# A SENSITIVITY STUDY OF BOW VARIANTS ON THE DISTRIBUTION OF SEA SPRAY IN REGULAR HEAD SEAS



by

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B.S., Marine Engineering
Maine Maritime Academy
(1979)

NPS

Submitted to the Department of Ocean Engineering
in Partial Fulfillment of the
Requirements for the Degrees of

N00123-89-G-0580

NAVAL ENGINEER

and

MASTER OF SCIENCE IN NAVAL ARCHITECTURE
AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1990



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# Abstract

There has always been a need and desire to improve upon the operability of ships at sea. The driving force behind making improvements can be safety, economic, or militarily oriented. This paper deals with improving a ships operability by studying the effects of bow flare on the quantity and distribution of spray across the main deck under varying environmental conditions.

A 1:36 scaled model of a 3600 LTon displacement ship, resembling a U. S. Navy FFG-7 class combatant, was used throughout this study. The model was tested with four different bows with varying degrees of flare. A surfactant was added to the towing tank water to reduce the surface tension and increase the Weber Number in order to better simulate spray at the model scale. Environmental conditions imposed were regular head seas of a mean sea state 6 and generated true wind equivalent to 32 knots. One bow form was first tested in ordinary tank water so that a comparison could be made between the two surface tension conditions.

A 64% reduction in surface tension was achieved through the addition of the brand name surfactant AEROSOL OT-75. Though this value is relatively great, it corresponds to a Weber Number that is 22 times smaller then the required full scale value. The visual effect on the spray was to cause a finer droplet size and break up of the water sheet that normally is present rolling off the bow. With respect to the measurements taken, the reduction in surface tension resulted in; (a) a smaller volume of spray water being captured, (b) a change in the density distribution of the spray across the main deck, and (c) an increase in the wetted area on the main decking.

In the absence of any specific spray criteria in which to judge each bow's performance against, the general trend was to reduce the quantity of spray water delivered and limit its distribution with an increase in the bow flare. The one knuckled bow that was tested performed much worst then any of the conventionally flared bows.



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# Acknowledgements

I would like to acknowledge the U. S. Navy who sponsored my education at MIT and the David Taylor Research Center who supported and funded this thesis.

I want to thank Dr. Charles Ryerson of the Cold Regions Research and Engineering Laboratory, U. S. Army, for his initial encouragement and Mr. Rodger Compton, U. S. Naval Academy, for providing the model used throughout this thesis.

Finally, I want to thank my parents and close friends who provided me with the support and encouragement needed to survive through this unusually difficult period of my life. And to my sister Darla, whose help as a laboratory partner made this project possible.

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# Nomenclature

| | |
|---|---|
| DWL | Design Waterline |
| F | Freeboard |
| $F_k$ | Freeboard to Knuckle |
| $F_n$ | Froude Number |
| g | Acceleration due to gravity $9.8m/s^2$ |
| h | Height of fluid in pipette above beaker level in meters |
| $N_w$ | Weber Number |
| r | Inside radius of pipette in meters |
| LBP | Length Between Perpendiculars |
| T | Draft |
| $x_o$ | Bow overhang measured forward of station 0 at the freeboard height |
| $\delta_2$ | Deck edge angle at station 2 in degrees |
| $\delta_k$ | Knuckle defining angle at station 2 in degrees |
| $\rho$ | Fluid density in $Kg/m^3$ |
| $\sigma$ | Surface Tension in $lbs_F/Ft$ or Dynes/cm (conversion factor; multiply $lbs_F/Ft$ by 14695.75 to obtain Dynes/cm) |

# 1 Introduction and Background

## 1.1 Introduction

When one thinks of deck wetness both the professional mariner and the inexperienced layman conjure up thoughts of the fo'c'sle awash in green water. These may be accompanied by visions of a ship's bow plunging deep into oncoming waves, throwing mountains of seawater onto itself. Whether these memories stem from personal experience or the viewing of films such as "Victory at Sea"[1], they tend to ignore the less dramatic method of seawater delivery, *spray*.

## 1.2 Background

The present day design of the above water bow section form involves satisfying an operational seakeeping requirement by applying the laws of statistics and probability to ship motions, and extracting from this marriage linear dimensions that the naval architect will mold into a set of hull lines. Further complicate this process by requiring a minimum (or maximum) volume forward, limiting bow freeboard for visibility, maintaining continuity of the hydrodynamicist's design in transition across the waterline while still keeping the structure producible, and it is no wonder that bow spray characteristic are accepted at their default value. This is not to say that the reduction of spray is not considered at all. Attempts are made to design flush housed anchors and locate as much equipment and fittings below deck as possible. But more often then not, the first indication of an unacceptable spray condition is when the ship first goes to sea. As an example, the U S Navy's FF-1052 Knox class warships experienced an unforeseen deck wetness problem. This was corrected successfully by retrofitting with spray rails and bulwards, but such remedial action may not always be so successful. It therefore remains prudent to improve our ability to predict full scale performance before detail design is initiated.

The term "deck wetness" tends to be author specific. Many adjectives have been used to describe varying degrees of the seawater delivery phenomenon. Among them, R. N. Newton[2] proposed three degrees of wetness back in 1959, they were;

| | |
|---|---|
| Dry ............. | Light spray wind delivered |
| Wet ............. | Heavy spray, breaking waves above the weather deck providing the source of wind delivered spray |
| Very wet ......... | Submergence of the weather deck and shipping of green water |

Additional terms that appear frequently in the literature are mild wetness, severe wetness, and green water. Each description applies well within the context of a specific paper, but may lack correlation when compared to a similar report by a second author. For the purpose of this paper, spray will be defined as wind delivered water droplets and deck wetness will relate to the shipping of green water. In reference to Newton above, spray will include both the light and heavy conditions but will not be source dependent.

There are basically two distinctions that differentiate deck wetness and spray. They are: the mechanism leading to the origination of the wetting event and the delivery process of the seawater.

Generally, deck wetness has its origin in the large relative motions between a ship's bow and the instantaneous height of the waves just below the point of interest. This point is usually a station or sectional position along the deck edge. When the ship's vertical plane motions exceed a threshold value (based upon the ship's length, speed, heading with respect to the wave direction, and wave spectrum) the probability of the local forward freeboard being exceeded is great. This exceedence generally results in a deck wetness event.

As the ship's bow pitches down about the transverse axis of rotation, the distance between the weather deck and water surface decreases. If the pitching motion is in phase with the ship's heaving motion, then the freeboard is further decreased by the resultant parallel sinkage. Any trim by the bow, associated with powering of the ship, further reduces the separation between the water surface and the weather deck. These mechanisms effectively bring the weather deck closer to the ocean's surface by reducing the local freeboard, hence increasing the probability of a deck wetting event.

The second half of the process is the rising of the water surface relative to its mean level. The height of the surrounding sea is the summation of three different elevating actions. The most obvious is the actual height of the individual wave itself, or the characteristic height of the wave spectrum. Next, superimposed upon this is the bow wave caused by the powering of the ship. Finally, there is the dynamic swell up of water displaced by the hull as it pitches and heaves downward. The combination of these three events provides the instantaneous height of the wave above its mean level.

Both processes are time dependant within a given wave spectrum. As the processes become further out of phase with one another, the probability that the combination of down pitching and wave height will exceed the linear measured freeboard distance increases. This is the origination of the deck wetting event and the present basis for predicting them.

It is recognized that not every freeboard excedence event results in a wetting. The reason for this lies in the delivery method. For shipping green water, the effects of wind can generally be ruled out because of the large mass of water involved and the limited time duration that the forces of the wind have to act upon this suspended mass. Delivery can occur if the seas are head seas and the ship is slow in its recovery motions. The locally elevated water mass above the deck edge is allowed time to partially collapse inwards onto the weather deck under the influence of gravity. If the seas are approaching at an angle on the bow from forward of the beam, and exceed the local freeboard, the forward momentum of the wave will carry it onto the ship. The resulting wetness event is a spilling tumbling mass of water, similar to a wave breaking upon a beach.

Spray on the other hand is generated from points known as spray roots. Saunder's[3] describes these spray roots as an area of high dynamic pressure accompanied by a large pressure gradient. The pressure gradient serves to accelerate the fluid rapidly, and under the influence of internal/external turbulence and gravity, the accelerated fluid tears into irregular shapes. The accelerated fluid may initially appear as large undefined volumes of water or nearly transparent sheets. These shapes then continue to rupture into smaller particles till the surface tension forces prevent further disintegration under the existing environmental conditions. At this point most of the liquid is in the form of spherical spray drops of approximately uniform size. As the individual shapes and droplets become smaller, their mass has reduced to the point enabling them to be influenced by the prevailing local winds. This then becomes the method of delivery resulting in what we call spray.

Spray roots that are associated with high dynamic pressures are generally ship structural items that protrude into the fluid stream. Some examples are bulwarks, breakwaters, exposed anchors and their flukes, and blunt bow stems. Ricketts and Gale[4] reported that a major source of spray generation on the USS Midway (CV-41) was from scupper extensions and boat guards that were installed near the waterline. These structures protruded from the ship's side into the flow from the rising wave pattern. It was not uncommon for the spray generated here to reach the flight deck some forty feet above.

High degrees of flare can cause spray by accelerating seawater above a threshold velocity to the point of instability and turbulence. Water that jets out from under a planning craft hull is a form of spray that results from the high loading pressures and gradients associated with planning. Additionally waves that approach the bow at an angle and slap into the ship's vertical (or flared) sides create high pressures zones that locally cause a break up of the fluid and can result in spray. If the curvature of the bow stem is too blunt, high stagnation pressures result at the stem causing a bow feather. This is a form of spray that climbs up the stem and fans out, usually to both the port and starboard sides of the bow.

The final spray source is from the breaking tops of rolling or cresting waves. These waves must be locally elevated above, and in the vicinity of, the deck edge such that their turbulent white caps can be transported to the ship by the prevailing winds. These waves can build rapidly by the constructive interference of the out going bow wave and incoming sea wave. Zakrzewski[5] reported that the quantity of wind-generated spray off the surface of waves doesn't amount to much even for small ships in high seas with respect to water delivery. This is because any water torn from the surface will generally re-enter the sea a short distance later. The wind forces involved do not generate a great enough pressure gradient to rupture the water droplets into transportable sizes. Hence their probability of delivery to the ship is low unless they are initially elevated and thrown from the sea's surface by the action of the breaking or cresting wave. Zakrzewski continues on to state that the major source of sea spray that is delivered to the ship is from wave/ship impacts and what we term spray roots.

In a comparison between deck wetness and spray, there is no question that the shipping of green water is the severest form of delivery and deservedly receives priority when it comes to establishing a bow design. Each green water event can involve tons of water locally concentrated over a relatively small area. This may result in structural damage with possible flooding, the carrying away of deck cargo and deck mounted equipment, and in the extreme case the capsizing of the vessel. It will affect the ship's operability by limiting access to weather decks and can limit mobility by necessitating course changes and/or speed reductions.

In contrast, a single spraying event may deliver hundreds of pounds of water to a ship. The criticality of this single event is reduced because the mass of water delivered is such a small fraction of the total ship's weight and is distributed over a greater area. This has been the justification in the past to accept the resulting bow performance with respect to spray without specifically incorporating features into the design. Yet spray can have a major impact on ship operability and survivability through the cumulative effects of repeated events. Zakrzewski[6] reported in Table 1.1 that the vast majority of recorded icing events are sea spray related. The threat from the accumulation of topside ice is a seriously impaired stability condition. Secondary effects are limited access to the weather decks and the possible degradation of topside mounted equipment and sensors. If ice accretion is rapid, the ship will be required to alter course and speed to limit further ice growth and possibly be forced to seek a safe harbor until the ice can be removed.

Spray also acts to obscure vision, keep any deck cargo and equipment continuously wet, and with respect to military operations, spray makes a ship more detectable by enhancing the wake, creating a bow glow if bioluminescent organisms are present, and increases radar reflexivity due to the presence of a spray cloud.

Model testing has been performed by many notable authors in an attempt to determine the merit of different above water bow forms on the severity of deck wetness. The majority of the tests were conducted in regular and irregular head seas with varying bow designs in the absence of wind. The papers generally agreed on the positive benefits

Table 1.1 Causes of Icing of Ships

| Region | Number of Observations | Sea Spray | Spray, Fog, Rain, Snow | Other Type |
|---|---|---|---|---|
| All Seas | 400 | 89% | 7% | 4% |
| North Pacific North Atlantic | 3000 | 89.8 | 7.5 | 2.7 |
| Arctic | Unkwn | 50 | 41 | 9 |
| Gulf of St. Lawrence | 100 | 81 | 2 | 17 |
| Scotian Shelf | 536 | 94.2 | 3 | 2.8 |
| Grand Banks | 100 | 97 | 2 | 1 |
| NE Newfoundland Shelf | 233 | 95.9 | 1.4 | 2.8 |
| Labrador Sea and Davis Strait | 72 | 86.9 | 11.1 | 1.7 |

associated with increased freeboard, but varied greatly on the merits pertaining to other architectural parameters. The survey by Lloyd[7] of many authors and commentators bares this out and is reproduced in Table 1.2.

A search of the literature dealing with spray centers mostly on the late 1930's to early 1940's era. The research dealt with controlling the height of spray blisters originating from flying boat pontoons (planing craft). Pontoon hull forms were tested in tow tanks and categorized according to their resistance first, then porpoising while in the displacement mode, and finally with respect to the dimensions of their spray blisters when in the planing mode. Corrections were then sought to control the spray blister dimensions by experimenting with spray strips after the design was complete. More recently Koelbel[8] performed a literature search on the spray and wake characteristics of high speed planing craft. His work is an excellent listing of approximately 300 references, some of which relate hull parameters of planing craft to spray characteristics.

Table 1.2 Literature Survey on effects of

Above Water Bow Form on Deck Wetness

| Author | Reference | Freeboard | Flare | Overhang or Rake | Knuckle |
|---|---|---|---|---|---|
| Hovgaard | 11 | | + | | |
| Kent | 12, 13 | | + | + | |
| McDonald & Telfer | 14 | | + | | |
| Edward & Todd | 15 | + | + | | |
| Allan | 16 | | + | | |
| Saunders | 17, 18 | + | - | - | |
| Abkowitz | 19 | | + | | |
| Newton | 20 | + | + | | + |
| Tasaki | 21 | | - | | |
| Swaan & Vossers | 22 | | - | | |
| Van Sluijs & Gie | 23 | | + | | + |
| Lloyd | 24 | + | - | + | |
| O'Dea & Walden | 9 | | + | | O |
| Bhattacharyya | 25 | + | + | | |

+ : Benefical Effects
- : Detrimental Effects
O : No Effects

The authors he references generally agree on the merits of spray strips in controlling the distribution of spray, which has some application towards displacement craft. But because of the high speeds and planning characteristic of these craft, the hull form above the chimes is not referenced with respect to spray. This is due from the fact that the origin of spray occurs at the interface between the planning surface (underneath portion of the craft) and the water's surface. Design investigations were concentrated in this area. All of the tests were conducted in the absence of wind.

## 1.3 Objectives

The objective of this paper is to determine the effects of bow flare on the distribution of sea spray across the foredeck of a large displacement craft under varying environmental conditions. Tests were performed on a scaled 3600 LTon modern warship equipped with a series of interchangeable bows. To help overcome the known scale effects surface tension has in model spray testing, a wetting agent was added to the towing tank water. This is to partially scale the Weber Number to help develop trends that can be expanded upon so as to more accurately predict full scale performance.

# 2 Equipment Description

## 2.1 Model

The model used was that of a modified U. S. Navy FFG-7 class frigate. This particular model was chosen because of its availability and the unique characteristic of having a family of interchangeable bows. It had previously been used in deck wetness experiments by Lloyd[7], O'Dea and Walden[9], and in a transom geometry study by Kiss[10]. The modifications from class design affected the afterbody (station 10.7 and aft) and the forebody (station 5 and forward).

The afterbody had what Kiss[10] referred to as the "narrow" beam variant (16.74% narrower transom then baseline design). The resulting lines from this variant were smoothly faired into the midbody at the point of maximum sectional area (station 10.7). The modification was accomplished while keeping the prismatic coefficient, block coefficient, and displacement-length ratio constant. Reference 10 gives a detailed description of the narrow beam afterbody.

The forebody differed from class design by incorporating 4 geometrically altered bows. Each bow varied in degree of flare and was constructed to fair smoothly into the hull at the design waterline (DWL) and station 5. This maintained the underwater hull form constant while only affecting the above water bow characteristics. The forebody was also fitted with a scaled superstructure to account for its presence as an obstruction in the path of wind and spray. Figure 1 shows the general model profile.

The model is a 1:36 scale made of sugar pine (foreward of station 10.7) and closed-cell foam (aft of station 10.7). It was designed and constructed at the U. S. Naval

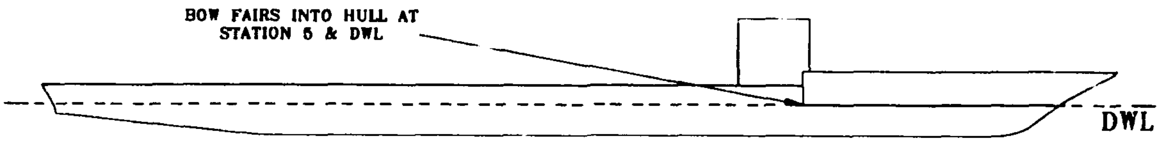



Figure 1. Model Profile

Academy, Annapolis, Maryland, and was loaned to the Ocean Engineering Department by the Hydromechanics Laboratory to support this study. The overall hull characteristics are given in table 2.1.

Table 2.1 Hull Characteristics

| Item | Model | Ship |
|---|---|---|
| LBP | 11.32 FT | 407.52 FT |
| Beam | 1.286 FT | 46.3 FT |
| Draft | 0.427 FT | 15.4 FT |
| Trim | Level | Level |
| LCG Aft Midship | 0.049 FT | 1.8 FT |
| Mass | 171.41 lbs Fresh Wtr | 3672 Long Tons Salt Wtr |

All four bows were designed as a series defined by the flare angle at the deck edge of station 2. See figure 2. The waterlines, section shape at station 2, and the stem profile were all defined by polynomials. Each polynomial was derived to satisfy the chosen boundary condition of smooth fairing at station 5 and at the design waterline while meeting the desired flare defined at station 2 and the imposed bow rake.

