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TETHERED AEROSTAT OPERATIONS IN ARCTIC WEATHER

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1. Abstract

The Air Force Geophysics Laboratory (AFGL), part of the Air Force Systems Command (AFSC), was tasked by a sister AFSC organization, the Electronic Systems Division (ESD), to study the feasibility of operating a large tethered aerostat system in an arctic environment. AFGL entered into a contractual arrangement with the TCOM Corporation for the conduct of a multi-phased joint investigation. TCOM has been operating tethered aerostats in various climates in different parts of the world for more than a decade. There has been considerable experience with 250,000 cubic foot aerostats operated during the winter in the Republic of Korea. During these winter operations, methods were developed to fly the aerostat out of hazardous snow or ice conditions and to remove snow from the aerostat while it was moored on the ground. In 1981 TCOM operated a small 25,000 cubic foot tethered aerostat in the Arctic region of the Beaufort Sea north of the Northwest Territory of Canada. Problems were intensified by the fact that the aerostat was operated from a small surface vessel making it very difficult to gain access to the aerostat during rough sea conditions. Phase I AFGL—TCOM investigation included a review of TCOM winter flight experiences and problems in order to evolve better techniques for combatting snow and ice conditions. Phase II involved the flying of a 25,000 cubic foot aerostat in the winter months of 1983 in northern Vermont. (See Figure 1.) The aerostat successfully flew through several snow storms and icing conditions. Although snow presented no problem to the aerostat in flight, the accretion of rime ice was experienced on many occasions. This paper reports the results of the first two phases of the AFGL—TCOM investigation.

2. Introduction

The Air Force Geophysics Laboratory (AFGL), part of the Air Force Systems Command (AFSC), was tasked last year by a sister AFSC organization, the Electronic Systems Division (ESD), to study the feasibility of operating a large tethered aerostat system in an arctic environment. The envisioned aerostat would carry a gap-filler radar for better surveillance of Distant Early Warning (DEW) Line areas of concern. This study would be in support of ESD's North Warning System Project Office, which is undertaking a general upgrading of Dew Line radar facilities.

Although AFGL had operated tethered aerostats for many years and launched hundreds of high altitude free flying balloons, it has virtually no cold weather experience relevant to Arctic operations. To gain such experience, AFGL entered into a contractual arrangement with the TCOM Corporation for the conduct of a multi-phased joint investigation. The investigation would begin with a short paper study, drawing on TCOM's prior Arctic experience. The next step would involve tethered aerostat flight demonstration in the Northern United States at a severe winter weather location. The final phase would be given over to tethered aerostat tests at an actual Arctic site for a winter season.

Phase I, the feasibility study and Phase II, the Northern U.S. winter flight demonstration portions of the AFGL North Warning program, have been completed, and the study and test results are reported in this paper. Phase III, operational test flights in the Arctic, is currently in the planning stage.

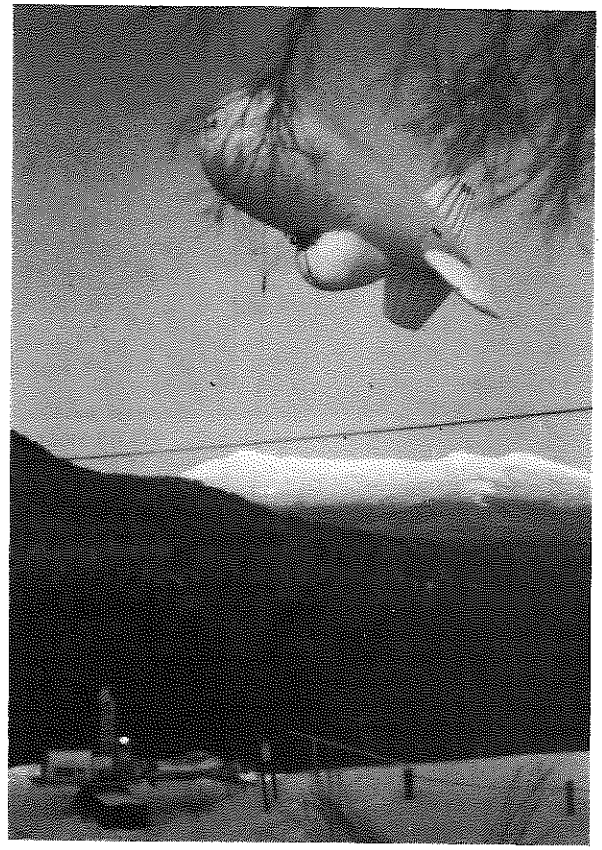

Fig. 1. The STARS aerostat during winter operations at Ethan Allen Firing Range near Burlington, Vermont

3. Background

TCOM, a wholly owned subsidiary of the Westinghouse Electric Corporation, has for 12 years been involved in the development and marketing of tethered aerostat systems for communications in third world countries. During this period, TCOM has sold or leased 26 systems ranging in size from 25,000 to 411,000 cubic feet. For three years TCOM operated two large aerostats in the mountains of Korea about 80 miles from Seoul — in the heart of the Korean snow belt where effective wintertime snow removal procedures had to be developed quickly to insure uninterrupted operations. TCOM's Korean winter experience was supplemented by later operations in the Beaufort Sea, about 100 miles above the coast of Canada's Northwest territories. Under a 1981 contract with the Dome Petroleum Ltd. of Canada, TCOM mounted a radar-equipped "STARS" tethered aerostat on a small vessel, which was to patrol the waters in the vicinity of Dome's drilling rigs and maintain a 24-hour surveillance of the movement of the advancing ice packs.

