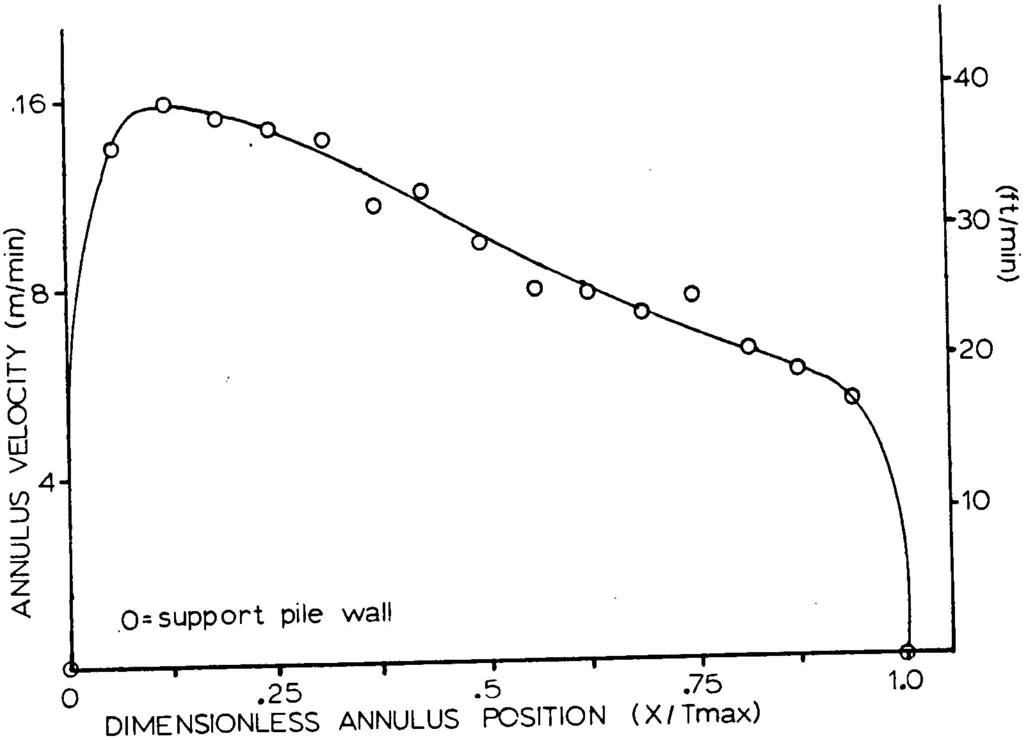

Figure 35. Annulus Velocity Profile for Partial Ice Blockage

Results from the tests on the effectiveness of the air bag in stopping the ice from forming were encouraging. At the end of 7 days of operation, no ice had formed on the outer pile wall; only a very thin layer of frost was present. However, between the days 7 and 10, a large leak developed in the bag. Other tests yielded the same results, a large leak would develop in the bag after about 7 days of operation.

Analytical Results

Approximate calculations were made to determine if the ice would sublimate out of the pile during the winter. Two cases were evaluated: (1) total blockage of the annulus and (2) partial ice blockage. of the same mass as determined experimentally after 50 days of simulated arctic summer operation. Calculations showed that the ice would sublimate out in approximately 75 days for the case of a total blockage. However, for the case of a partial blockage, which will probably be the case in the field, the pile will be cleared of ice in approximately 8 days. If the pile is cleared in 8 days, operation of the pile will not be affected by the ice. A sample calculation for both cases is shown in Appendix B.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Preliminary tests have verified the presence of an ice problem in the air convection pile and that the ice results from mass diffusion. Results from the ice formation tests have shown that typical summer environmental conditions have no effects on the amount or rate of ice formation. These tests also showed that the amount or rate of ice formation was dependent on the height of the above-ground section. For test conditions and no induced flow, if a pile with a neck of 2.1 m (7 ft) or longer is used there will be very little ice formed on the outer wall of the pile. If the temperature of the permafrost remains at approximately -6°C (1.2°F) the ice will not reach a thickness greater than 3.8 centimeters (1.5 in) under stagnant conditions. However, tests on the effects of a wind induced flow showed that the effect of the flow can possibly result in massive ice formation. Although, at this time, sufficient data on the effects of the wind on circulation in the pile are not available. Results from other tests have shown that even a large ice blockage will not affect the start up or operation of the device. In any event, ice formed during the summer would sublimate during the cold arctic winter. Typical winter temperatures in Fairbanks average -24°C (-11°F) with a relative humidity of 70 percent (3). This translates to a very low vapor pressure, approximately 0.0005 atmosphere. The upper vapor pressure limit for sublimation to occur is 0.0063 atmospheres (22, 23).

Tests on the vapor bag have shown that it would be effective in preventing the ice from forming. However, more work will be required to ensure the reliability of operation of the air bag.