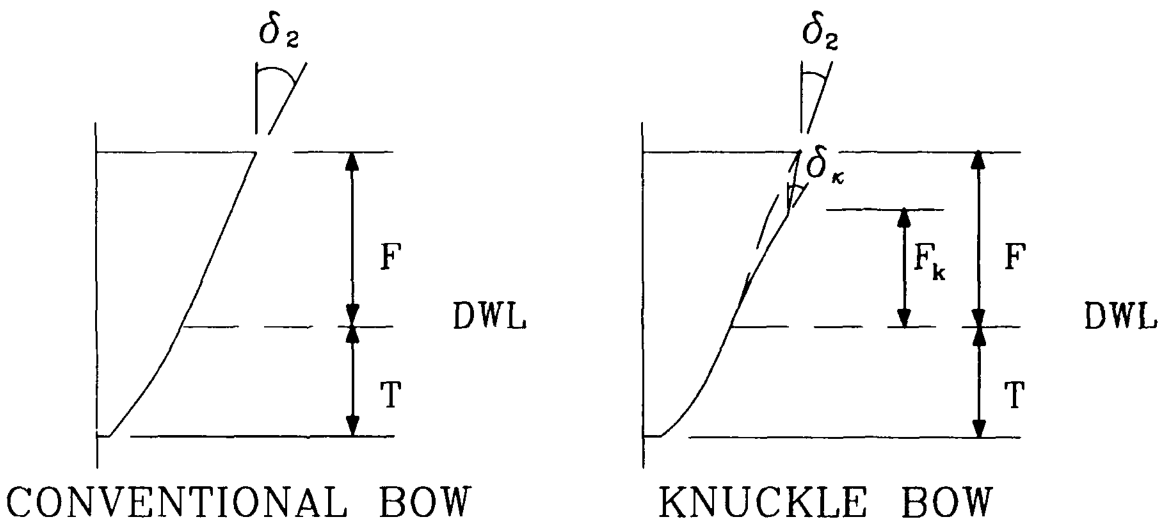



Figure 2. Defining Flare Angle

All four bows had a constant freeboard that was equal to 6% of the ship's length (LBP). This represented a full scale height of 24.5 FT which corresponds to the full scale freeboard at station 0.5 in the absence of the bulwark. Additionally the overhang of each bow was defined by the relation:

$$\frac{X_o}{LBP} = 0.002\delta_2$$

$\delta_2$ in degrees

This causes the overhang to vary directly with the degree of flare and establishes the bow rake parameter that each polynomial must meet. Table 2.2 identifies the flare and overhang relations associated with each bow used.

Bow 4 differs from bows 1-3 by including a knuckle in its design. The knuckle is defined by the angle $\delta_\kappa$ and by the "phantom" deck edge angle $\delta_2$ in figure 2. The

Table 2.2 Bow Parameters

| Bow | $\delta_2$ | $\delta_\kappa$ | $\frac{X_o}{LBP}$ |
|---|---|---|---|
| 1 | 35 | 0 | 0.07 |
| 2 | 45 | 0 | 0.09 |
| 3 | 55 | 0 | 0.11 |
| 4 | 35 | 45 | 0.07 |

phantom angle of 35 degrees results in bow 4 having the same deck shape, deck area, and rake as bow 1. The knuckle height was arbitrarily set to be parallel to the keel and 3.75% of LBP above the designed waterline.

The body plans, waterlines, and stem profiles for all four bows are diagramed in figures 3, 4, and 5 respectively. Figure 6 shows the distribution of flare along the freeboard deck edge. Complete details on the bow design and manufacturing process are reproduced in appendix A of this paper.

In order to generate spray below the region of flare, spray root devices were fitted to each bow in the same manner as turbulent stimulators are fitted in resistance testing. The devices were made of plastic strips measuring 3.00 x 0.56 x 0.19 inches that were attached to each hull using silicon rubber cement. The strips were located such as to give a spray origin at the design waterline between stations 0 to 1. This resulted in spray rising above the freeboard at approximately the same stations. These strips were placed in the same location on each bow form as follows;

(a) 1 strip 2 inches forward of station 0 at the stem intersection,

(b) 1 at station 0 starting at the design waterline,

(c) 2 - 2 inches aft of station 0 stacked with the lower strip extending one half its self length below the design waterline,

(d) 1 at 4.5 inches aft of station 0 starting at the design waterline,

(e) 1 at 6.5 inches aft station 0 extending one half self length below the design waterline.

All spray root devices were installed perpendicular to the calm water's surface and on the port side only. See figure 7.

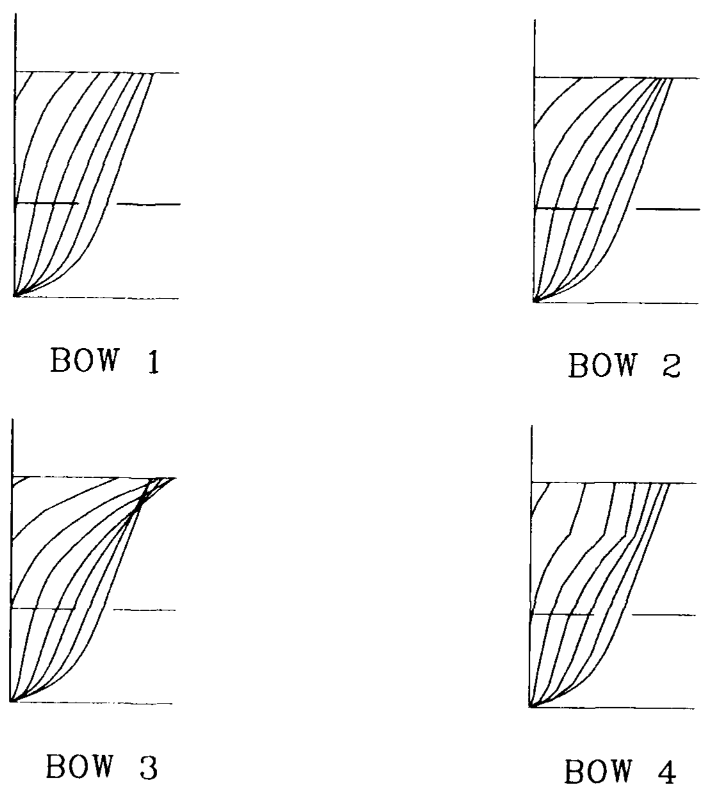



Figure 3. Body Plans

The model was ballasted with lead to the weight in Table 2.1 and a longitudinal center of gravity for an even keel (0 trim). The lead ballast was then distributed to obtain a gryradius of 25% the length between perpendicular.

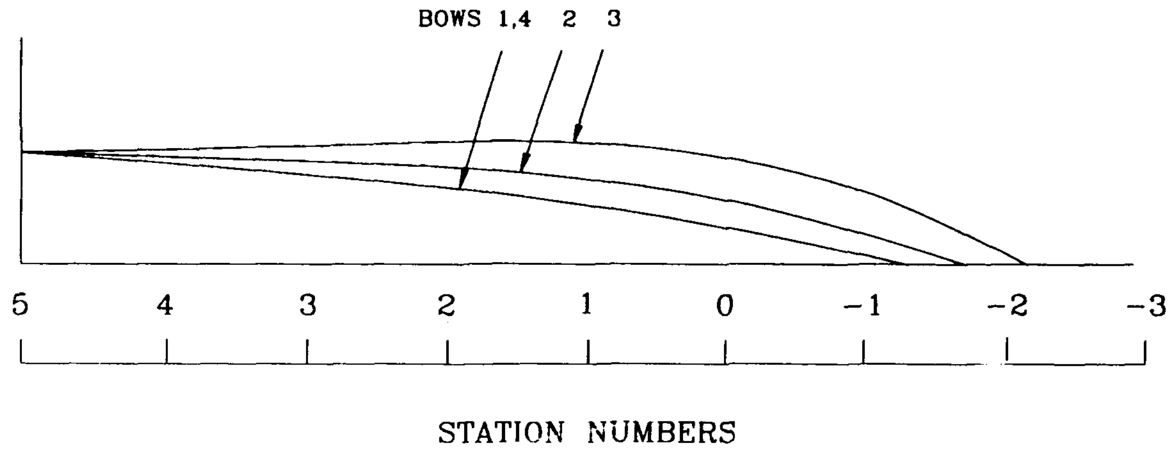



Figure 4. Plan View

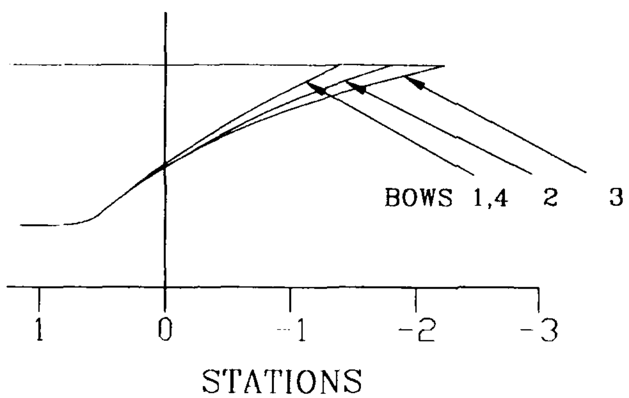



Figure 5. Stem Profile

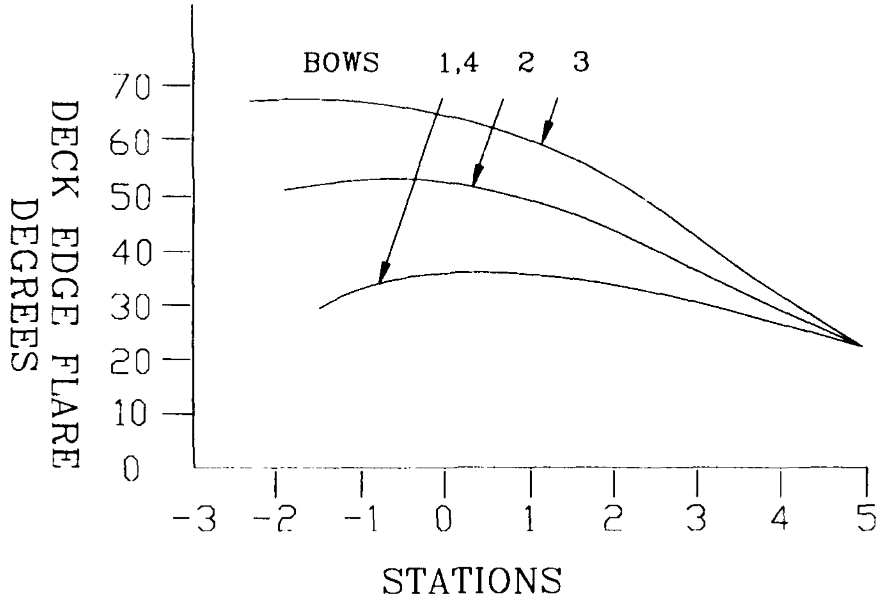



Figure 6. Flare Distribution

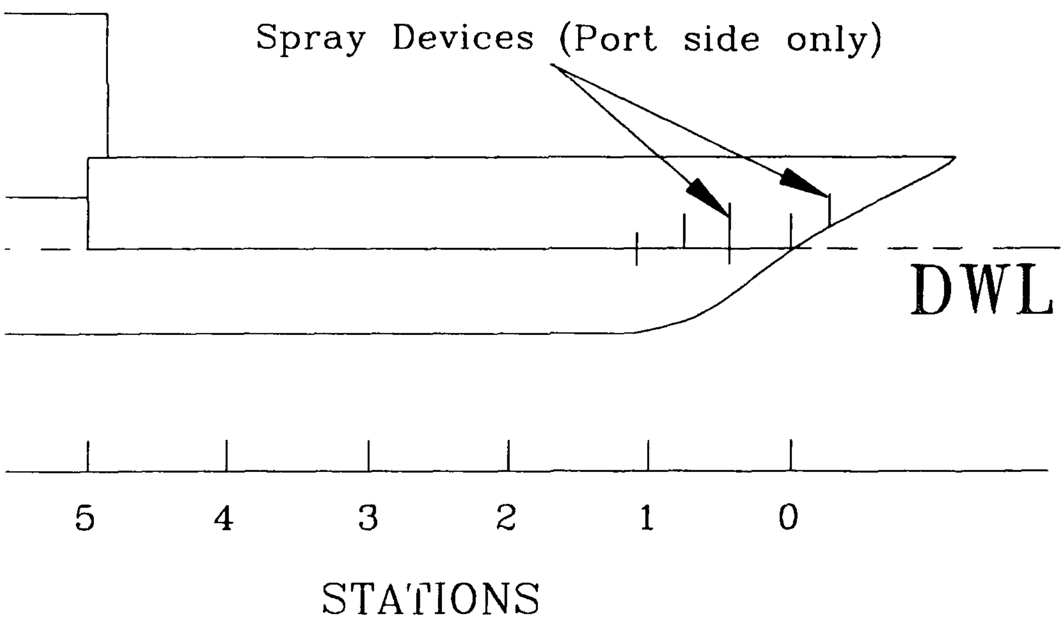



Figure 7. Spray Root Device Location

## 2.2 Tow Tank

All model testing was performed at the Massachusetts Institute of Technology's 108 foot Ship Model Tow Tank. The width of the tank is 8 feet 7 inches and water level was maintained at 3 feet 8.75 inches throughout the testing sequence. Water temperature was kept at 80°F. This facilitated in water model alterations and surfactant dilution.

Regular waves were generated using the installed wave making system.

Wind generation was accomplished by a double inlet squirrel cage blower belt driven by a 1 horsepower motor. The blower was mounted on the carriage and moved with the model down the tank. Its output was re-directed 180° by a 24 inch exhaust hose into a 5 foot square ducting. The ducting housed a series of 1.5 inch diameter tubes that reduced any turbulence induced from the 180° turn in the hose. Down stream of the tubes was installed a grid of horizontal PVC piping to produce a one seventh power velocity profile. Spacing of the grid piping is given in reference 26 and selection of the velocity profile was from the <u>NATO Sea State Numeral Table for the Open Ocean North Atlantic</u>. The entire ducting arrangement was able to swing off center to a maximum of 15°. This allowed for relative winds to be generated in addition to head winds, because the blower traveled with the model. It had the capacity to develop the resulting relative wind vector (true wind and ship speed).

# 3 Experiment Procedure

## 3.1 Model

The model was connected to the overhead towing carriage by a device that allowed it to pitch and heave freely. Yaw, surge, roll and sway were locked during all runs. A velocity of 18.38 knots full scale (Froude Number 0.271) was selected and used throughout the testing sequence. After each bow was fitted to the parent hull, the hollow dug-out present in each bow was overlaid with a 1.2 MIL thick sheet of plastic that served as a catch tank for spray. The sheet was weighted such that the spray water collected at a central point. This facilitated the removal of water after each run. Each bow was then decked over with ordinary window screening that was cut to fit within the deck plan. The screening served two purposes; it first allowed spray to penetrate the main deck and collect below while shielding this volume of water from the effects of the generated winds. Secondly, it supported horizontally the blotter paper that was used to map the spray distribution over the main deck.

The model was started down the length of the tank only after the first fully developed wave had passed completely astern.

## 3.2 Waves

All model runs were into the same regular head seas. Each wave had a characteristic significant mean wave height of sea state 6, but with a considerable shorter model period. The generated wave characteristics are given in table 3.1.

It was recognized early on in the preliminary testing phase that extra-ordinary measures would have to be taken to achieve spray while avoiding the shipping of green water. Initially spray was attempted by taking advantage of extreme ship motions to

Table 3.1 Generated Wave Characteristics

| Item | Tank | Full Scale |
|---|---|---|
| Wave Height | 0.458 FT | 16.4 FT |
| Wave Length | 5.1 FT | 183.6 FT |
| Percent LBP | 45% | 45% |
| Frequency | 1Hz | 0.17Hz |
| Period | 1 second | 6 seconds |

produce a "slam" generated spray. Various wave length to ship length ratios were tried at Froude Numbers that resulted in the greatest relative vertical velocity between the falling bow and rising wave. These combinations produced out of phase ship/wave motions and achieved the desired impacts, but also resulted in fore foot emergence and bow stem plunging with the associated shipping of water. To decouple the spray event from the deck wetting event (green water), the wave length was shortened to limit model pitching motions and its slope was steepened to increase the rate of convergence with the bow and spray root devices. Although the probability of encountering the resulting wave characteristics at sea is unknown, it did achieve a desired spray event. By generating regular head seas, each bow/wave collision also resulted in a spray event that proved to be very repeatable. For the scope of this study the regular waves eliminated the time associated with waiting for a spraying event in irregular seas.

## 3.3 Wind

Each bow was tested under the same three wind conditions listed in table 3.2. The full scale velocities are within the sustained wind speed range associated with sea state number 6 at a height of 19.5m above the ocean's surface.

Table 3.2 Wind Conditions

| Ducting Angle on Port Bow | Ship Speed (Knots) | True Wind (Knots/Degree) | Relative Wind (Knots/Degree) |
|---|---|---|---|
| 0° | 18.38 | 32.6/0.0 | 51/0.0 |
| 7.5° | 18.38 | 32.8/11.7 | 51/7.5 |
| 15° | 18.38 | 33.6/23.2 | 51/15 |

## 3.4 Surfactant

The purpose of the surfactant addition is to document the effects a reduction in surface tension has on spray distribution and captured water quantity.

The bow with the 35 degree flare at station 2 (Bow #1) was tested in fresh water before the surfactant was added. This was to establish a baseline that the same bow could be compared to after the surface tension was reduced. The remaining three bows were then tested in the a[illegible]d tank water. The data from both sequences of runs involving the 35° flared bow were compared to assess the effect that partially scaling Weber Numbers, in addition to Froude scaling, has on the ability to predict full scale performance.

The surfactant, brand name Aerosol OT-75, was poured into the tank water after completion of the first series of tests on bow #1. The solution was then mixed using a combination of the installed filtering system, tank circulating system, wave making paddle and small outboard trolling motor. The tank water was mixed until all visible evidence of striations were eliminated and the water appeared as a homogeneous light cloudy solution. Samples were drawn from the tank so that the surface tension could be determined. Appendix B gives the results in determining the towing tanks surface tension.

## 3.5 Video

A video camera was mounted on an arm that extended out from the carriage. It's field of view was an aerial perspective of each bow. A video camera recorder was mounted on the carriage and recorded each model run to assist in data analysis. A remote sending unit was also employed so that the control room operator could view each run in real time on a remote monitor.

## 3.6 Spray Distribution and Water Collection Measurements

### 3.6.1 Spray Distribution

Spray distribution was marked by placing a colored sheet of absorbant blotter paper over each bow. The overlays were cut to fit each deck and included a 2 inch square grid system whose origin was centered at station 0. As spray landed on the paper it was immediately absorbed leaving a discoloration that varied in intensity directly with the quantity of water absorbed.

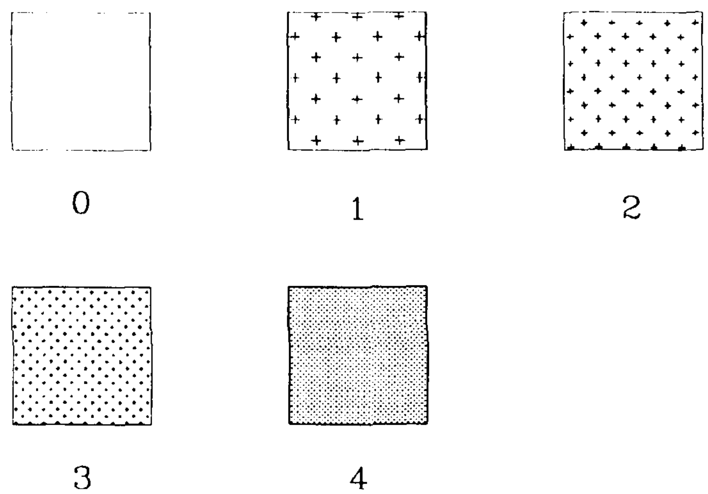
At the end of each run, a still picture of the overlay was taken in addition to the video record. The overlay was then removed for drying while the model was toweled off in preparation for receiving the next overlay.