The Beaufort Sea project was quite successful. The aerostat was inflated under a net in a snow storm with 20+ knots of wind on a barge in Tuktoyaktuk Harbor in early September and transferred to the CANMAR TEAL. (Figure 2 shows the STARS aerostat on the re-supply ship, the CANMAR TEAL, in the bay at Tuktoyaktuk, Northwest territory.)

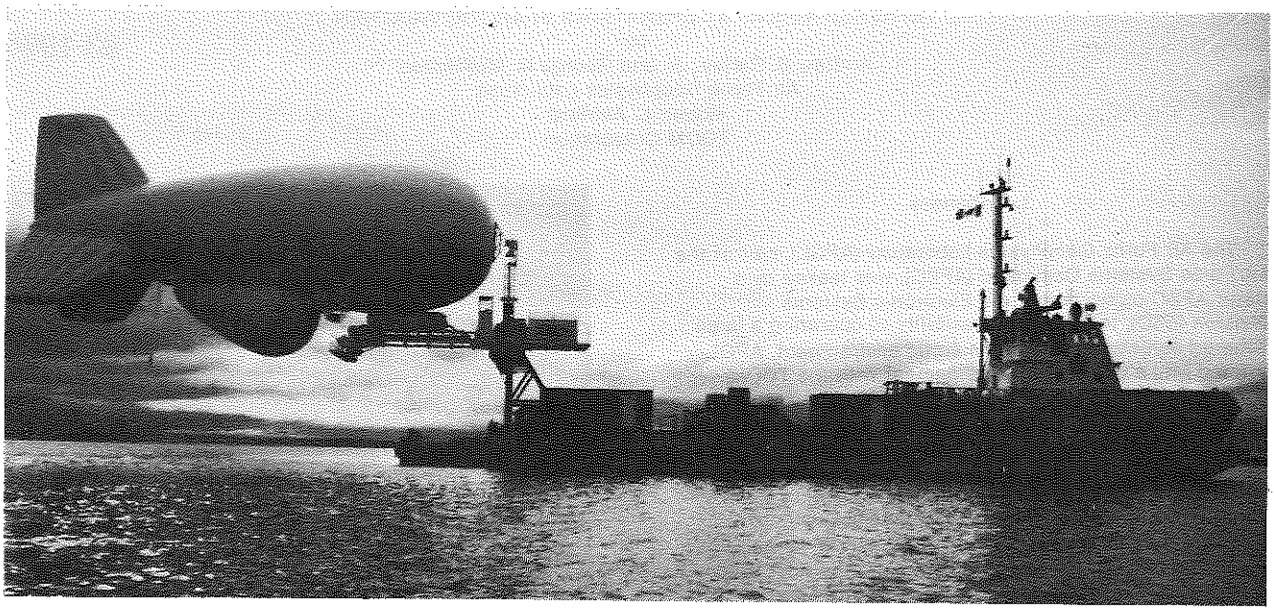

Fig. 2. STARS moored on deck of the CANMAR TEAL in Tuktoyaktuk

The CANMAR TEAL made four sorties to the drilling area. The aerostat would be launched as the ship left port and recovered upon return to port. On occasion the aerostat would be recovered briefly at sea, for adjustments or ice removal, and relaunched. About 415 hours of flight time were accumulated during these operations. The major problem experienced was ice accretion, particularly rime ice. It was as a result of this background in cold weather aerostat operations that AFGL contracted with TCOM to assist in the studies for North Warning.

4. The Joint AFGL—TCOM Investigation of Tethered Aerostat Operations in Arctic Weather

Phase I — The Cold Weather Aerostat Study

Under AFGL contract, TCOM spent the summer and early fall of 1982 re-examining its Korean and Beaufort Sea experiences for applicability to the North Warning demonstration program. The effort also included a survey with AFGL of the expected environmental conditions at the selected test site, the Ethan Allen Firing Range near Burlington, Vermont. TCOM gave particular attention to problems encountered during and results obtained from prior Arctic deployments of tethered aerostats. The purpose here was to identify the modifications required by the STARS system for successful operations in the Vermont winter environment. That environment did not constitute a true Arctic environment but it offered a reasonable facsimile from time to time.

Several tests were conducted in a cold chamber to test the effectiveness of various proposed ice-removal techniques:

1. Pressure pulsing.
2. High and low frequency vibrators.
3. Polymer coatings to lessen ice adhesion.
4. Polyurethane coated rigging.
5. Heaters on valves, blowers and anemometer.
6. Heated Ethylene Glycol and water mixture.
7. Methods of cold weather laminate repair.