Continued research needs to be done on the problem of ice formation in the air convection pile. Specifically, an analytical model should be developed to verify the experimental results of this study. More work should also be done in testing the effects of different pile geometries on the rate of ice formation.

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APPENDIXES

APPENDIX A

ICE VOLUME COMPUTER PROGRAM

```
        DIMENSION X(500),Y(500),YY(500)
        DATA BLANK/'     /'
1       WRITE (5,61)
61      FORMAT (' WHAT IS THE NAME OF THE DATA SET?')
        ACCEPT 642,NAM
        OPEN(UNIT=1,MODE='ASCII',ACCESS='SEQIN',FILE=NAM)
103     READ (1,77) N
        DO 106 I-1,N
106     READ (1,77) INT, X(I), Y(I), YY(I)
        CLOSE (UNIT=1, FILE=NAM)
        GO TO 23
23      ID=1
        CLOSE(UNIT=1, FILE=NAM)
77      FORMAT (1X,I4,3(3X,F14.5))
        ZI=3.1415
        K=N-1
        DO 100 M=1,K
        W= X(M+1) - X(M)
        D= ABS (Y(M) + Y(M+1))
        AREA = 0.4*W*(Y(M+1))
        IF (Y(M) .GT. Y(M+1) GO TO 30
        Y(M) =B
        GO TO 20
30      Y(M+1) = B
20      YMENT = (B*W*B*0.50) + W*D*0.5*(B+((1/3)*D)))
        YBAR = YMENT/AREA
        VOL = AREA*(9.0 -YBAR)*2*ZI
        SUMN= SUM + AREA
        SU = S + VOL
        SUM = SUMN
        S=SU
100     CONTINUE
        WRITE (5,60) SUM
        WRITE (5,62) S
60      FORMAT (' THE AREA IS', F14.6,'1N**2')
62      FORMAT(' THE VOL IS ', G14.6, ' IN.**3')
40      FORMAT(' DO WANT TO START OVER')
        ACCEPT *,ANS
        IF (ANS .EQ. 1) GO TO 1
642     FORMAT(A5)
        STOP
        END
```

APPENDIX B

SUBLIMATION CALCULATIONS

In winter the air inside the pile is below 32°F. The ambient air is at -20°F and 50 percent RH. As the air passes through the pile the air is heated to 0°F (temperature of air as it passes over ice) (7).

<u>Partial Blockage</u>

From test data:

Velocity of air across ice 540 ft/min

Hydraulic diameter of annular passage 4 in

Length of ice mass 6 in

Mass of ice 11.8 lbs after 50 days of simulated operation

Calculate convection heat transfer coefficient and corresponding sublimation coefficient governed by h_D.

$$\theta_f = \frac{30 + 0°F}{2}$$

$$\mu = 0.0404 \frac{lbm}{hr\text{-}ft} \qquad K = 0.0135 \frac{BTU}{hr\text{-}ft\text{-}°F}$$

$$Pr = 0.716$$

$$C_p = 0.24 \frac{BTU}{lbm - °F} \qquad Sc = 0.60$$

$$R_{e_D} = \frac{\rho UD}{\mu}$$

$$R_{e_D} = \frac{(0.0835 \frac{lbm}{ft^3})\ (540 \frac{ft}{min}\ (.33\ ft)\ 60 \frac{min}{hr}}{0.040 \frac{lbm}{hr\text{-}ft}}$$

$$Re_D = 2.2 \times 10^4$$

From reference 24, the Nusselt number for an annular passage heated along the outer wall is:

$$NU_A = 52.5$$

$$NU_A = \frac{hD_H}{K}$$

$$h = \frac{52.5\ (0.0135)\ \frac{BTU}{hr\text{-}ft\text{-}°F}}{.33\ ft}$$

$$= 2.2\ \frac{BTU}{hr\text{-}ft^2°F}$$

$$\frac{h}{hD} = \rho C_p\ (\frac{Sc}{Pr})\ 2/3$$

$$= (0.0835\ lbm/ft^3)\ (0.24\ \frac{BTU}{lbm°F})\ (\frac{.6}{.716})^{2/3}$$

$$\frac{h}{hD} = 0.0178\ \frac{BTU}{ft^3°F}$$

$$hD = \frac{h}{0.0178}$$

$$= \frac{2.2\ \frac{BTU}{ft^3°F}}{0.0178\ \frac{BTU}{ft^3°F}}$$

$$hD = 123.6\ ft/hr$$

SUBLIMATION RATE m_s

$$m_s = hD\ A(C_w - C)$$

At 30°F $P_{SAT} = 0.0887 \frac{lb_f}{in^2}$

$$C_w = \frac{P_w}{R_w T_w} \frac{(0.0887 \frac{lb_f}{in^2})(144 \frac{in^2}{ft^2})(18 \frac{lb}{lb_{mole}})}{(1545 \frac{ft\text{-}lb_f}{lb_{mole}\ °R})(490°R)}$$