The spray distribution was then mapped by viewing the video footage at one sixth normal playback speed. Each two inch square cell was assigned a value of 0 to 4 depending on the severity of the wetness evident at the end of each run. The 0 to 4 scale values had the following visual representation:

| | |
|---|---|
| 0 | No wetness or discoloration present |
| 1 | 1 to 24% of cell area slightly discolored |
| 2 | 25 to 60% of cell area discolored slight to medium when compared to the base color |
| 3 | 61 to 99% of cell area discolored medium to heavy when compared to the base color. |
| 4 | 100% of cell area medium to heavily discolored |

When assigning cell values, it was reasonably easy to distinguish between choices by using a combination of discoloration (slight, medium, and heavy) and percent coverage. For instance, no cell assigned a value of 1 had heavy discoloration unless it bordered a cell assigned the value of 4. In these cases it was evident that the repeated wetting and subsequent absorption of water in the 4 cell spread over into the 1 cell. This fact was verified through video footage and occurred exclusively in runs of the 35° flared bow, in regular tank water, and the knuckled bow. Likewise cells that were assigned a value of 2 never exhibited heavy discoloration and were easily categorized separate from value 3 cells. Exceptions noted were cells that border between areas of like values. These cells were considered to have two value when border lines were being drawn up.

Once all cells were assigned values, natural boarders became evident. The main deck plan view for each bow type was constructed using computer drawing software (AUTOCAD). The natural boarders between like cells were then transferred onto the plan views. A varying density of crosses were then used to shade each different cell area. This gave a visual feel for the spray density distribution that occurred over the main deck. The shading densities are shown below. No attempt was made to quantify the amount of spray water associated with each shade or cell value.




The total shaded area was then measured using the same AUTOCAD software. This area was averaged with subsequent runs under the same environmental conditions. It was then compared to the total deck area to arrive at a percent coverage. Appendix C contains these deck drawings for each bow type under the conditions tested.

### 3.6.2 Water Collection

Spray water was collected by running the model with just the screen decking after completion of the spray distribution tests. Water would penetrate the screen and collect in the weighted depression on the underlying plastic sheet. A non-absorbant mesh was placed in the depression to break up the waters' surface area and prevent it from moving with the ships motions.

The amount of water collected was bow specific as expected. Trial runs were conducted until the number of runs was determined that resulted in the collection of a measurable amount of water. Once this value was known a series of runs were preformed. One individual series would vary from 1 to 4 runs depending on the bow being tested. It was desired to limit the amount, and therefore weight, of water collected forward. This minimize the effect such weight had on the models' trim and pitch/heave motions.

When a collection run was completed, the deck screen and non-absorbing mesh were removed. Any water trapped in these items was deposited in the catch depression by gently tapping them until all apparent water had been rejected. The pooled water was then removed through a straw and suction device into a graduated cylinder. The model was then towel dried in preparation for its next run.

During data analysis the video footage was used to count the actual spray events so that an average quantity per event could be determined. The video was also used to verify the similarity of each spray event under the same testing condition. This fact of similarity and reproducibility was necessary in justifying a high correlation factor between the spray distribution and water collection runs. In this way the water collected during one run could be compared with the spray distribution obtained for a separate run, but under the same conditions.

# 4 Data Analysis

## 4.1 Interpretation of Reduced Surface Tension Results

It is worth noting again at this time the factors that were held constant and those that varied in the testing sequence. Table 4-1 list the major items that remained fixed during all phases of testing. Those items that varied under controlled conditions are listed in Table 4-2. Because the true wind direction varied directly with the position of the ducting, and the ducting position is synonymous with relative wind, all three terms are used interchangeably in this paper. Data gathered during each phase of testing was quantity of spray water and spray pattern distribution across the main deck.

Table 4-1 Fixed Parameters

| Item | Value |
|---|---|
| Ship Speed | 18.38 Knots |
| Waves | Mean Sea State 6 |
| Freeboard | 6% of LBP |
| Displacement | 3672 LTons |
| Dimensions | Underwater Hull Form |
| Spray Devices | Same Location |

Table 4-2 Varying Parameters

| Item | Value |
|---|---|
| Wind Direction | 0° 7.5° 15° |
| Bow Flare | 35° 45° 55°<br>35° Knuckle |
| Surface Tension | 26 Dynes/cm<br>72 Dynes/cm |

All the data taken has been reduced to three forms that are used to support the following analysis. They are the drawings that appear in Appendix C, Table 4-3, and the figures that are presented in this chapter.

The surface tension of the tank water was reduced 64% during the testing of the 35° flared bow form. Figure 8 compares the reduction in surface tension to the percent of the main deck area that noticeably received spray. As the surface tension was reduced the spray covered a greater percentage of the main deck. This trend held as the angle of the ducting (ie. relative and true wind) increased from 0° to 15°.

Table 4-3 Numerical Data

| Bow Type Flare Angle (Degrees) | Duct Angle (Degrees) | Water Qty Per Event (ml) | Spray Cover Main Deck (% Area) | Average Spray Flux $(ml/cm^2)10^{-3}$ |
|---|---|---|---|---|
| 35 | 0.0 | 0.22 | 48.83 | 0.164 |
| No | 7.5 | 0.40 | 70.23 | 0.208 |
| Surfactant | 15 | 0.55 | 66.67 | 0.301 |
| 35 | 0.0 | 0.10 | 55.67 | 0.066 |
| | 7.5 | 0.42 | 83.33 | 0.184 |
| | 15 | 0.88 | 98.57 | 0.326 |
| 45 | 0.0 | 0.10 | 86.37 | 0.035 |
| | 7.5 | 0.28 | 86.20 | 0.097 |
| | 15 | 0.29 | 95.90 | 0.090 |
| 55 | 0.0 | 0.07 | 44.70 | 0.037 |
| | 7.5 | 0.09 | 53.90 | 0.039 |
| | 15 | 0.03 | 73.47 | 0.096 |
| 35 | 0.0 | 1.64 | 93.40 | 0.641 |
| Knuckle | 7.5 | 5.34 | 95.83 | 2.033 |
| | 15 | 6.55 | 94.97 | 2.516 |

The increase in deck area coverage is attributed to the further extent that finer spray travels under the influence of the relative wind. Finer spray refers to visibly smaller

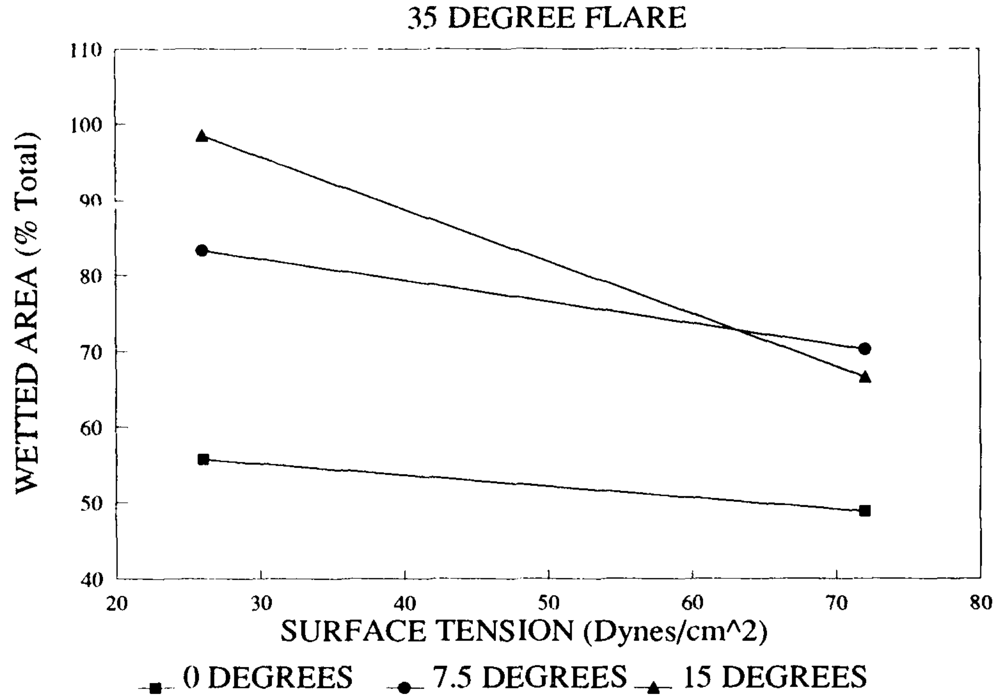



Figure 8. Spray Distribution vs. Surface Tension

particles of water. The break up of the spray into these smaller droplets is a direct result of the reduced surface tension and is evident when viewing the video tapes. A comparison of the corresponding duct angles of the 35° flared bow in appendix C, with and without surfactant, initially shows that as the surface tension was reduced, the extent of heavy spray decreased while the area of light to medium spray increased. Without surfactant the droplets did not scale down and remained relatively large. Hence their distribution was limited because of their size (mass) and lack of transportability by the wind. These larger droplets resulted in a heavy spray distribution in the vicinity of the port deck edge (recall that spray generators were only installed on the port side). When the surfactant was added the reduction in surface tension allowed the droplets to rupture into smaller particles. These smaller particles were then carried further onto the main deck, under the same wind conditions, reducing the amount of spray being distributed heavily along the deck edge. Appendix C shows diagrammatically the changing spray distribution and the apparent trade off between the heavy and lighter spray densities with surface tension.

From 7.5° to 15° positioning of the ducting, there was very little change in the wetted area and spray density distribution of the untreated water runs. However, the 15° wind angle with the reduced surface tension condition showed the re-emergence of the heavy spray distribution along with a continued growth of wetted deck area. Review of the video footage showed that not all of the spray was rupturing into a consistently fine particles. Some larger particles and remnants of a water sheet still existed and were now influenced enough under the greater relative wind angle to be carried back onto the deck.

Figure 9 shows that as the wind's angle on the bow increases, the quantity of spray water per event increases as expected. Simply stated, as the relative angle of the wind increases, its resulting force vectors act more in the direction required to favorably transport spray onto the main deck. The smaller the individual particle mass the easier it is to redirect. Spray that consists of a large quantity of small particles will be influenced to a greater extent then if the spray were formed of large particles. This becomes evident by the larger quantity of water collected per event for the reduced surface tension at the higher wind angles.

Figure 10 compares the quantity of spray water against the reduction in surface tension.

When considering head winds, the amount of water per spray event decreases with surface tension. A comparison of the distribution mapping in appendix C shows that there is a reduction in the heavy to medium spray area along the port deck edge when

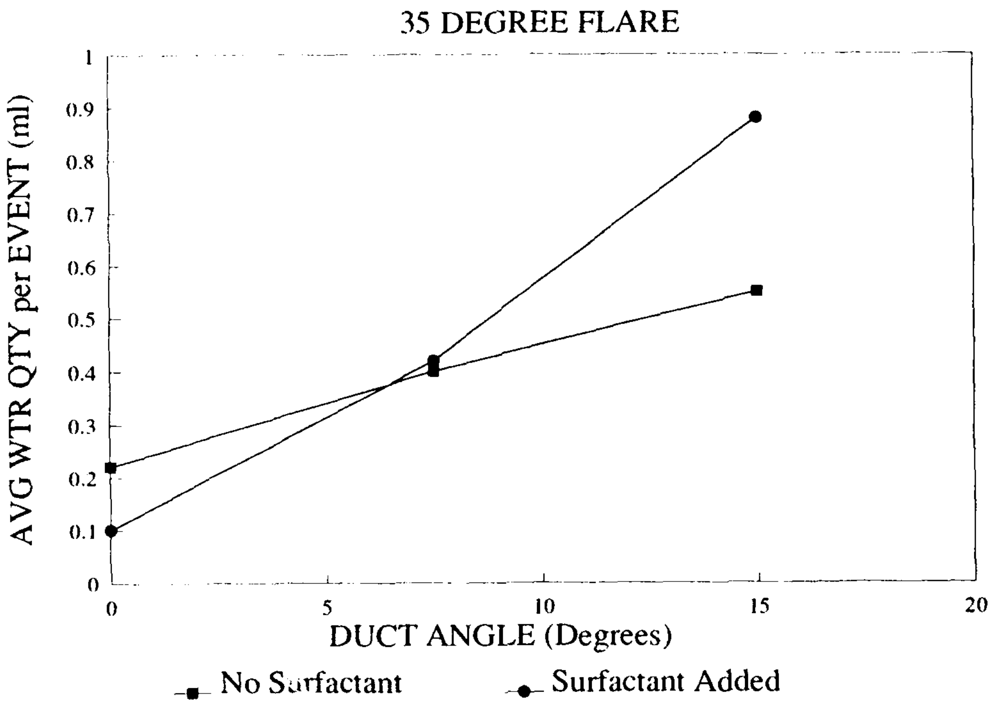



Figure 9. Spray Water Quantity vs. Wind Direction

surfactant is added. The video footage reveals that the large spray droplets associated with the untreated water are responsible for the heavy spray patterns. These large droplets of spray tend to curl around the deck edge and land on the main deck. When the surface tension is reduced, the finer spray particles tend to follow the flare of the bow and are rejected outboard when they exceed the freeboard height. Local wind turbulence and the moderate deck edge flare combine to distribute spray over the main deck even in this head wind condition.

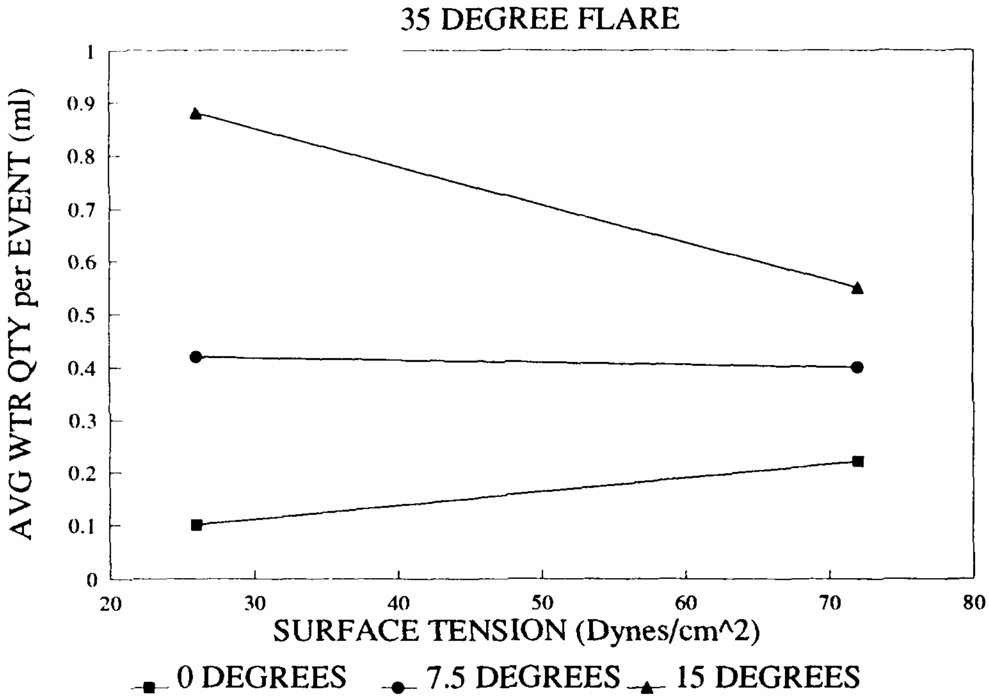



Figure 10. Water Quantity vs. Surface Tension

With the ducting angle set at 7.5°, figure 10 shows that approximately the same amount of spray was collected per event for both surface tension conditions. When reviewing the corresponding diagrams in appendix C, the same trend was noted as for the head wind condition with regards to the density of spray distribution. That is a greater percentage of the wetted deck area of the untreated water runs exhibited a higher density of spray. Figure 8 showed the extent of spray in the reduced surface tension condition at 7.5° wind angle covered a greater deck area. Then for the two conditions to have equal captured spray quantities per event, a trade off existed between the extent of spray coverage and the density of spray distribution. This is visually evident by a comparison of the corresponding areas in appendix C of this bow for this condition.

For the duct angle of 15°, the reduced surface tension condition in figure 10 represents a large increase of water quantity over both the 7.5° reduced surface tension and 15° untreated conditions. This event is explained by referring back to the discussion on figure 8. At that time it was noted that as the total wetted area increased under these wind conditions, appendix C showed that a heavy spray distribution began expanding on the deck of the reduced surface tension condition. This heavy spray density was due to the fact that not all the generated spray ruptured into equally fine particles. These larger particles were of a great enough mass as not to be influenced by relative winds equal to and less then 7.5°. When the wind angle was increased to 15°, the larger droplets were now being deposited on the main deck. These larger particles obviously contained a greater volume of water and therefore caused a substantial increase in the measured water quantity per event for the reduced surface tension condition.

When the average spray flux ($ml/cm^2$) per event is graphed against the duct angle and surface tension, figures 11 and 12 respectfully, the effect that the surfactant has on spray particle size is evident. When the surface tension is reduced through the addition of a surfactant, appendix C and figure 8 have shown that the wetted deck area is increased while the corresponding quantity of spray water per event is initially less (figure 9). This is due to the ease of influencing the smaller particles of spray. As the duct angles are increased, the quantity of spray per event increases faster then the corresponding wetted area for both surface tension conditions. This results in the positive sloping curves in figures 11 and 12. At approximately the 11° point in figure 11, the treated water flux crosses over the untreated water flux curve. A first cut assumption about this point is that it represents the angle at which the wind forces begin to transport the larger size spray particles onto the deck. This would account for the greater flux from a heavier spray density distribution in lieu of the fact that the percent wetted area is still increasing at this time (figure 8).