The STARS mooring system was examined for its application in extreme cold weather. This mooring system already had been modified with heated enclosures for the machinery and the operator. It had been used in the Dome Petroleum project. However, much colder temperatures were expected in Vermont. The structural steel used in the mooring system has a nil ductility temperature at about 0°F where the steel becomes brittle and subject to fracture somewhat like glass. However, the safety factor in the structure was determined to be sufficient to safely operate in Vermont. On the other hand, operations in a true arctic winter with temperatures descending to around -50°F will require special alloys for the mooring system.

Phase II — Winter Flight Tests

Upon completion of the study, Phase II of the program commenced wherein TCOM modified a STARS aerostat system to make it as survivable as possible within the cost constraints of the program. The following aerostat system modifications were implemented and include features of the mooring and tether system:

Pressure Pulsing

The Aerostat Pressure Control Unit (APCU) was designed as a dual mode system. In the normal operating mode it uses a 400 Hz, 3-phase blower with a capability of pumping about 300 cubic feet of air per minute against a pressure head of 4.0 Inches of Water Gauge (IWG) and with a cutoff (stalling) pressure of more than 10.0 IWG. This blower capability is much more than required for normal operations, but becomes most useful for pressure pulsing as described below. The primary ballonet air relief valve is a 15 inch electrically driven valve adapted from the large aerostat programs. The valve opens at 3.7 IWG and closes at 3.4 IWG. The blower turns ON at 3.0 IWG and shuts OFF at 3.3 IWG. In addition to the primary blower and valve there are two independent emergency battery powered blowers which operate at about 1.4 IWG. Two ballonet overpressure magneto-mechanical poppet valves are set to OPEN at about 4.7 IWG, one windscreen overpressure poppet valve is used at 4.0 IWG and one windscreen fill valve is employed between the ballonet and the windscreen to operate between 0.7 and 0.9 IWG thus maintaining the windscreen pressure slightly below that of the ballonet.

In the alternate mode of operation a pressure pulse cycle is initiated by a signal via the telemetry up-link. The blower is turned ON to raise the hull pressure to 4.5 IWG which the oversize blower can do in less than 2 minutes. At 4.5 IWG the blower shuts OFF and the valve opens lowering the pressure to 1.6 IWG at which point the system reverts to the normal operating mode. The valve closes and the blower comes ON and returns the hull to the normal pressure of about 3.0 IWG. The pressure pulse cycle causes the aerostat to expand and contract slightly in a fashion similar to the action of an airplane de-icer boot.

Vibrators

The results of cold chamber tests conducted during Phase I indicated that vibrating the aerostat hull, particularly after ice or snow was loosened by a pressure pulse cycle, might induce ice or snow to fall free of the aerostat or rigging. Two commercial motor driven eccentric vibrators were procured and installed on racks laced to the aerostat belly inside the windscreen. The small, high frequency vibrator weighed 5 pounds and operated intermittently (30 seconds on, 30 seconds off) at a frequency of 160 Hz. The low frequency vibrator had an adjustable eccentric which was set for maximum amplitude. It weighed 37 pounds and was operated by a DC motor and a variable voltage source. The speed varied according to a triangular wave shape from zero to about 20 Hz. At very low frequencies the fins could be observed to shake; at other frequencies various items of the rigging, blowers, valves, etc. could be observed to vibrate. The vibrators were commanded ON or OFF via the telemetry up-link.

Hydrophobic Coating

The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) has tested a chemical coating with hydrophobic properties consisting of a block co-polymer of polycarbonate and dimethylsiloxane with 10% silicone oil added by weight. This coating was developed to reduce ice adhesion to lock walls of the St. Marys River locks and permit winter navigation of the river. In certain tests this co-polymer coating reduced ice adhesion by as much as 97% compared to similar uncoated surfaces.

Portions of the STARS aerostat were coated with the CRREL co-polymer preparation in order to get a comparison between coated and uncoated areas in terms of snow or ice accumulations.

Polyurethane Coating of Rigging

All of the rigging on the aerostat uses braided Dacron of varying diameter. The rigging includes fin guy wires, closehaul handling lines (main and aft), nose line, suspension lines and mooring lines. In cold weather operations these lines have been observed to soak up water and subsequently freeze. The added water weight is undesirable and the "soft" exterior surface of the braid seems to promote ice and snow adhesion. A set of rigging (complete except for the nose line) was procured with polyurethane as an outer covering on the Dacron braid. The coating served two purposes; first, it sealed the line so that water could not soak into the line and, second; it provided a smooth outer surface which we hoped would discourage ice and snow accumulations and which might even be coated with the hydrophobic co-polymer.

Heated Ethylene Glycol

TCOM owns two steam generator type cleaning machines similar to those used by commercial airlines to wash snow and ice from aircraft wings, control surfaces and fuselages. One of the machines was sent to the manufacturer for a complete refurbishment and subsequent use in Vermont. The high pressure capability of the machine was sufficient to reach all surfaces of the aerostat with a hot mixture (about 50 - 50) of ethylene glycol and water.

Heaters

Each of the valves and blowers on the aerostat was equipped with an electrically powered heater blanket encased in an outer insulation jacket. Each heater had its own thermostatic control built into the heater blanket. The aerostat anemometer was heated on top and at the base. The emergency descent blower batteries were also kept warm with a thermostatically controlled heater.