$$C_w = 0.000303 \frac{lbm}{ft^3}$$

At -20°F $P_{SAT} = 0.0062 \frac{lb_f}{in^2}$

$$RH = 50\% = \frac{p}{P_{SAT}}$$

$$p = (.5)(.0062) \frac{lb_f}{in^2}$$

$$p = 0.0031\ lb/in^2$$

$$C = \frac{P}{R_W T}$$

$$= \frac{(0.0031 \frac{lb_f}{in^2})(144 \frac{in^2}{ft^2})(18 \frac{lbm}{lbmole})}{(1545 \frac{lbf}{lbmole}\ °R)(440\ °R)}$$

$$C = 0.0000118 \frac{lbm}{ft^3}$$

$$m_s = hDA(C_w - C)$$

$$\frac{m_s}{A} = 123.66 \frac{ft}{hr} (0.000303 - 0.0000018) \frac{lbm}{ft^3}$$

$$\frac{m_s}{A} = 0.0350 \frac{lbm}{hr\text{-}ft^2}$$

$$A = 1\ (\pi)(2)(Ri)$$

$$= .5\ (\pi)(1.2)$$

$A = 1.8\ ft^2$ Surface Area of Ice

$$m_s = (0.0350 \frac{lbm}{hr\text{-}ft^2})\ (1.8\ ft^2)$$

$$m_s = 0.06 \frac{lbm}{hr}$$

Mass of Ice = 11.8 lbm

Average time for ice to sublimate

$$\tau = \frac{11.8\ lbm}{0.06\ lbm/hr}$$

$$= 184\ hr$$

$$\tau = 7.7\ days$$

FOR THE CASE OF COMPLETE BLOCKAGE (no flow of air across ice)

$$\theta_f = \frac{30 + -20}{2} = 5°F = 465°R$$

$$\beta = \frac{1}{\theta_f} = \frac{1}{465°R} = 0.00215\ R^{-1}$$

$$Gr\ Pr = \frac{cp\beta g\ (Tw - T)\ (\rho)^2\ (L)^3}{k\,\mu}$$

$$= \frac{(.24 \frac{BTU}{lbm\text{-}°F})\ (0.00215°R^{-1})\ (490 - 440°R)\ 32.2 \frac{ft}{sec^2}}{}$$

$$\frac{(3600\ \frac{\text{sec}}{\text{hr}})^2\ (.084\ \frac{\text{lbm}}{\text{ft}^3})^2\ (.333)^3}{.0131\ \frac{\text{BTU}}{\text{hr-ft°F}}\ (0.131\ \frac{\text{lbm}}{\text{hr-ft}})}$$

$$Gr\ Pr = 5.4 \times 10^6 \qquad \therefore \text{ LAMINAR}$$

$$h = 0.27\ (\frac{T}{L})^{1/4}$$

$$= \frac{(490 - 440)}{(.333)}^{1/4}$$

$$h = 0.945\ \frac{\text{BTU}}{\text{hr-ft}^2}$$

$$\frac{h}{hD} = 0.0178\ \frac{\text{BTU}}{\text{ft}^3\text{°F}}$$

$$hD = \frac{0.945\ \frac{\text{BTU}}{\text{hr-ft}^2\text{°F}}}{0.0178\ \frac{\text{BTU}}{\text{ft}^3\text{°F}}}$$

$$hD = 531\ \text{ft/lb}$$

$$m_s = hD\ A(C_w - C)$$

$$= 53.1\ \frac{\text{ft}}{\text{hr}}\ (1.22\ \text{ft}^2)(0.000303\ \frac{\text{lbm}}{\text{ft}^3} - 0.000018\ \frac{\text{lbm}}{\text{ft}^3})$$

$$m_s = 0.01833\ \frac{\text{lbm}}{\text{hr}}$$

Assumption: No flow will occur until ice is completely sublimated from pile.

$$\text{Ice sublimation rate} = \frac{m_i}{m_s}$$

$$= \frac{33.4 \text{ lb}}{0.01883 \frac{\text{lb}}{\text{hr}}}$$

$$= 1809 \text{ hrs}$$

$$\tau = 75 \text{ days}$$

VITA

Ernest H. Hudgins was born in Waynesville, North Carolina, on January 25, 1956. He was graduated from Pisgah High School in June, 1974. He entered The University of Tennessee in the summer of 1974, and received a Bachelor of Science in Mechanical Engineering in June, 1978. He accepted an assistantship at The University of Tennessee, Knoxville, in the Mechanical Engineering Department and began study towards a Master's Degree in June, 1978. This degree was awarded in December, 1983.

The author is a member of ASME. Mr. Hudgins will be employed by Daniel, Mann, Johnson, and Mendenhal, Oak Ridge, Tennessee, after graduation.