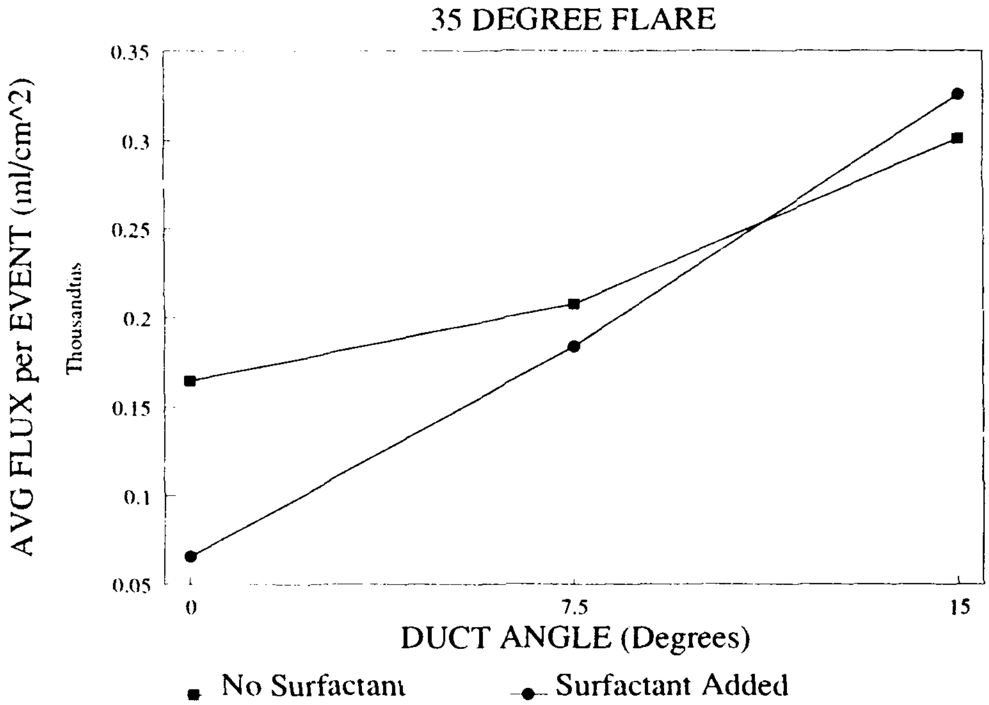



Figure 11. Average Spray Quantity per Unit Area

The reduction in surface tension is important in achieving a more realistic spray at the model testing level such that better full scale predictions can be made. As the Froude Number is used to scale velocities in model resistance testing when surface waves are involved, Weber Number scaling is needed to accurately model surface tensions when model scales are used. The Weber Number is the square root of the ratio of inertia forces to surface tension;

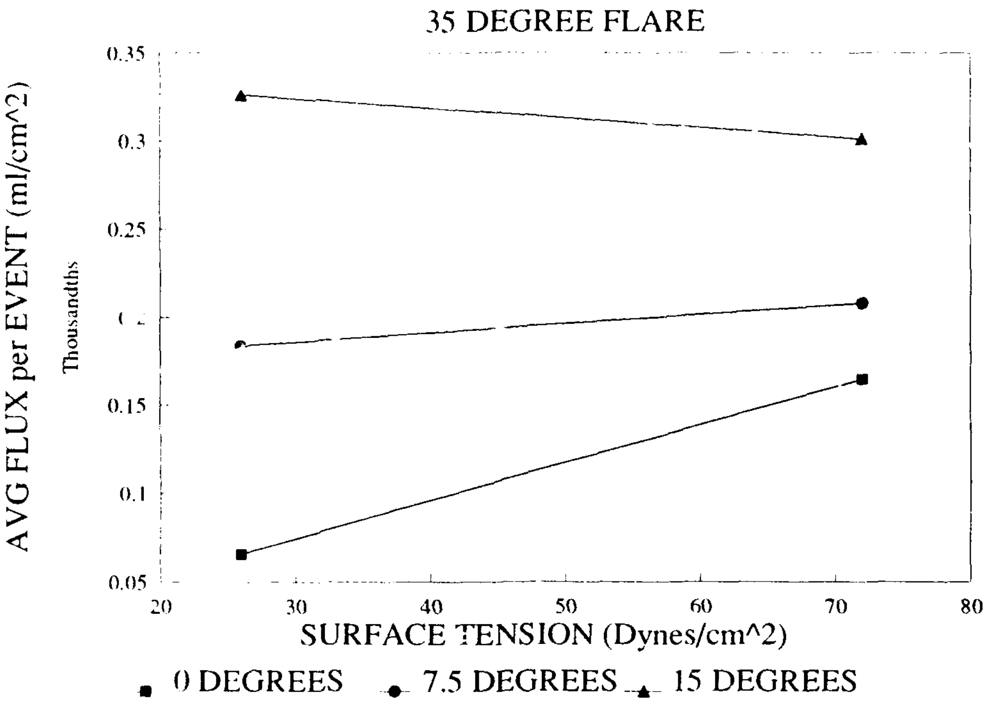



Figure 12. Flux vs. Surface Tension

$$N_w = \frac{V}{\sqrt{\frac{\sigma}{\rho L}}}$$

The full scale Weber number under these conditions is approximately 70,577 using an ocean surface tension of 74.1Dynes/cm ($\sigma_{ocean}$). This number scales to 1964 for the untreated tank water, 36 times smaller. The surface tension of the tank water was 72Dynes/cm ($\sigma_{tank}$). After the addition of the surfactant, the tank water's surface tension was reduced to 26.1Dynes/cm ($\sigma_{stnk}$), a 65% actual reduction over the ocean's value. The water's Weber number was now 3259, 22 times smaller then the full scale requirement.

This value was about the lowest that could be achieved under the testing conditions in the laboratory. To maintain a constant Weber number of 70,577, the tank water's surface tension would have to be reduced to a value of 0.057Dynes/cm.

## 4.2 Interpretation of Bow Comparison Results

All four bows were tested under the same varying environmental conditions in the same treated tank water (surfactant added). Table 4-3 provides the numerical data that was used in the following analysis.

When the percentage of the variant's wetted deck areas are compared, the 55° bow performs the best under all environmental conditions, figure 13. As expected, the greater the relative wind the greater the percentage of deck area is wet with spray. This trend converges at 100%, when all the area of the main deck is wet with spray.

The initial poor performance of the 45° bow was not obvious in the video footage. An analysis of appendix C diagrams reveals that the density distribution of spray across the 45° variant consisted mostly of the finer two patterns (cells 1 and 2). The increased degree of flare over that of the 35° bow serves to accelerate the spray water outboard of the model. The increase in acceleration also breaks up the spray into smaller particles. It is reasoned that although the flare was great enough to create a finer spray then the 35° variant, it was not great enough to adequately distance and suppress the spray particles from the model. The local wind turbulence was then able to capture this fine spray and transport it to the model's deck. Whereas the 55° flare was great enough to suppress the spray so that it was not transported back onto the deck in the head wind condition.

The knuckled variant imparted very little outward motion to the spray. It rose above the deck in the vicinity of the deck edge then collapsed back onto it under its own weight and the influence of the head wind.

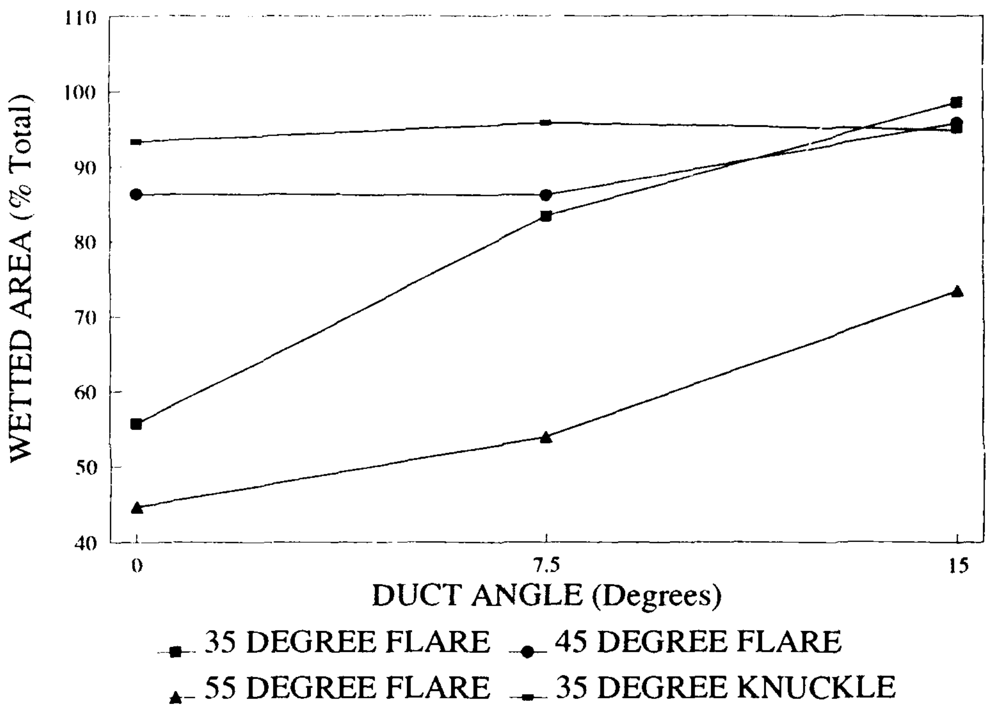



Figure 13. Comparison of Percent Wetted Area

The 55° bow has the advantage in this comparison because of its greater total deck area. It has approximately 20% more area then the 45° variant and 34% more area then both the 35° and knuckled variants. If the actual extent of each variant's wetted areas are compared, then the 35° flared bow form appears to have the performance advantage, figure 14.

Although the total area of wetness is important, it is just one factor that must be understood when deciding on a bow design. An optimum goal would be the total elimination of spray, therefore the quantity of water delivered to the ship is important. Figure 15 gives a comparison of the average amount of water captured per spray event

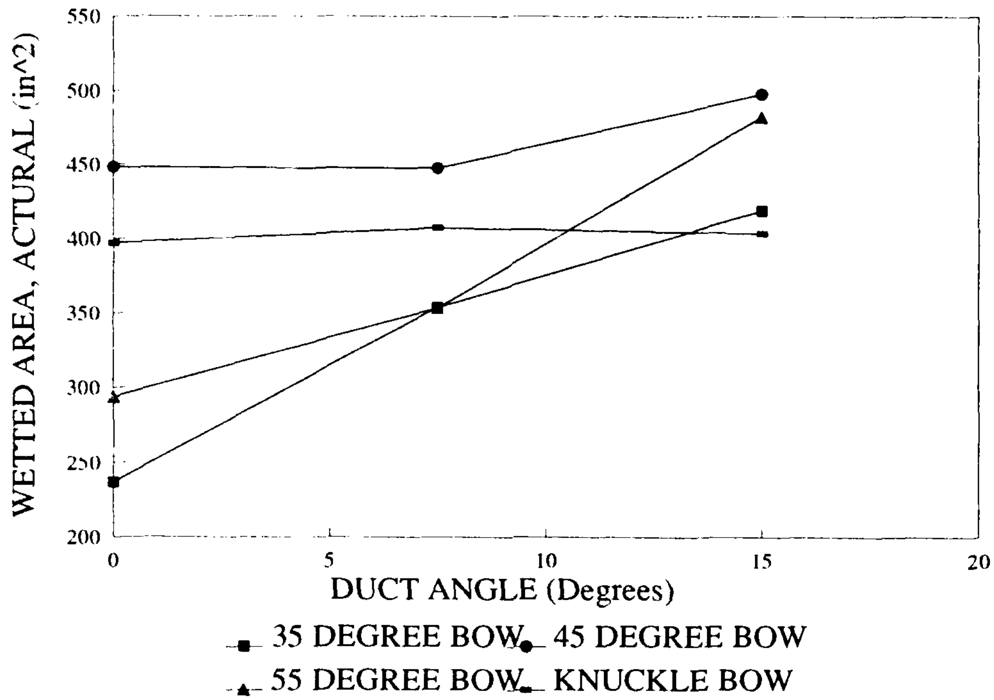



Figure 14. Wetted Areas

for varying angles of relative wind. The 55° flared bow performed best with the knuckled variant noticeable worst. Again as expected, an increase the angle of relative wind tends to transport more spray back onto the ship.

When the average quantity of spray water per event is compared to the actual wetted area, an average flux emerges. Figure 16 compares the average volume of spray delivered per unit area (flux) under the varying wind conditions for each bow. As in figure 15, the 55° variant shows the best ability in reducing this parameter, followed closely by the 45° and 35° bow forms. The knuckled bow performed very poorly in comparison. Recall that if the bows were to be compared on wetted area alone, the 35°

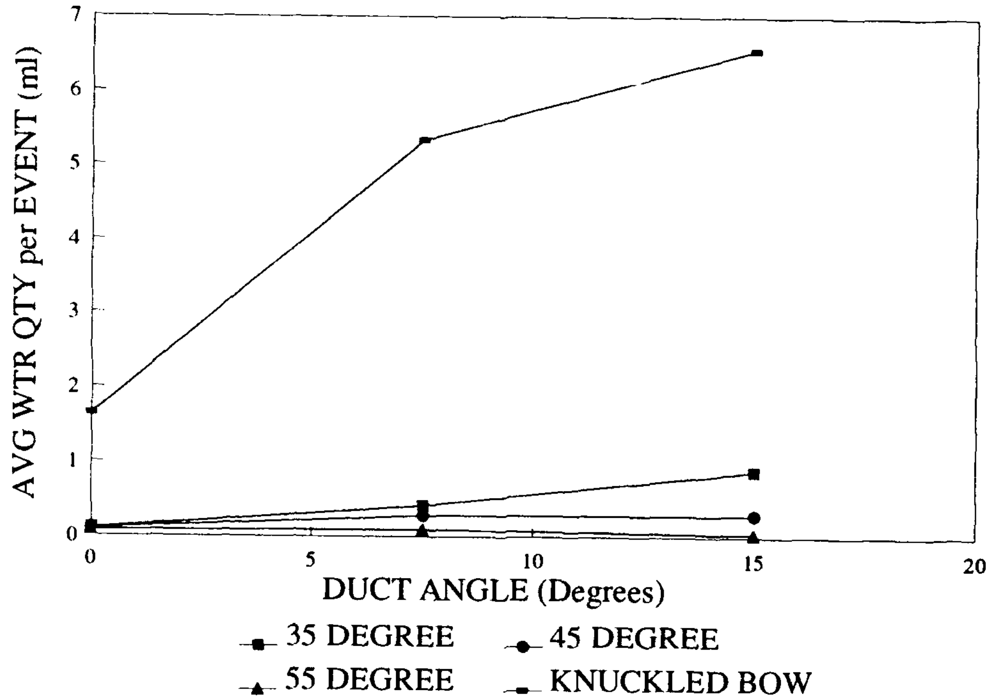



Figure 15. Average Water Quantity per Spray Event

bow out performs the 45° variant. Worth noting also is the actual spray density distribution with bow flare depicted in appendix C. As the flare increased, the spray patterns became lighter and less water was introduced onto the deck. This trend also held true as the angle of wind on the bow was decreased from 15° to 0°.

The knuckled bow again had the worst performance of all the variants tested. It had heavy spray distribution along both port and starboard deck edges in the vicinity of stations -1 to 3 for the head wind condition. The density distribution became less in the direction of the centerline and aft. As the angle of relative wind increased, the heaviest spray distribution shifted to the port side (windward) and diminished towards the

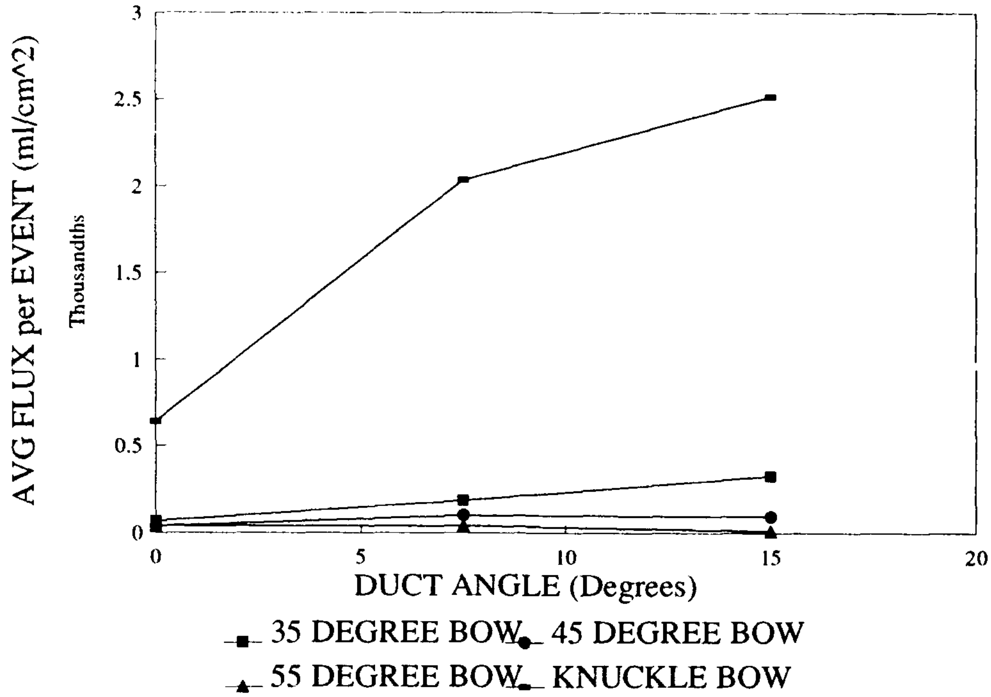



Figure 16. Bow Spray Flux

starboard and aft.

The affect of having the knuckle interrupt the smooth continuous flare, from the waterline to the deck edge, was to allow the generated spray to remain close outboard of the model. Even though the deck edge has the same ending flare angle as the 35° bow (see figure 6), their performances were significantly different. The location of the knuckle close to the spray generating strips limited the effective length of freeboard available to redirect the spray before the flare angle was reduced (see figure 2) . The horizontal spray acceleration was less, limiting the distance the spray travel outward from the model. The result was a greater amount of larger spray droplets close enough to be influenced and carried onboard by the prevailing winds. This accounts for the heavy spray distribution pattern and subsequent greater quantity of water collected per event.

The 35° variant showed a similar distribution but to a more tempered extent. Appendix C mapped a small area of heavy spray along the port deck edge from stations -1 to 1 for the head wind condition. The spray density rapidly dropped off to the lightest case as you moved to starboard and aft. As the relative winds moved off to the port, the heavy spray pattern increased followed by a proportional increase in the number of 3, 2, and 1 cell densities.

The cumulative effect of flare up to the deck edge was great enough to keep the heavy spray pattern to a minimum for the head wind condition. But like the knuckled variant, the flare in this case was not sufficient to distance the spray far enough outboard and in the following two wind conditions the heavy spray pattern expanded. Though similar in trends, the 35° bow out performed the knuckled variant in all areas.

In comparison, the 45° and 55° variants showed little, if any, increase of the heavy spray pattern with changes in the relative wind. The greater degree of flare served to displace the spray further outboard, preventing its transport onto the main deck by the forces of the wind. As the relative wind angle increased, the 45° variant's wetted area remained essentially constant while the water quantity per event increased slightly. The large degree of wetted area in all wind conditions was owed to a large distribution of fine spray as mentioned earlier. The 45° flare, while accelerating the spray outboard, also served to enhance its breakup into finer particles. The resulting trajectory of these particles from the deck edge carried them high enough to be brought back over the main deck by the wind. Though the wetted deck percentage remained high, the quantity of water delivered per event was less then both the 35° and knuckled variants (see Figure 15). A comparison of the diagrams in appendix C shows a greater percentage of wetted area is occupied by denser shading for the 35° and knuckled bows over the 45° variant. This reflects the fact that finer spray of cumulatively less volume is being delivered to the 45° variant (see Figure 16).