A heated pitot-static tube was mounted on the aerostat as a back-up for the normal anemometer system, especially at wind speeds above 40 knots. However, the pitot-static system was more useful as the pressure reference sources for the APCU. All of the heaters on the aerostat, with the exception of the pitot-static tube, could be commanded ON or OFF via the telemetry up-link.

Aerostat Repair Methods

For several years, TCOM has been developing and improving methods for the field repair of damage to aerostat hulls. Although it has been a rare occasion when an aerostat has been damaged, a quick and reliable repair method must be at hand, hopefully never to be used. During the Phase I study we had tested several "conventional" one part and two part adhesives in the cold chamber. In all cases, when the temperature drops below freezing the adhesive systems require heated containers and local heating at the repair area. Unfortunately, most of the two part mixes will not cure properly at low temperatures.

For more than 3 years TCOM has been practicing with, and perfecting the use of an electrically heated, pressure operated "glue gun". The chamber of the gun is loaded with a cartridge of thermoplastic resin about 1.5 inches in diameter and 2.0 inches long. A pneumatically operated piston forces the resin slug forward into the heated chamber where it is melted enough to flow through the nozzle as required for the repair. The thermoplastic resin used is Dyvax, a trade name for a somewhat softer form of Hytrel, the basic resin that holds all TCOM aerostats together. Since the hot glue method had worked quite well in the cold chamber, a field repair kit was assembled for use in cold weather conditions.

Snow Scraper

Several years ago the U.S. Navy was forced, on occasion, to moor non-rigid airships on a mast during a winter snow. As expected, the snow load which accumulated on the horizontal fins and the upper surface of the hull rapidly became too much for the airship to support on its landing gear. One method used to remove the snow from the hull was to see-saw a rope back and forth over the top of the hull and literally drag the snow off. TCOM has improved somewhat on this simple scheme; they use a Teflon scraper board about two feet long and a few inches high. The scraper is see-sawed back and forth using lines attached to the Teflon board. A scraper board was deployed with the aerostat as part of the ground snow removal equipment.

High Velocity Blower

A high velocity, backpack, gasoline powered blower was procured which produced a nozzle velocity of 230 knots.

The blower, equipped with extension tubes, could reach most of the upper surface of the lower fins of the inverted "Y" tail. However, this blower was intended also as a method to remove snow from the mooring system.

Data Recording System

TCOM uses three Hewlett-Packard 9825/26 computer systems at their Columbia, Md. Headquarters. Flight simulations and performance predictions for tethered aerostats are routinely accomplished with these computers. One system consisting of the main console, a printer and disc recorder was used in the North Warning aerostat tests in Vermont. All of the flight parameters that were measured on the aerostat as well as several status conditions were sampled once each second, converted to a digital word and transmitted as a serial bit stream to the ground via the telemetry down-link. All of the signals, analog and status, were displayed on a ground console and the digital bit stream was recorded by the HP 9825 onto a disc. Each recording contained 5 hours of real time data. The recorded discs could be examined on site to insure that the system was working properly. Completed discs were sent back to TCOM headquarters where the discs were converted to calibrated engineering values and plotted on charts.

The aerostat parameters that were transmitted to the ground and recorded included:

1. Hull (helium) pressure vs. pitot (dynamic) pressure.
2. * Hull (helium) pressure vs. static (ambient) pressure.
3. Ballonet pressure vs. pitot (dynamic) pressure.
4. Aerostat pitch angle.
5. Wind velocity.
6. Ambient temperature.
7. Tether tension at the confluence point.

*All TCOM aerostat systems used the dynamic pressure of the wind as the reference pressure for the aerostat pressure control system. The hull pressure vs. static pressure is a measure of the true superpressure in the hull and is displayed for reference only.

In addition, the status of specific equipment was monitored

1. Air valve — Not Closed
2. Blower — ON
3. Heaters — ON
4. Pulse Pressure — Cycling
5. Emergency Battery Temperature — Too Low, Too High
6. Vibrators — ON
7. Emergency Blower #1 — ON
8. Emergency Blower #2 — ON
9. Telemetry on Emergency Battery — ON

In addition to the above, the tether tension as measured at the ground winch station was displayed and recorded.

Mooring System

Many minor modifications were made to the mooring system for use in the Vermont North Warning tests. Although the mooring system had been used in the previous cold weather project in the Beaufort Sea, several changes were required to accommodate a Kevlar powered tether in place of the steel tether used previously.

Kevlar Power Tether

TCOM has been operating tethered aerostats for the past six years using a tether which is designed to transmit the electrical power to operate the payload and the aerostat on three small, but well insulated conductors buried in the core of the tether. Power tether systems have been built to deliver as little as 3.5 kilowatts and as much as 31.5 kilowatts at the aerostat. Most recently TCOM has perfected tethers which combine the advantages of the power up the tether with the light weight and high strength of Kevlar. The tether used on the STARS system for the North Warning tests was a Kevlar power tether which delivered approximately 3.5 kilowatts of 400 Hz, 3-phase power at the aerostat. For comparison purposes, Table 1 shows the characteristics of the steel power tether used on the Dome Petroleum project and the Kevlar power tether used for North Warning.

Table 1.

	STEEL	KEVLAR
Total length	3,500 feet	3,500 feet
Power delivered	3.5 kW	3.5 kW
Weight, Lbs./1000 ft	142	97
Breaking strength	7,800 lbs.	12,000 lbs.

Winter Deployment in Vermont

The aerostat operating site at the Ethan Allen Firing Range had been selected by AFGL and TCOM personnel in July 1982. Considerable grading and land preparation was required and accomplished by National Guard forces during the fall of 1982. The aerostat, mooring system and the equipment and support trailer were shipped to Ethan Allen Firing Range in mid-December. On 3 January 1983 TCOM and AFGL personnel arrived in Burlington, VT and set-up of the site facilities began on 4 January. The site system included:

1. Mooring system.
2. Two travel trailers.
3. Emergency power trailer and workshop.
4. Transformer and power lines.
5. Two helium trailers (50,000 cubic feet each).

Figure 3 is a photograph of the site.

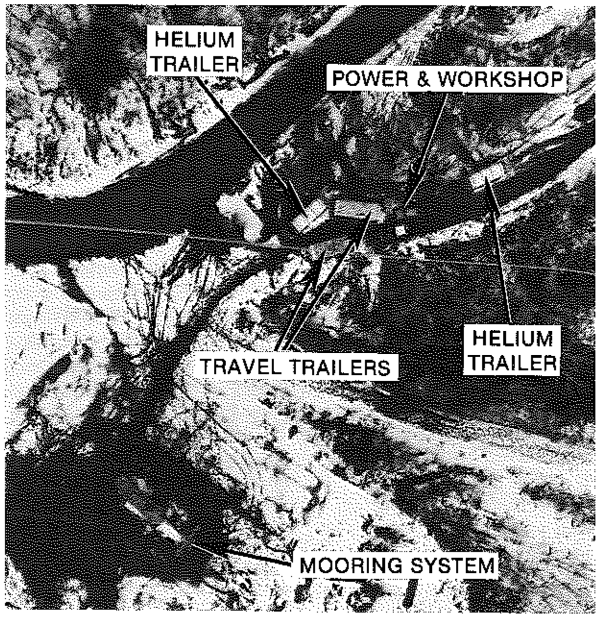

Fig. 3. An aerial view of the STARS operating site, Ethan Allen Firing Range — taken from STARS

On the 13th of January the site was ready in all respects, the weather was suitable and the aerostat was inflated. During the next day, the 14th of January, additional equipment was added to the aerostat and a short test flight conducted. Flight operations began in earnest on the 15th and continued at a brisk pace until the 2nd of February. During this 18 day period the aerostat accumulated 302.4 hours of flight time. On the weekend of 15, 16 and 17 January the aerostat flew continuously without incident through a major winter snow storm. On one occasion it was necessary to recover the aerostat because it had accumulated too much ice and was about to lose all of its free lift safety margin. On several occasions the aerostat was recovered briefly to observe and remove accumulations of rime ice which gathered on the aerostat, handling lines and tether before the free lift margin became critical.

Unfortunately, the first aerostat suffered a structural failure of a fin guy wire termination while flying in severe turbulence with winds of 55 to 60 knots which resulted in the aerostat crashing into the trees on the night of 2 February. Ground observers reported seeing the fins of the aerostat flaccid and streaming in the wind, but it was the ground recording system that provided an accurate account of the structural failure.

TCOM prepared another STARS aerostat for the North Warning program and modified the fin guy system to preclude a recurrence of the same failure. Eighteen days later on 20 February, TCOM and AFGL personnel inflated the second STARS aerostat and the project continued. During the second inflation an improperly installed valve ring trapped some loose hull laminate which created a tear about six feet long in the aft hull section. This time TCOM had a chance to put the hot glue gun repair technique to work. The repair took 2.5 hours to effect, but it is agreed by all observers that no other repair method could have been used satisfactorily in the cold weather environment. It had been planned to demonstrate a cold weather field repair; the demonstration was unscheduled.

The second aerostat flew for a total of 529.3 hours between 21 February and 25 March when the tests were completed. This aerostat encountered much of the same weather as the first one. When the wind blew from the south the mountainous terrain created severe turbulence. Rime ice was repeatedly encountered in clouds at below freezing temperatures. Both wet and dry snow storms were encountered but posed no problem and resulted in very little accumulation on the aerostat in flight. The several devices mounted on the aerostat to combat snow and ice accretion were tested at every opportunity. Table 2 lists the devices tested and rates the usefulness of each of them in various situations.

Each of the devices used or actions taken to remove snow or ice from the aerostat as evaluated in Table 2 is further described and amplified below. The last four items in the table were impromptu actions taken by the AFGL/TCOM operations crew at the Ethan Allen site.