The 55° variant demonstrated improvements over the 45° bow in all areas tested. The increase in flare along the deck edge served to break the spray up into finer droplets while suppressing their trajectories further then the 45° variant. The lower droplet trajectory correlates directly to a smaller area of coverage. Not until the duct angle was set at 15° did the actual wetted areas of the 45° and 55° bows approach the same magnitude (see Figure 14). An analysis of the diagrams in appendix C shows that the 45° bow has a larger degree of heavier spray distribution then does the 55° bow for the same wind angles. This agrees with figure 17 showing that the 55° bow received less water per spray event.

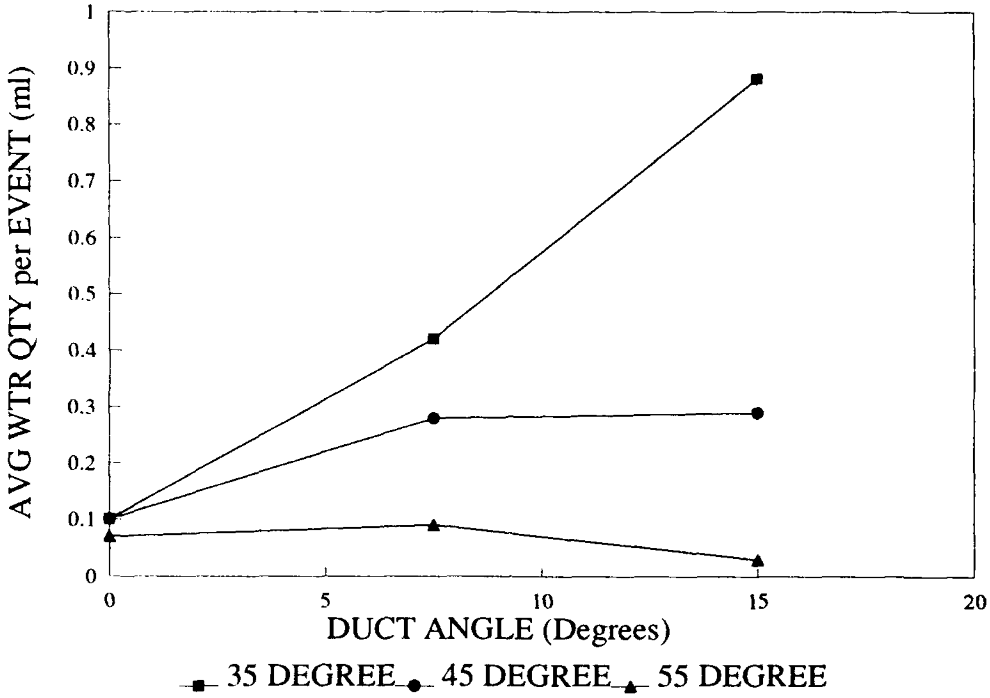



Figure 17. Spray Quantity

# 5 Conclusions and Recommendations

## 5.1 Conclusions

The results of this investigation on how bow flare effects the spray distribution across the main deck of a large displacement craft, under varying environmental conditions and reduced surface tension, led to the following conclusions. These conclusions are based upon the three wind conditions and one spray/wave configuration tested on a particular model with interchangeable bow forms.

a. The addition of a surfactant to the tank test water to reduce surface tension and increase the model Weber Number created a finer spray particle size that resulted in a different spray density distribution, an increase in the wetted deck area, a difference in the quantity of spray water capture per event, and a difference in the average flux delivered to the model over what was achieved in untreated tank water.

b. An increase in flare reduced the actual wetted deck area in head winds.

c. An increase in flare reduced the quantity of spray water that was collected and the density distribution across the main deck.

d. An increase in flare reduced the distance the spray travel aft.

e. An increase in flare produced finer spray droplets at the deck edge.

f. The knuckled bow tested performed worst then any of the conventionally flared bows concluding that a continuous flare from the waterline to the deck edge is more advantageous, at least when the knuckle is located near the elevated water surface.

## 5.2 Recommendations

Based on the measurements and observations noted during this project, future work should center around two distinctly different areas. One being the further investigation into the effects of varying degrees of a surfactant on spray distribution. The second being the creation of spray by running a model in other then head seas.

The effect of reducing the scaling error in spray studies, by altering the surface tension of the test water, can best be used by studying the incremental effects of this variation. Because of the size of models used to predict full scale performance, it is impossible to perform testing at like Weber Numbers. If trends can be established within our present ability to alter surface tension values, then possibly through the extrapolation of these curves a full scale prediction will be possible. This method could then be applied to other areas of model testing in order to more accurately determine full scale performance.

In order to separate the shipping of green water from spray, model motions were almost entirely eliminated. The addition of spray root devices was then required to create spray in the vicinity of the bow where it is normally observed. If the model were tested in other then head seas, a natural spray might be possible without the need for spray generating devices. This would test the model under more realistic conditions. Of course the problem of performing these tests in a maneuvering basin involves the generation of wind and dedication of the basin once the surfactant is added.

Though no criteria presently exists on the degree or quantity of spray permitted at sea, ships will continue to be designed and built with some degree of forward flare in order to meet other more demanding requirements. The knowledge of how spray behaves with varying degrees of flare could be used in the design spiral to help decide on a final bow form. This understanding can also be used in the determination of where to place spray sensitive equipment and to determine icing rates under varying environmental conditions.

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# Appendix A Bow Design Method

1. Introduction

The bows were all designed to fare smoothly into the FFG-7 hull from at station 5 and at the chosen waterline (draught = 0.0375L or 4.66 m, level trim). All bows had a freeboard of .06L (7.46m) and no shear.

The bows were generated using a system of polynomial curves to represent waterlines, section shape at station 2 and the stem profile. This method resulted in a family of bows defined only by a single parameter, the flare angle at station 2. Details of the design method follow.

2. Coordinate System

The origin of coordinates is at the intersection of the stem and the forward perpendicular. $x_s$ is positive forward, z is positive down and y is positive to starboard.

3. Flare Angle and Overhang

Flare angle is defined at station 2 as shown in Figure 2. Overhang is arbitrarily defined as:

$$\frac{x_o}{L} = 0.002\delta_2 \qquad (1)$$

$\delta_2$ - Flare angle @ station #2

$x_o$ - Extent of overhang @ weather deck level (freeboard)

Thus large flare angles are associated with large overhangs.

4. Section Shape at Station 2

Above the load waterline the section shape is defined by:

$$\frac{y_2}{L} = b_o + b_1 \frac{z}{L} + b_2 \left( \frac{z}{L} \right)^2 \tag{2}$$

Boundary conditions are:

a. Offset at load waterline

$$\frac{y_2}{L} = 0.01655 \quad \text{at} \quad z = 0$$

(from FFG-7 body plan)

b. Slope at load waterline:

$$\frac{dy_2}{dz} = -0.2734 \quad \text{at} \quad z = 0$$

(from FFG-7 body plan)

c. Slope at deck:

$$\frac{dy_2}{dz} = -\tan(\delta_2) \quad \text{at} \quad \frac{z}{L} = -\frac{F}{L} = -0.06$$

Hence $b_o = 0.01655$

$b_1 = -0.2734$

$$b_2 = \frac{\tan(\delta_2 + b_1)}{0.12}$$

Thus the section shape at station 2 is completely defined by the single parameter $\delta_2$. Hence, if $\delta_2$ is known, the offset $y_2$ at any waterline can be determined.

5. <u>Stem Profile</u>

Above the load waterline the stem profile is defined by:

$$\frac{x_s}{L} = C_o = C_1 \frac{z}{L} + C_2 \left( \frac{z}{L} \right)^2 \quad (3)$$

Boundary Conditions are:

a. Overhang at origin of coordinates

$$\frac{x_s}{L} = 0 \quad \text{at} \quad z = 0$$

b. Slope at origin of coordinates

$$\frac{dx_s}{dz} = -0.8333 \quad \text{at} \quad z = 0$$

c. Overhang at stem head

$$\frac{x_s}{L} = \frac{x_o}{L} \quad \text{at} \frac{z}{L} = -\frac{F}{L} = 0.06$$

Hence $C_o = 0$

$$C_1 = -0.8333$$

$$C_2 = \frac{\left(\frac{x_o}{L} - 0.05\right)}{0.0036}$$

If the flare angle is defined $\frac{x_o}{L}$ can be determined from equation 1. Hence the stem shape can be determined if $\delta_2$ is known.

6. <u>Waterlines</u>

Above the load waterline the waterlines are given by:

$$\frac{y}{L} = a_o + a_1\left(\frac{x}{L}\right) + \frac{a}{2}\left(\frac{x}{L}\right)^{+} a_3\left(\frac{x}{L}\right)^3 \qquad (4)$$

(The coefficients $a_o$ - $a_3$ are different for each waterline).

Boundary conditions are:

a. Overhang at stem:

$$\frac{y}{L} = 0 \quad \text{at} \quad \frac{x}{L} = \frac{x_s}{L}$$

b. Offset at station 5:

$$\frac{y}{L} = \frac{y_5}{L} \quad \text{at} \quad \frac{x}{L} = -0.25$$

(From FFG-7 Body Plan)

c. Slope at station 5:

$$\frac{dy}{dx} = \left(\frac{dy}{dx}\right) \quad \text{at} \quad \frac{x}{L} = -0.25$$

(From FFG-7 Body Plan)

d. Offset at Station 2:

$$\frac{y}{L} = \frac{y_2}{L} \quad \text{at} \quad \frac{x}{L} = -0.1$$

(From quadratic already defined at Station 2)

Hence

$$a_3 = \frac{\left(\left((A-B)\frac{x_s}{L} + 0.25A - 0.1B\right)\left(\frac{dy}{dx}\right)_5 + \frac{Ay_5}{L} - \frac{By_2}{L}\right)}{\left(\left(\left(\frac{x_s}{L}\right) - 0.1875\frac{x_s}{L}\right)(B-A) + 0.03125A - 0.01775B\right)}$$

$$a_2 = \left(\frac{x_s}{L} + 0.1\right)\left(\frac{dy}{dx}\right)_5 + \frac{y_2}{L} - a_3 \frac{\left(\left(\frac{x_s}{L}\right)^3 + 0.1875\frac{x_s}{L} + 0.01775\right)}{A}$$

$$a_1 = \left(\frac{dy}{dx}\right)_5 + 0.5a_2 - 0.1875a_3$$

$$a_o = -a_1\left(\frac{x_s}{L}\right) - a_2\left(\frac{x_s}{L}\right)^2 - a_3\left(\frac{x_s}{L}\right)^3$$

where $A = -\left(\frac{x_s}{L}\right)^2 - 0.5\left(\frac{x_s}{L}\right) - 0.04$

$$B = \left(\frac{x_s}{L}\right)^2 - 0.05\left(\frac{x_s}{L}\right) - 0.0625$$

Thus if the flare angle $\delta_2$ is defined:

i. $\frac{y_2}{L}$ can be determined from equation 2.

ii. $\frac{x_o}{L}$ can be determined from equation 1.

iii. $\frac{x_s}{L}$ can be determined from equation 3.

iv. $\frac{y_5}{L}$ and $\left(\frac{dy}{dx}\right)_5$ are known already and the waterline value of $\frac{y}{L}$ can be determined from equation 4.

7. Bow Form Family

The equations described above form the basis of a NATS Computer program (subsequently implemented at AMTE (H)) entitled BMILL1 which was used to define the family of bows which were used in the experiment. Flare angles chosen for testing were 30 degrees, 35 degrees, 45 degrees, 50 degrees and 55 degrees.

8. Knuckle Bows

The equations described above were adapted to generate a family of knuckle bows along similar lines. The knuckle bows were defined by a knuckle flare angle and a "phantom" flare angle. The phantom flare angle was used to define the stem profile and the deck shape as for the ordinary bows, thus a knuckle bow with, say a 30 degrees phantom flare angle, would have the same stem profile and deck as an ordinary bow with a 30 degree flare angle.

The knuckle was arbitrarily defined as parallel to the load waterline and keel at 0.0375L above the load waterline. The knuckle flare angle $\delta_K$ was defined at the knuckle at station 2.

Equation 2 was used with the appropriately modified boundary condition, to define the section shape at station 2 between the load waterline and the knuckle.

Above the knuckle the section at station 2 was defined by a straight line between the knuckle and the edge of the deck.

In this way the stem profile and section at station 2 could be defined by specifying the phantom and knuckle flare angles, hence the waterlines could be generated in the same way as for the ordinary bows.

The above treatment gives a knuckle which merges into the rest of the hull form at the stem and at station 5 and a deck plan and stem profile identical to one member of the family of ordinary bows.

A modified version of program BMILL1 entitled BMILLK was used to generate a family of knuckle bows using a phantom flare angle of 35 degrees. A single knuckle bow with a knuckle flare angle of 45 degrees was selected for testing
from this family.

9. Bow Manufacture

The bows were made of wood on the CADIG numerically controlled milling machine using ordinates generated by the programs BMILL1 and BMILLK. These ordinates are stored in files entitled BSM and BSTEM. The ordinates were defined as 32 waterlines where waterline 13 corresponded to the load waterline. Thus milling was performed only from waterlines 13 to 32. Waterlines were 11.28 mm (0.444 inches) apart. Station spacing was 1/60 of the waterline length corresponding to 57.6 mm (2.267 inches).

# Appendix B Surface Tension Calculations

The surfactant used to reduce the tow tank surface tension was a wetting agent marketed under the brand name Aerosol OT-75 by the American Cyanamid Company, Process Chemical Department, Wayne New Jersey (1-800-438-5615). The surfactant is an anionic type whose chemical name is Sodium Dioctyl Sulfosuccinate ($C_{26}H_{37}O_7NaS$). Enough surfactant was added to the tank water to achieve a saturated solution and surface tension of approximately 0.00178$lbs_F$/FT (26.1 Dynes/cm).

The surface tension of the surfactant solution and that of distilled water (as a check) were determined with a capillary rise apparatus. Both tank water and distilled water were tested "as is" with no filtration introduced.

The capillary rise apparatus is a graduated glass pipettes placed in a large beaker after first ensuring that all parts of the apparatus were clean and dry. Fluid rose up through the pipette until it reached an equilibrium level. The difference in liquid heights between the fluid in the beaker and pipette was recorded using a hand held vernier caliper. The surface tension, T($lbs_F$/FT), was then calculated by employing the following relationship:

$$\rho g h = 2\frac{\sigma}{r}$$

g = Acceleration due to gravity

h = Height of fluid in pipette above beaker level

σ = Density of fluid

r = Inside radius of pipette

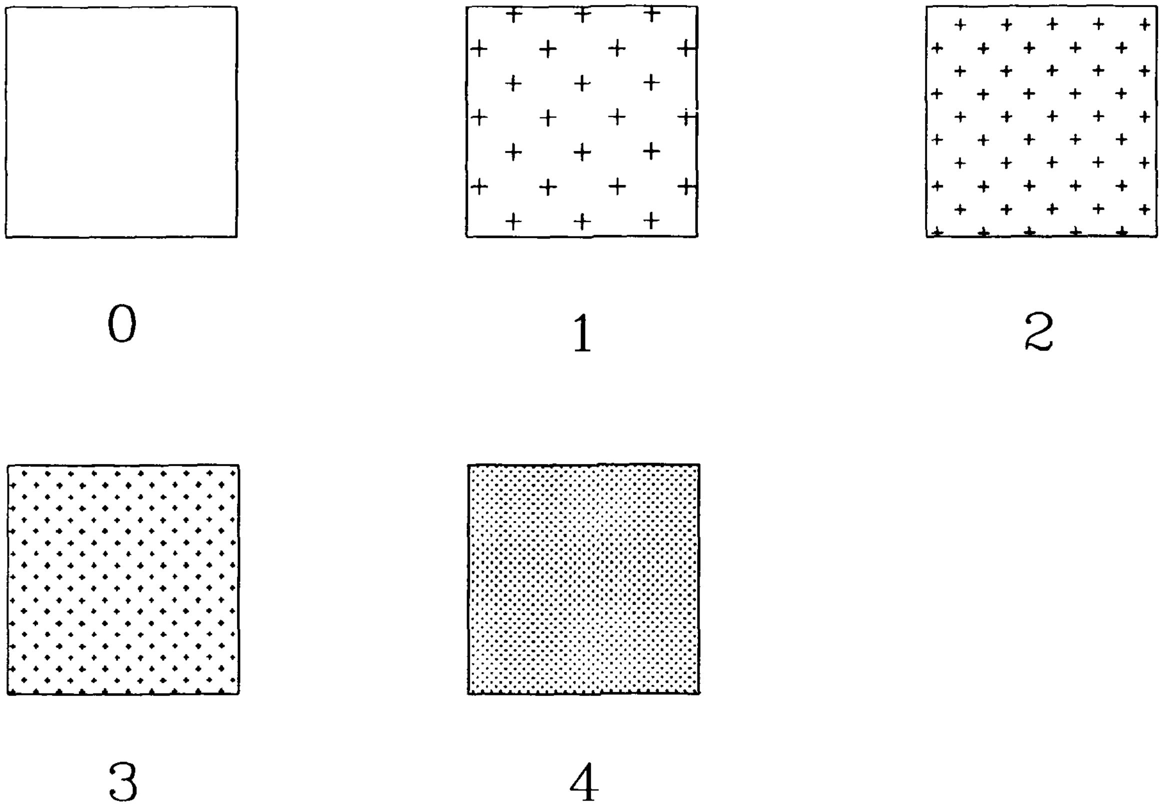
To verify measurements, the distilled water and two samples of tank solution (taken at different times) were weighed to determine densities and two different size pipettes were used to calculate surface tensions. The results are given in Table B-1. Some results are given in metric. Units as to be recognizable to readers. Differences from the expected surface tensions are considered to be insignificantly small and could have resulted from hand measurement taken within the vernier calipers and calculation of densities.