5. Test Results

In general, the test program in Vermont was successful in that the overall objective "Determine the feasibility of arctic winter operations of a tether aerostat system" was at least partially fulfilled. The Ethan Allen Firing Range in northwest Vermont had been selected as the test site because of its reputation for heavy winter snow and cold weather. January, February and March of 1983 had above normal temperatures with the least snow recorded for several years. However, whenever snow or icing opportunities were presented the aerostat was flown to maximum advantage in an attempt to find the worst possible conditions. On a few occasions, when a maximum safe load of ice had been collected on the aerostat, altitude was varied in an attempt to escape from the icing conditions. Although the winter could not be considered a severe one, sufficient bad weather situations occurred to stress the aerostat system to its limits.

Comments on the test items in Table 2 are:

Hydrophobic Coating

The co-polymer coating was applied to the top three gores on the port side and to the upper surface of the lower fins. The coating was also applied to the aft hull above the fins. Snow would slide off more readily from the coated areas. Rain and freezing rain would bead up and roll off the coated areas so that less would collect and freeze. The coating had no effect on the formation of clear ice or rime ice.

Table 2. Summary of Snow/Ice Removing Techniques

	Dry Snow	Wet Snow	Sleet	Freezing Rain	Clear Ice	Rime Ice
Hydrophobic coating	+ +	+ +	+	+	0	0
Vibrators	+	0	0	0	0	0
Polyurethane coated rigging	0	0	0	0	0	0
Pressure pulsing	0	0	0	0	0	0
Snow scraper	+ + +	+ + +	+ + +	0	0	0
High velocity blower	+ +	+	0	0	0	0
Heated ethylene glycol	0	+ +	+ +	+ +	+ +	+ +
Heaters (blowers, valves, pitot-static)	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +
Knotted rope on fins	+ +	+ +	0	0	0	0
Snapping of lines	+ +	+ +	+	0	0	+
Sudden stop on outhaul	0	+	+	0	0	0
Snowballs	+ +	+ +	0	0	0	0

0 No benefit
\+ Slight benefit
\+ + Moderate benefit
\+ + + Considerable benefit

Vibrator

The low frequency vibrator sometimes caused dry, light snow to fall off. This occurred as the vibrator was sweeping through a natural frequency of the aerostat. Vibration had no effect in removing wet snow or ice.

The high frequency vibrator had no visible effect at any time on any form of precipitation.

Polyurethane Coated Rigging

The first aerostat used on the project had polyurethane jacketed rigging. The extra weight of the coating was about as detrimental as the water which uncoated lines absorbed some of the time. Furthermore, the coated rigging and the Kevlar tether (which has a smooth polyurethane jacket) appeared to collect the same amount of ice as the uncoated nose line. The second aerostat used uncoated rigging which performed at least as well as the jacketed variety.

Pressure Pulsing

Pressure pulsing had no effect in removing snow or ice at any time. Either the expansion was not enough to crack the ice or cracked ice would still stick to the surface.

Snow Scraper

The snow scraper was very useful in removing snow or sleet from most of the hull while the aerostat was moored. The scraper could not be used on the fins, aft hull, or on the hull forward of the major diameter since it would slide off the nose. However, the scraper would not remove clear or rime ice without assistance from heated ethylene glycol.

High Velocity Blower

The back-pack blower was useful for removing dry snow and slightly useful in removing wet snow from the fins. Extension pipes were somewhat hazardous in that they could damage the aerostat. The blower was most useful in removing snow from the mooring system.

Heated Ethylene Glycol

The deicing machine was very useful in removing ice. It was slightly beneficial in removing wet snow or sleet. A strong stream would reach to the top center of the balloon. The hot ethylene glycol in conjunction with the snow scraper could be used to remove ice from the top of the hull. First the ice was softened by spraying a mist of deicing solution on the top of the hull, then the slush could be removed with the snow scrapers. The deicing solution always worked much better when hot.

Heaters

Heaters worked very well in preventing icing on the blowers, valves and pitot tube. These items were inspected during times when ice was present on the rest of the balloon and they always were found to be clear. However, the heaters were not very effective on the anemometer. They did prevent snow from clogging the anemometer, but ice and frost would form on the wire cage and stop the wind turbine from turning.

Knotted Ropes

Snow could be removed from the fins by striking them with a rope having heavy knots in it. This worked only at the extremities of the lower fins well away from the root of the fins.

Snapping of Lines

Snow could be removed from the handling lines by violently snapping them like a whip. This could also remove some rime ice or sleet.

Sudden Stops on Outhaul

On some occasions wet snow or sleet would slide off of the balloon if the winch was stopped suddenly during outhaul. This had no effect on ice removal.

Snow Balls

Snow could be removed from the upper fin or the root of the fins by throwing snow balls at it. Possibly this could be refined by using a tennis ball cannon or a similar device.

6. Other Findings

The aerostat flew continuously through two significant snow storms, one with cold, dry snow, the other with wet snow. No accumulation of snow could be detected on the aerostat while it was flying in either storm. In each case when the snow abated, the aerostat was recovered and inspected. Some snow had collected in depressions on the fins and wet snow had clung to impact areas on the aerostat. However, in no case was snow considered a problem with the aerostat flying.

While the aerostat is moored in light winds snow will collect on the hull and the scraper board was used to remove it. By far the best way to avoid snow is to fly at an altitude where there is some wind.