TABLE B-1

Surface Tensions

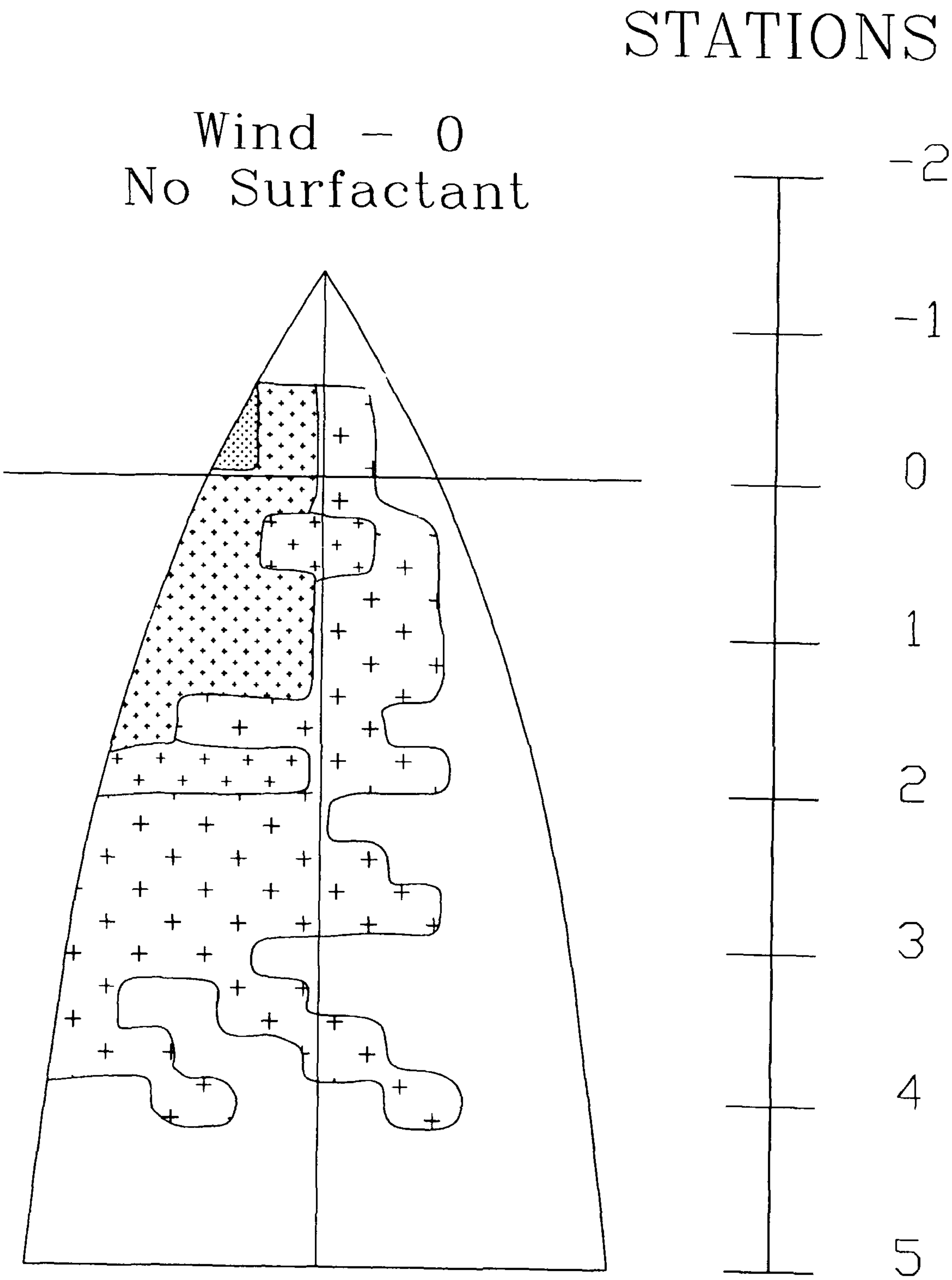
| Fluid | Temp °F | $\rho$ Kg/m$^3$ | $\sigma$ lbs$_F$/Ft | $\sigma$ Dynes/cm | $\sigma$ expected Dynes/cm |
|---|---|---|---|---|---|
| Distilled Water | 74.8 | 1002 | 0.00497 | 73.1 | 72.0 |
| Sample 1 | 69.0 | 1002 | 0.00186 | 27.4 | 26.1 |
| Sample 2 | 69.0 | 996 | 0.00183 | 26.9 | 26.1 |

# Appendix C Plotted Spray Distribution Data

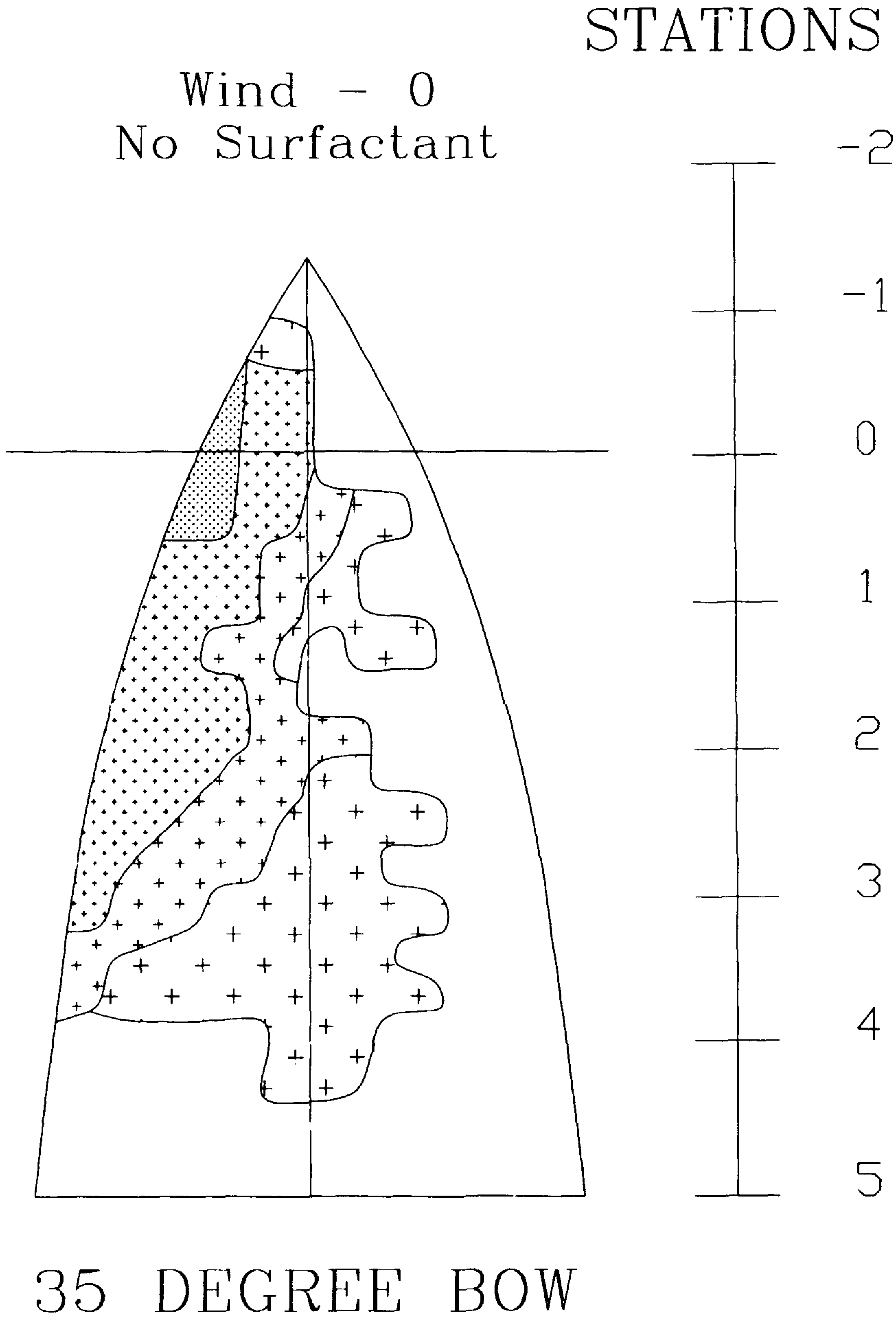


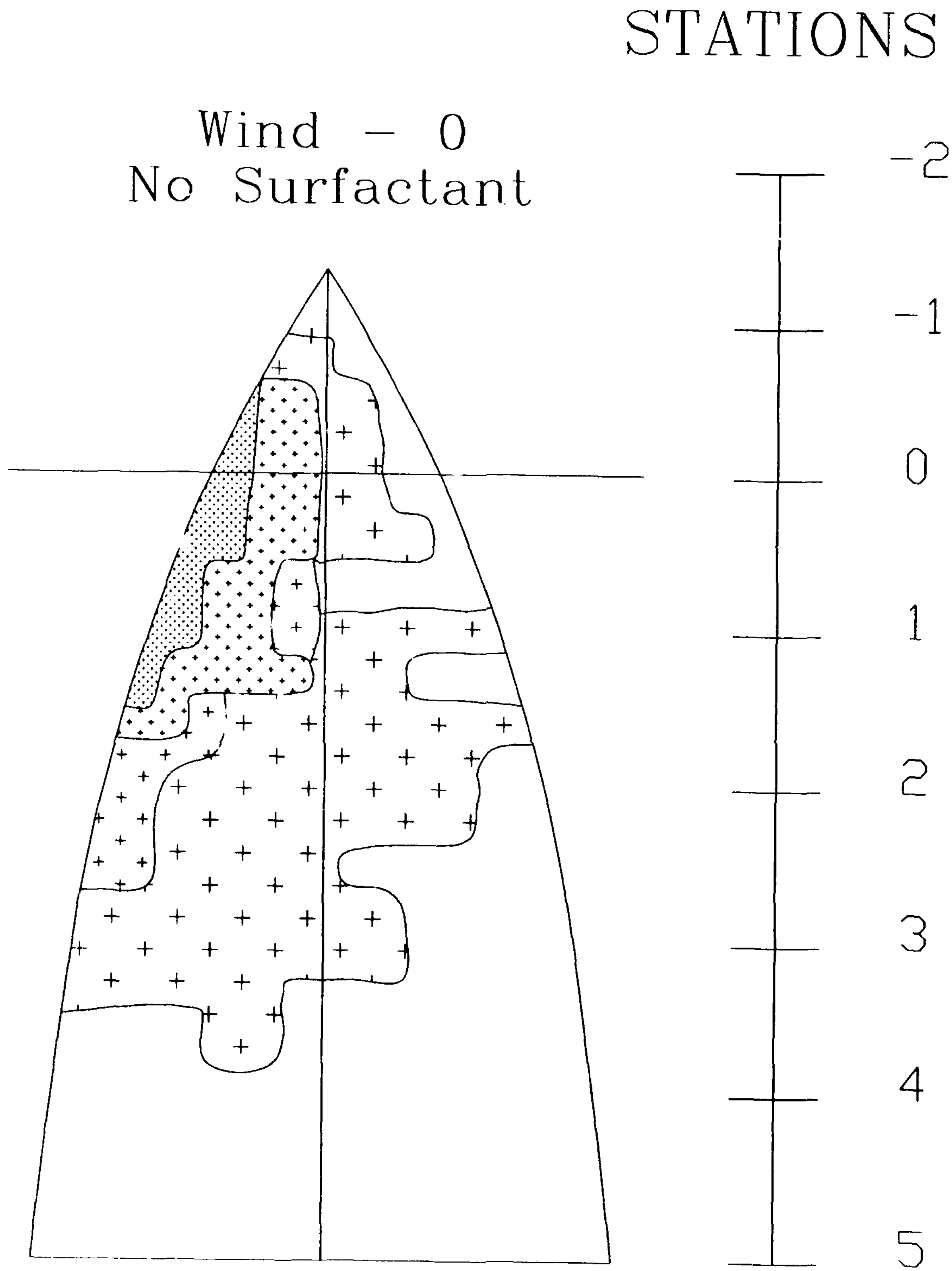

The hatching above corresponds to the cell density selections made when transferring the spray distribution data from video to paper. The 0 box representing no spray present to the 4 box representing 100% cell coverage.

The title above each picture refers to the angle of the relative wind on the bow (degrees) and whether or no the surface tension was reduced by the addition of surfactant.




35 DEGREE BOW


STATIONS
Wind - 0
No Surfactant
-2
-1
0
1
2
3
4
5
35 DEGREE BOW

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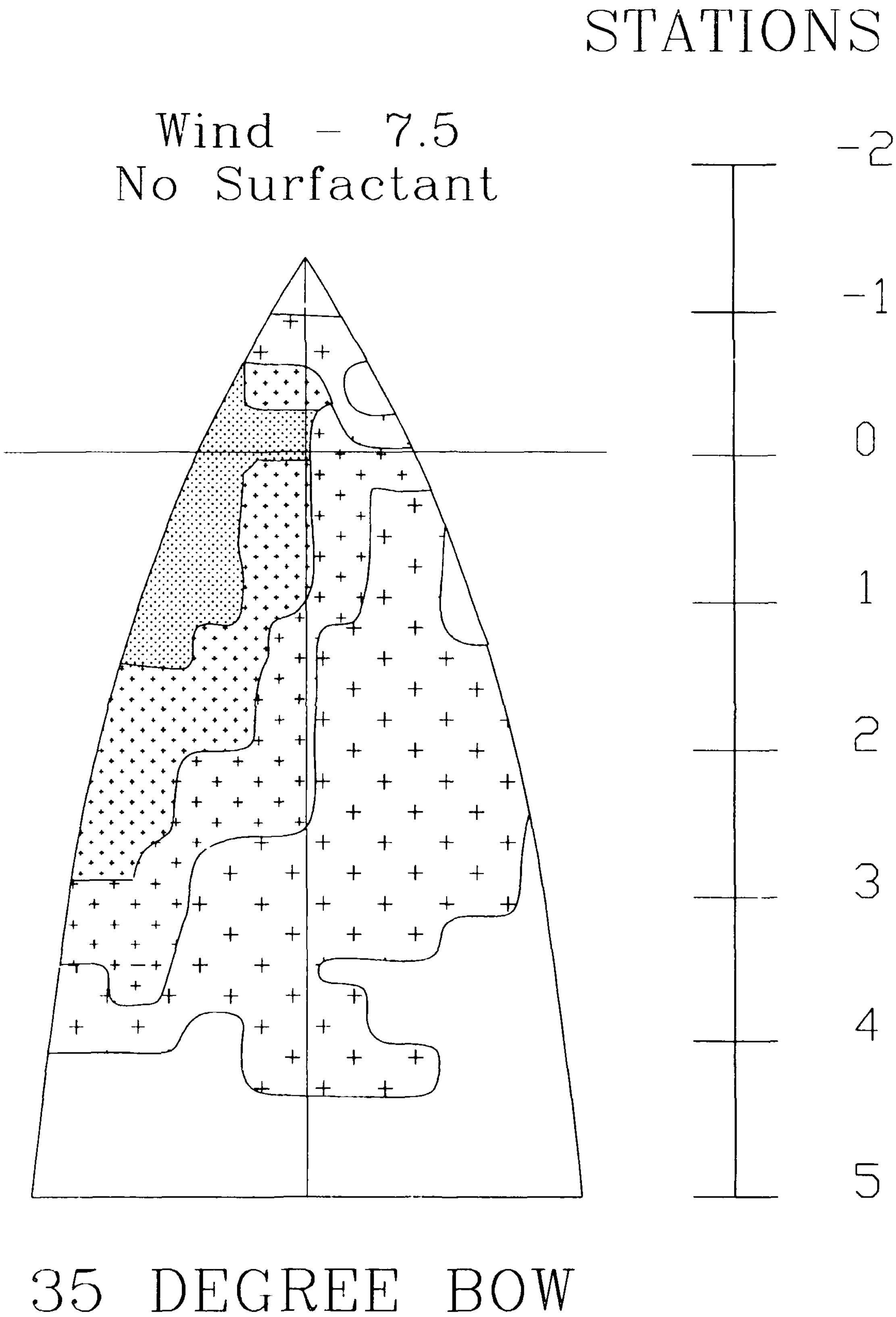
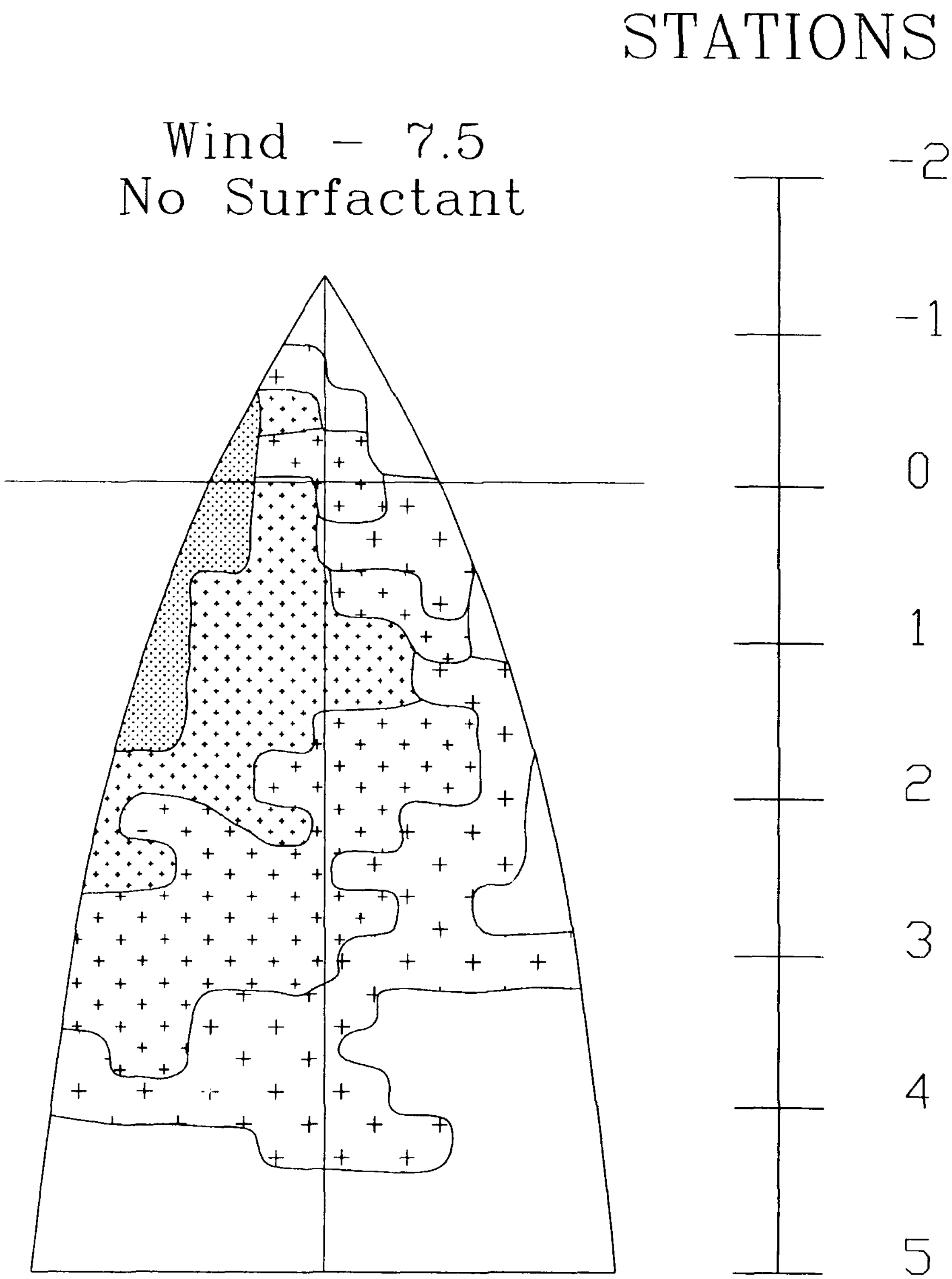

STATIONS
Wind - 7.5
No Surfactant
-2
-1
0
1
2
3
4
5
35 DEGREE BOW

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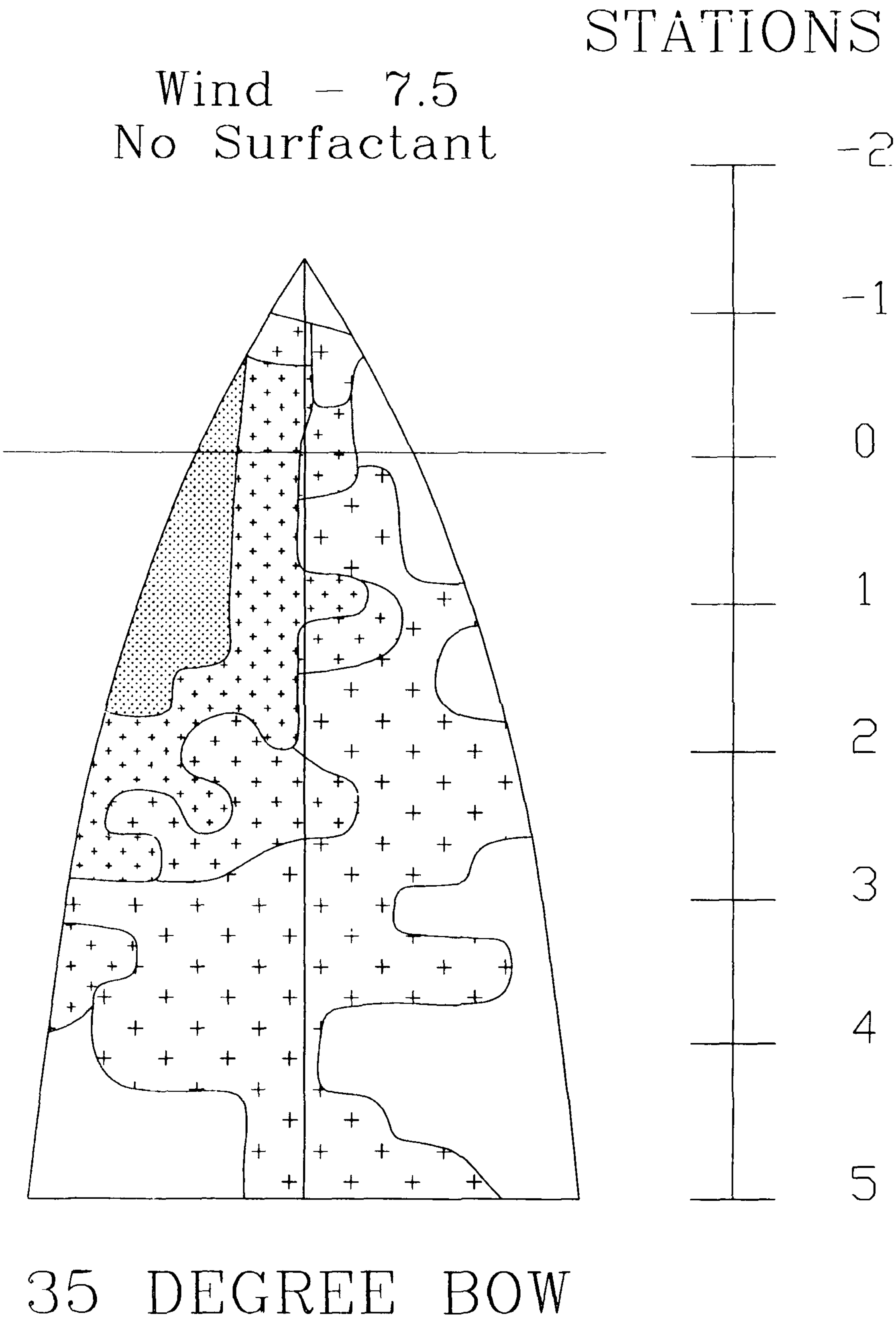
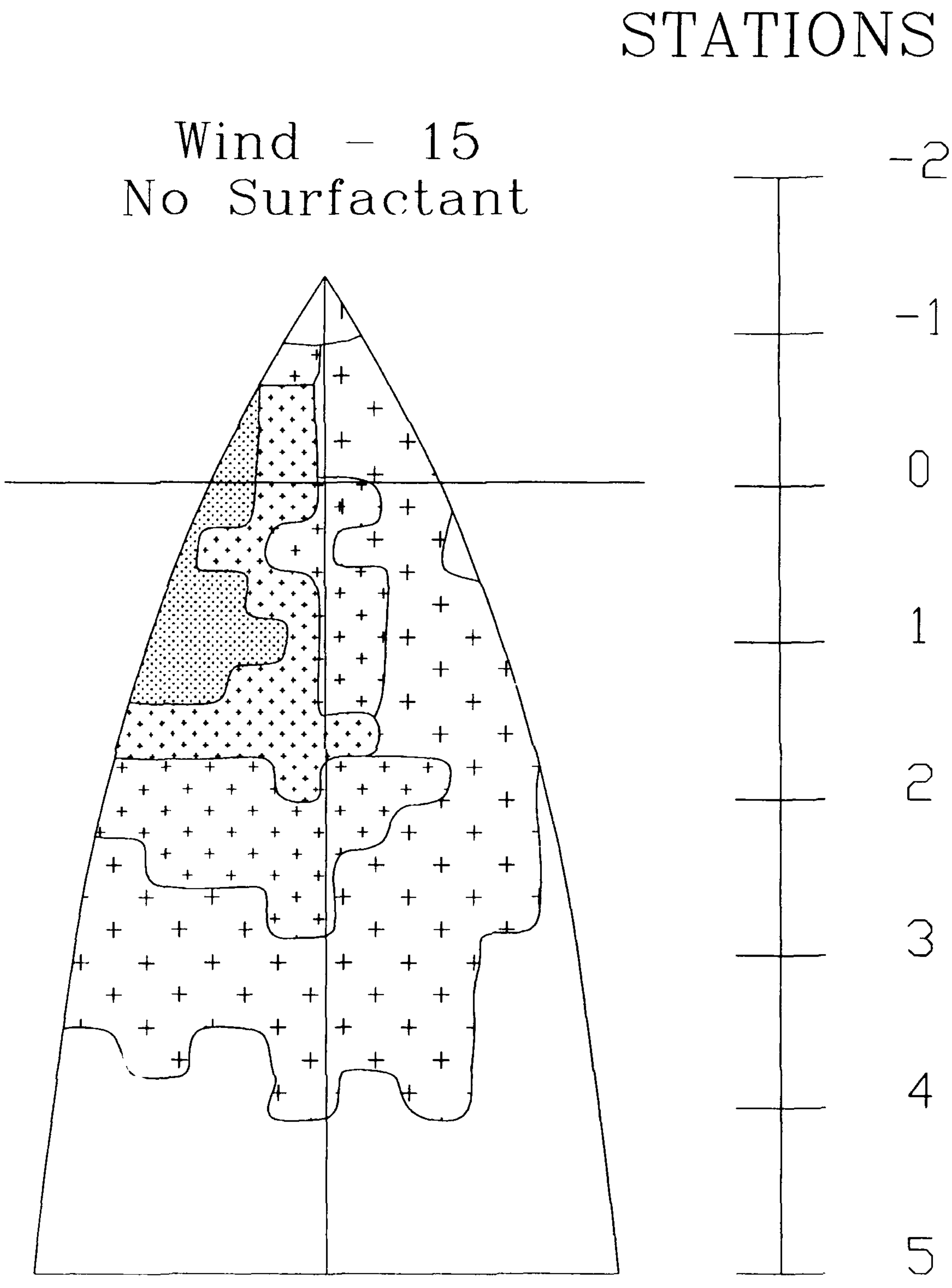

STATIONS
Wind - 7.5
No Surfactant
-2
-1
0
1
2
3
4
5
35 DEGREE BOW

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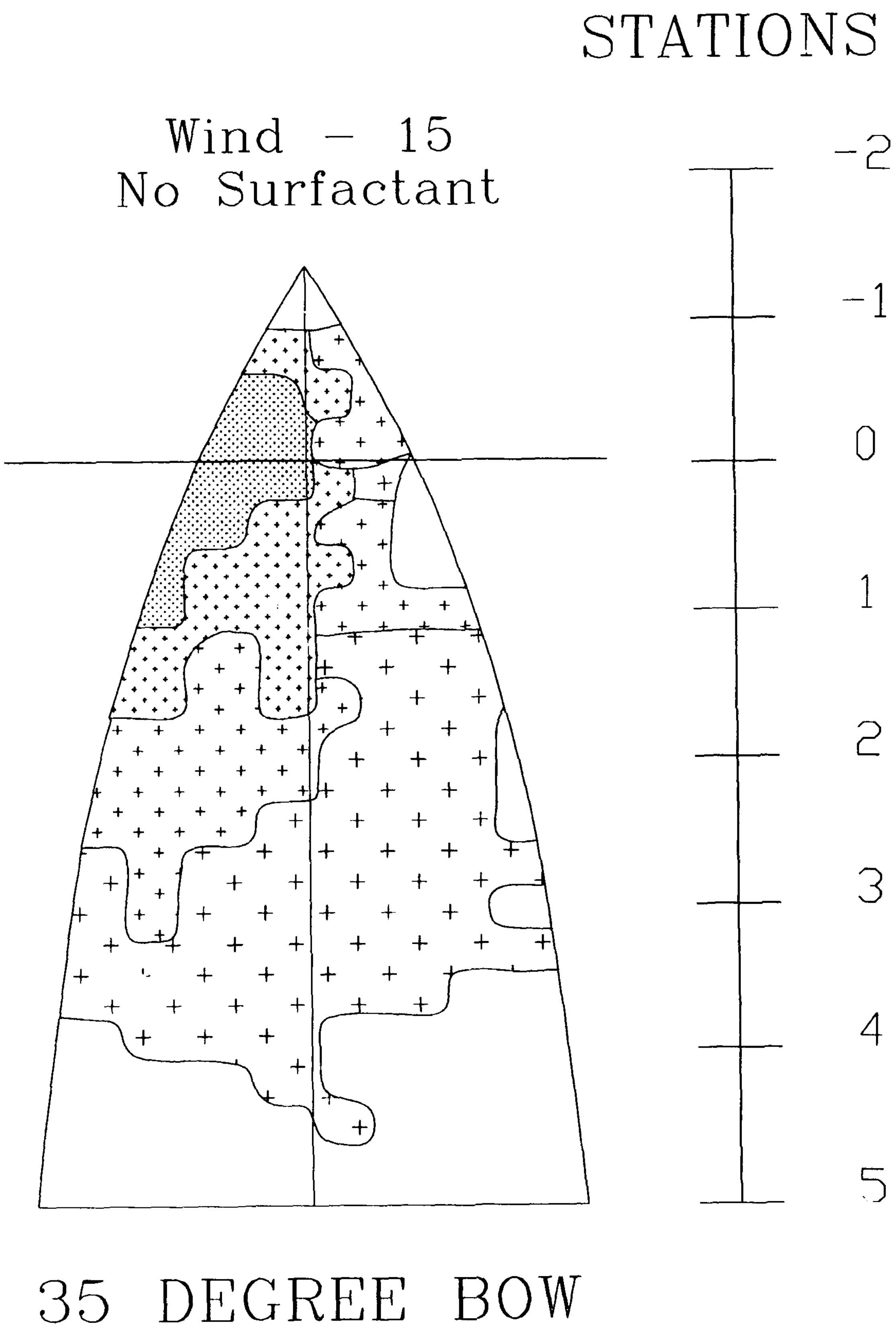
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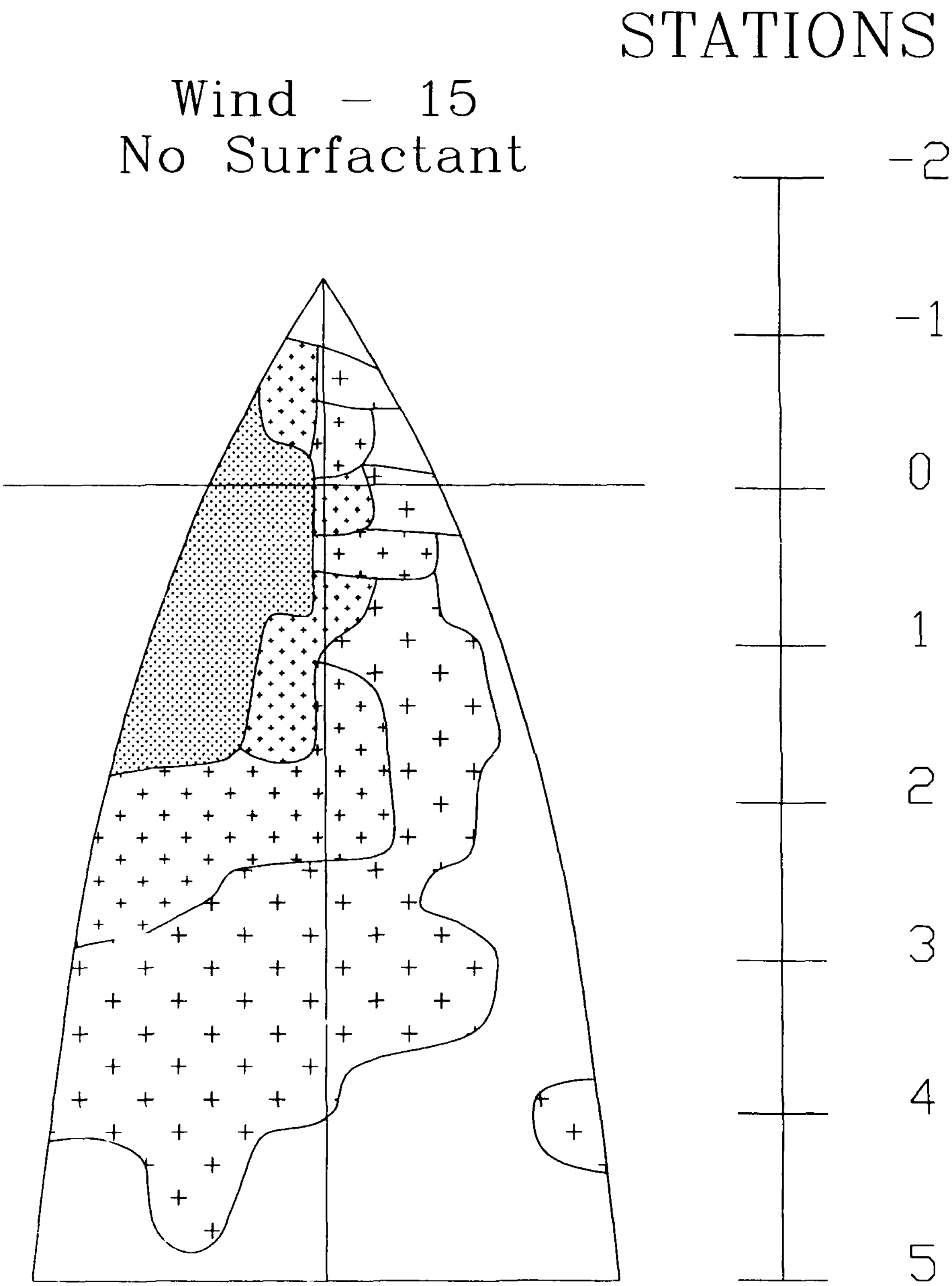
Wind - 15
No Surfactant
-2
-1
0
1
2
3
4
5
35 DEGREE BOW

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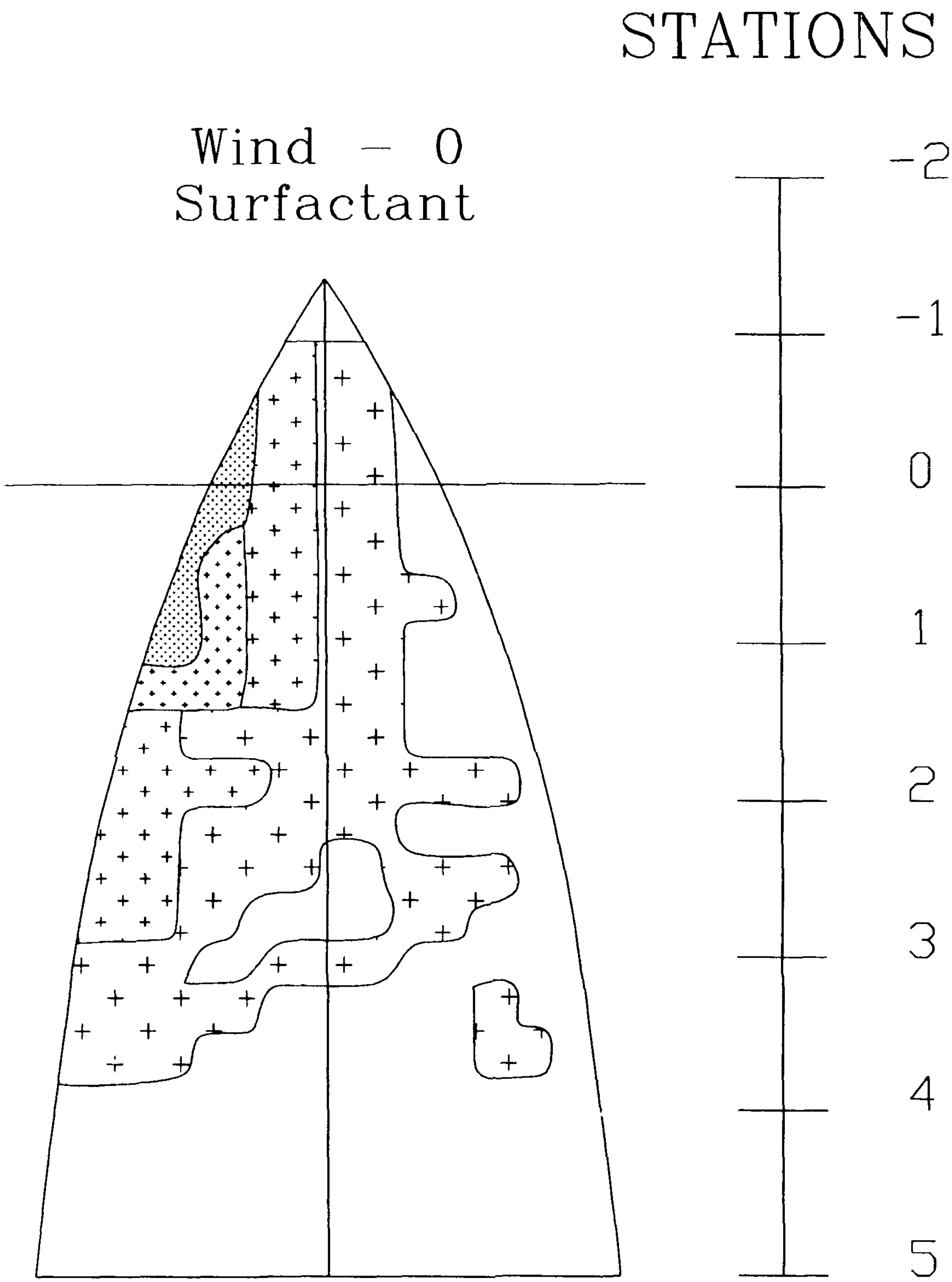