Ice in all forms is a problem. However, there are several warnings to the operators that ice is collecting; the tether tension slowly decreases and the pitch angle gradually increases since the ice load seems to collect well aft of the normal center of gravity. Although there are probably weather conditions that could cause very rapid ice accretion, these were not experienced in Vermont. In the worst conditions rime ice was collected at the rate of about 100 pounds per hour. This provided ample time for the ground crew to make adequate preparations for recovery if it became necessary. Of most significance is the unique set of conditions that must obtain for ice formation on the aerostat. In most cases the icing condition exists in a relatively narrow altitude band which suggests that it might be avoided. On several occasions the aerostat tether disappeared into the base of clouds, the temperature at the aerostat was below freezing and it was assumed that ice was being collected. Upon recovery, it was discovered that the tether was coated with ice along several hundred feet of its length, but the aerostat was free of ice. Figure 4 shows a typical collection of ice on parts of the aerostat.

Fig. 4. Ice collects on rigging and aerostat surface

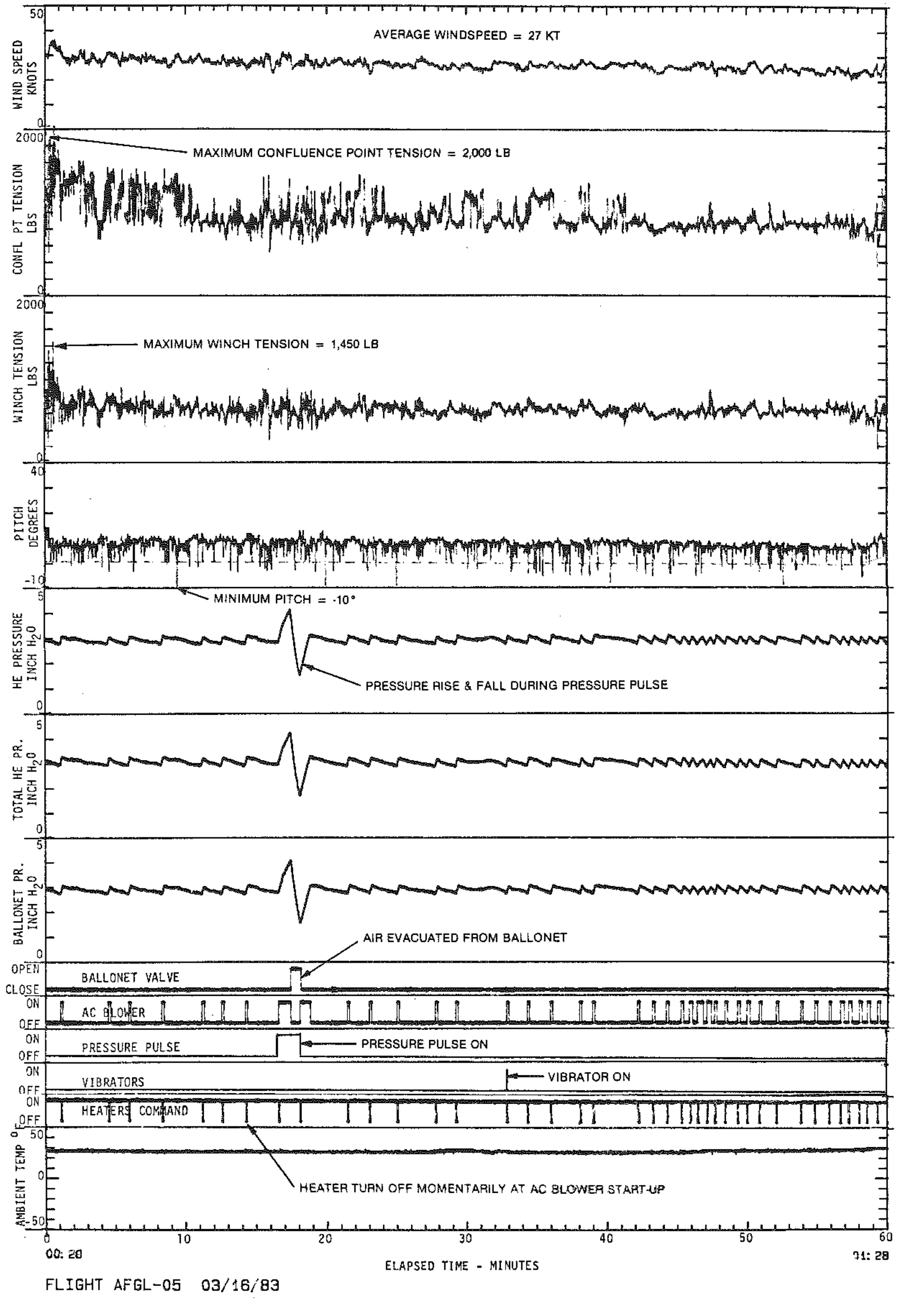

Fig. 5. Typical plot of aerostat flight data

Ice accretion on the tether is a separate problem. Although it is doubtful that the tether could collect enough ice weight to seriously affect the aerostat flight, the tether ice clogs the flying sheave at the end of the boom. If no effort is made to remove the ice from the tether before it passes over the sheave, the tether ice rapidly packs into and fills the groove in the sheave during aerostat inhaul. In fact, it takes no more than two or three rotations of the sheave to fill the groove. The ice must be removed with a sharp instrument. Heat is applied to the sheave from ducts on the mooring system heater. However, the present amount of heat is totally inadequate. It is very likely that the sheave icing problem can best be attacked by removing the ice from the tether before it contacts the sheave. This specific problem was not anticipated, but will require a workable solution for arctic operations.

The instrumentation recording system worked very well during the entire operations period thus providing a permanent record of all of the flight data. Figure 5 is an example of a typical recording made from the data collected on the HP 9825 discs. The figure is annotated to depict particular operational features.

The aerostat instrumentation performed well except for some early problems with the telemetry system. The microprocessor section of the telemetry was adapted from an existing system with several modifications. Several integrated circuits failed for unknown reasons at the beginning of the operational period, but the reliability of the overall system improved as the early failures were corrected.

The measurement of tether tension is of utmost importance to the safe operation of an aerostat, particularly in a winter environment. For this reason the tether tension was measured at two places, from a load cell located at the confluence point on the aerostat and from a load cell located on the level wind shaft of the tether winch. Although the load cells themselves are accurate, by the time the strain gauge bridge signals were amplified and reproduced at the ground console variations of several hundred pounds were often noted. Analog to digital conversion at the aerostat and the reconversion to an analog signal on the ground caused errors in the confluence point tension reading. Furthermore, the ground tension analog voltage was transmitted via a pair of wires buried in an underground conduit along with all of the power cable for the mooring and tether systems. Consequently, the tether tension readings which should have differed only by the weight of the tether supported by the aerostat, frequently varied in difference from 0 to 500 pounds.

Audible alarms were not part of the ground readout system initially. However, as the need for an audible alarm system became more apparent, the HP 9825 computer was programmed to emit an audible signal any time the helium pressure rose more than 0.5 IWG above the ballonet pressure (indicating pressure height) and whenever the helium pressure exceeded 4.0 IWG. Although not implemented, alarms for high and low tether tension and excessive pitch angle would have been useful.

7. Summary of Results

The STARS aerostats used in the North Warning project accumulated a total of 831.7 flight hours with the longest single flight lasting just over 160 hours. Heavy snow was encountered during two significant winter storms with no significant detrimental effect on the aerostat. Accretion of rime ice required the recovery of the aerostat when the ice load was becoming too heavy to support. Aerostat icing was searched out and frequently encountered. None of the airborne ice removal mechanisms were effective. The heated ethylene glycol mixture and scraper boards were, together, able to remove snow and ice loads from the moored aerostat. Table 3 is a summary of the 38 aerostat recoveries during the program showing the reasons for recovery.

Table 3. Summary of Aerostat Recoveries

Reason	Number of Occurrences
Checkout, test, routine docking	10
Maintenance	4
Telemetry Problems	6
Severe weather	4
Check, photograph and remove ice and snow	9
Add or remove helium	3
Demonstration	2
Total:	38

Figure 6 is a histogram of flying hours on a daily basis.

8. Conclusions

From the North Warning operations conducted in Vermont it can be concluded that:

1. Snow is not a problem for an aerostat in flight, but can be a significant problem for a moored aerostat in light wind conditions.
2. Adequate snow and ice removal techniques are available for use on a moored aerostat.
3. Ice accretion on an aerostat in flight can be a destructive problem in the temperature region between about 10°F and 35°F. Icing can be avoided by a larger aerostat capable of changing altitude by several thousand feet to get to a region free of icing conditions.
4. Many problems of extreme low temperature remain unanswered, but will require investigation prior to an arctic winter deployment.

The many recommendations for the improvement of a tethered aerostat for arctic deployment follow naturally from the test results and the conclusions. It is hoped that cold chamber tests can be conducted to qualify all parts of the aerostat and ground systems for operation in temperatures as low as -70°F. It is also hoped that a larger aerostat, capable of carrying a significant payload and operating as high as 15,000 feet can be deployed to the arctic for the winter of 1984 - 1985. The challenges of such a venture are exciting, but a methodical approach to anticipating, testing and solving of problems will be directed to a success oriented program.

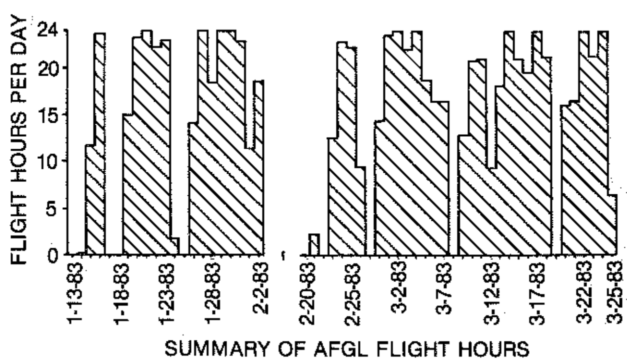

Fig. 6. Summary of AFGL flight hours

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