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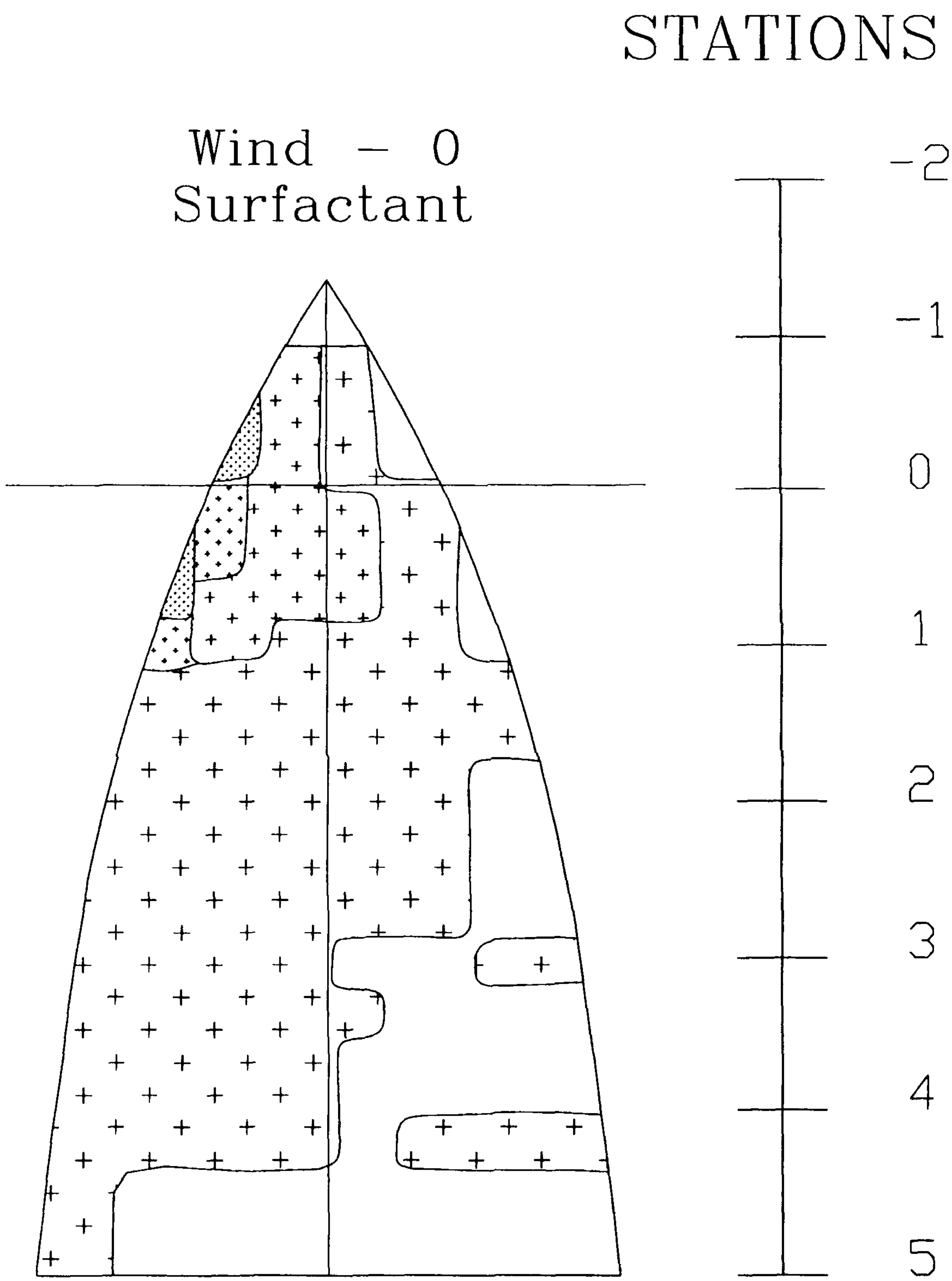


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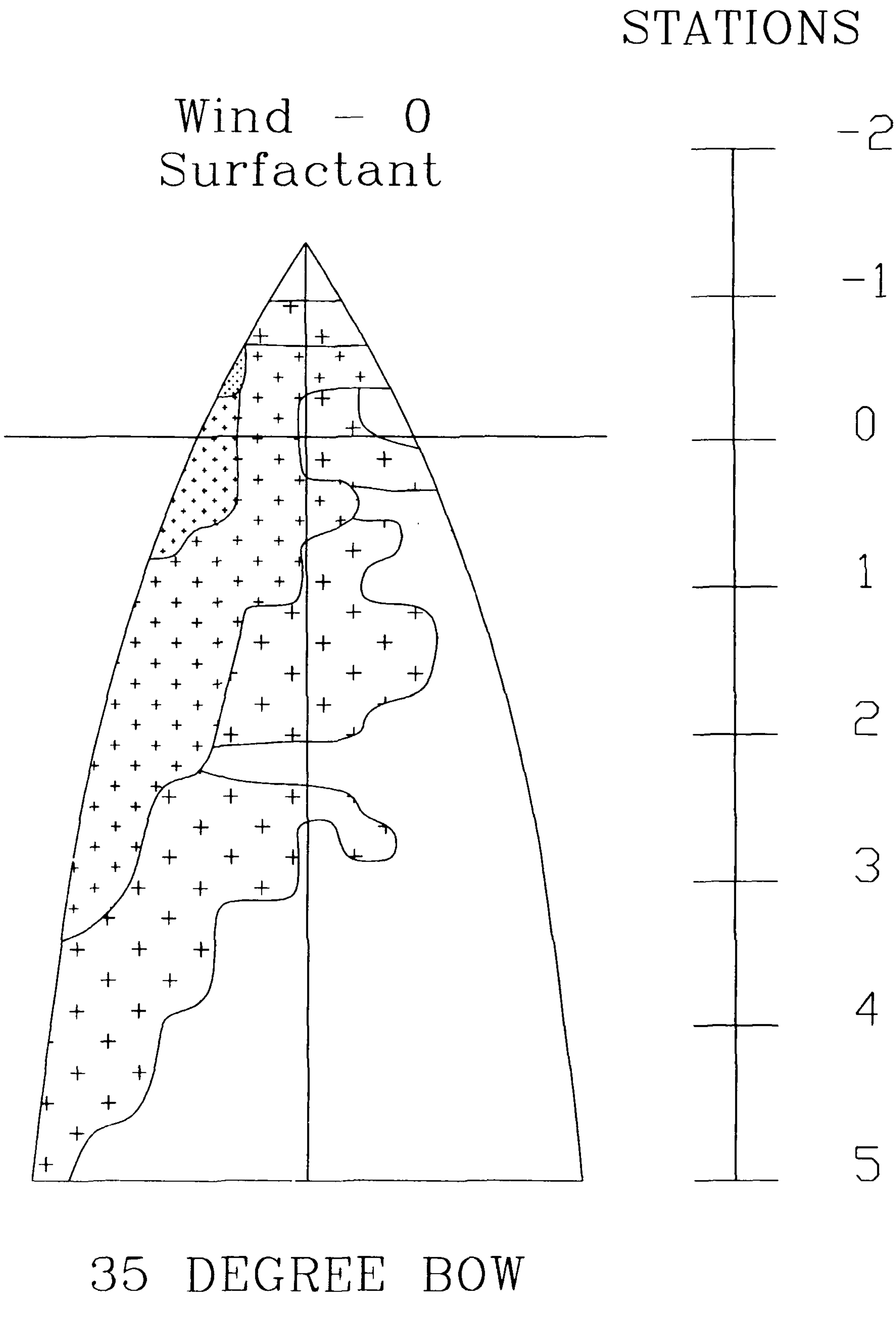
STATIONS
Wind - 0
Surfactant
-2
-1
0
1
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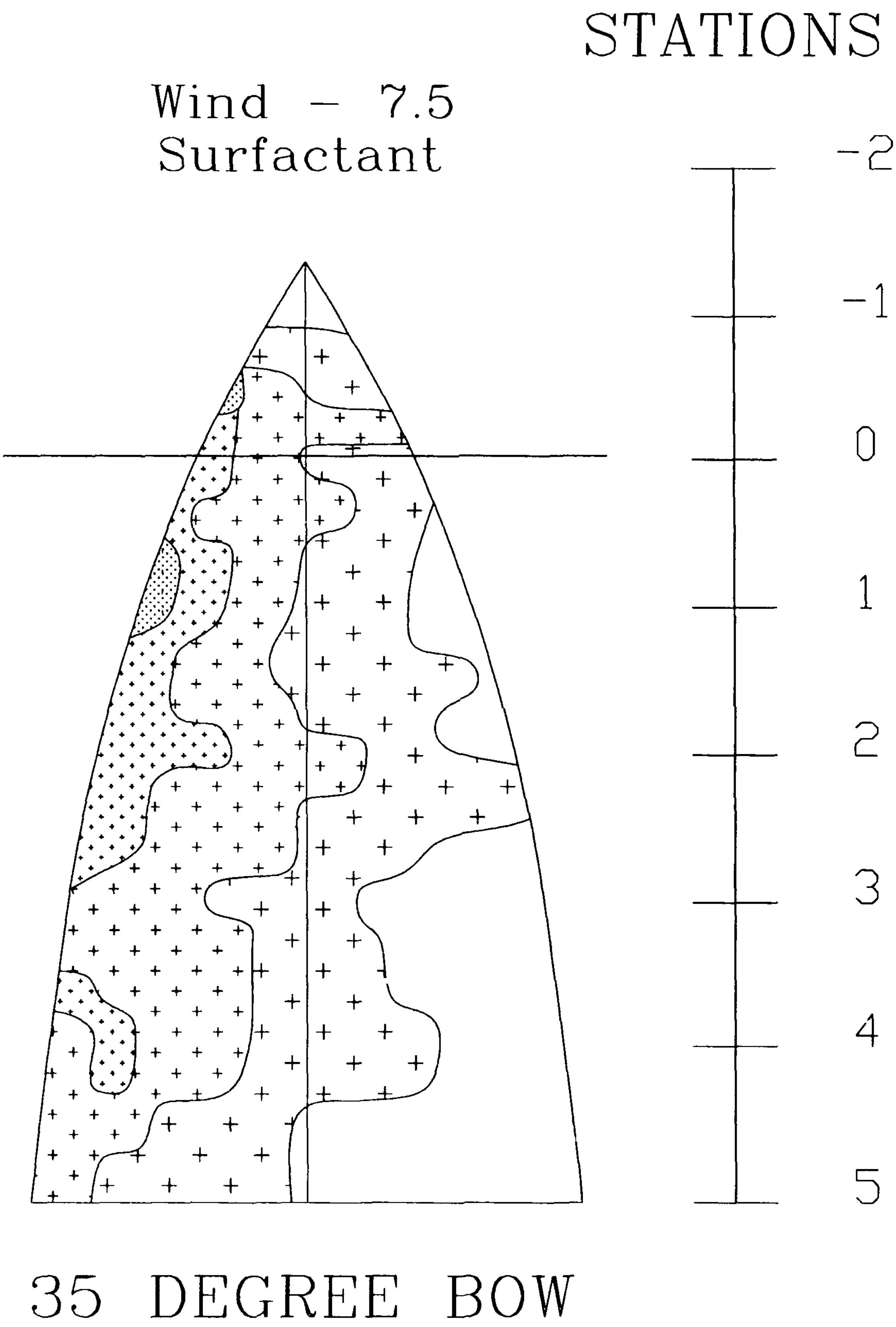
35 DEGREE BOW


STATIONS
Wind - 7.5
Surfactant
-2
-1
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1
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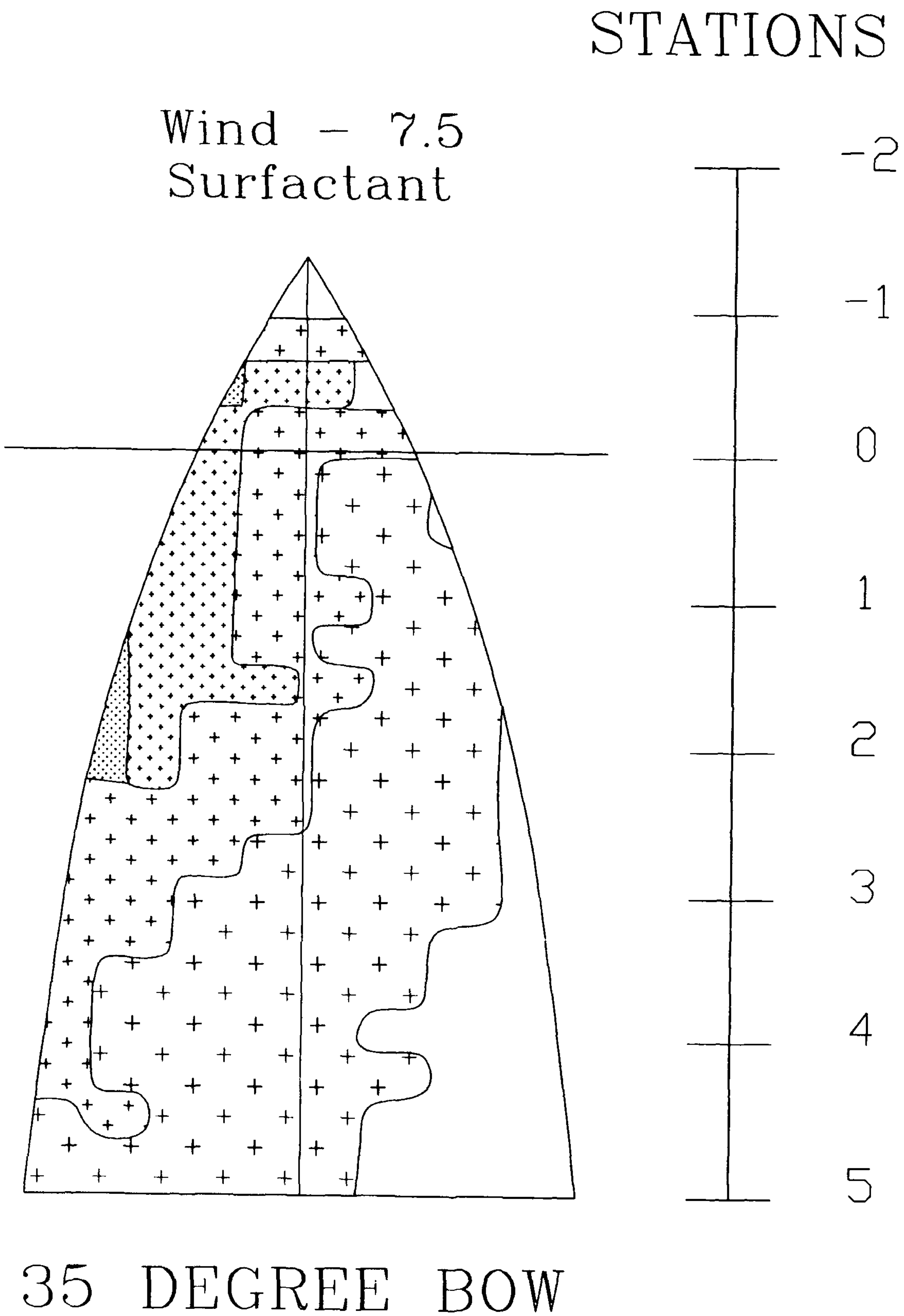
5
35 DEGREE BOW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Wind - 7.5
Surfactant
-2
-1
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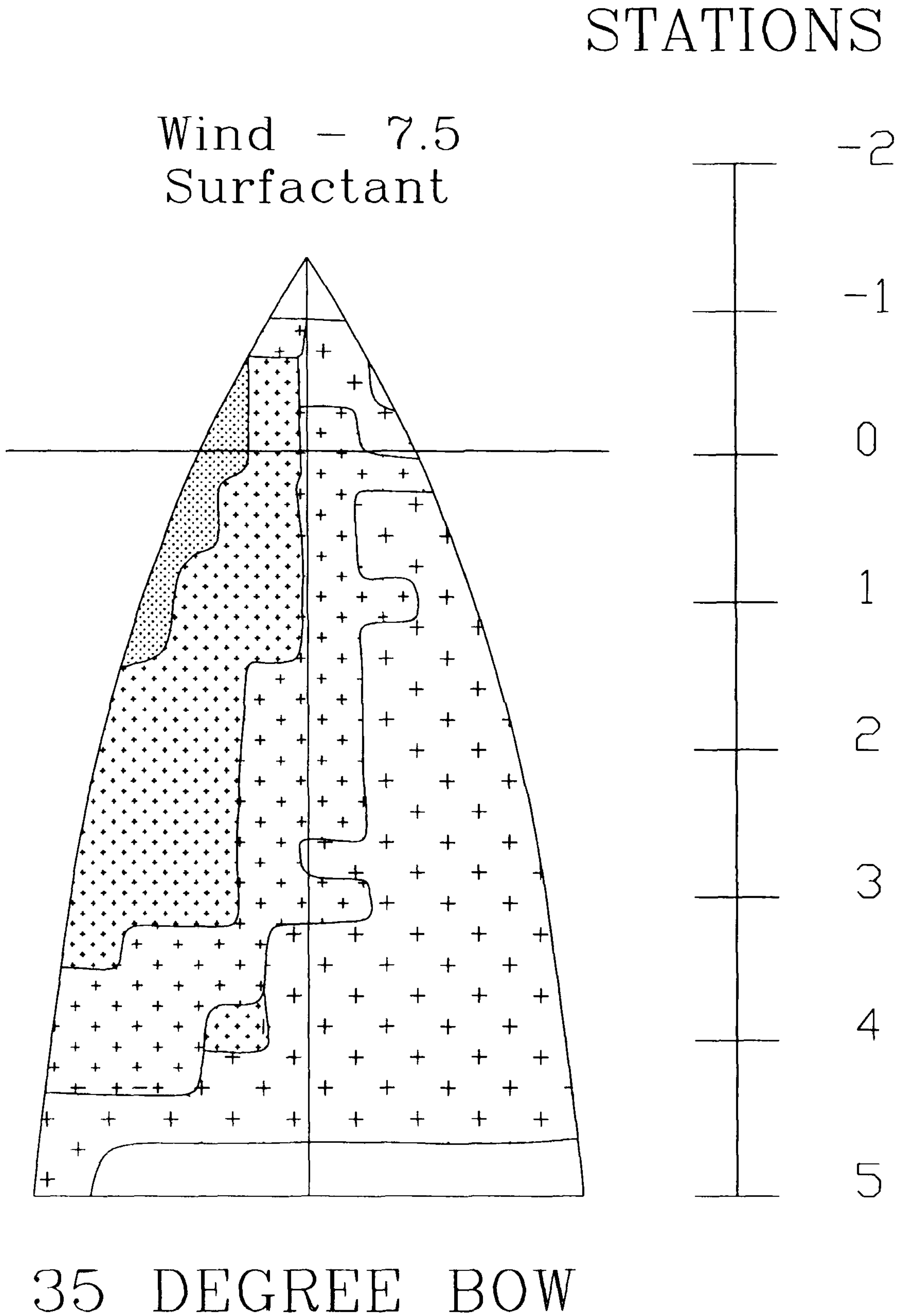
35 DEGREE BOW


STATIONS
Wind - 7.5
Surfactant
-2
-1
0
1
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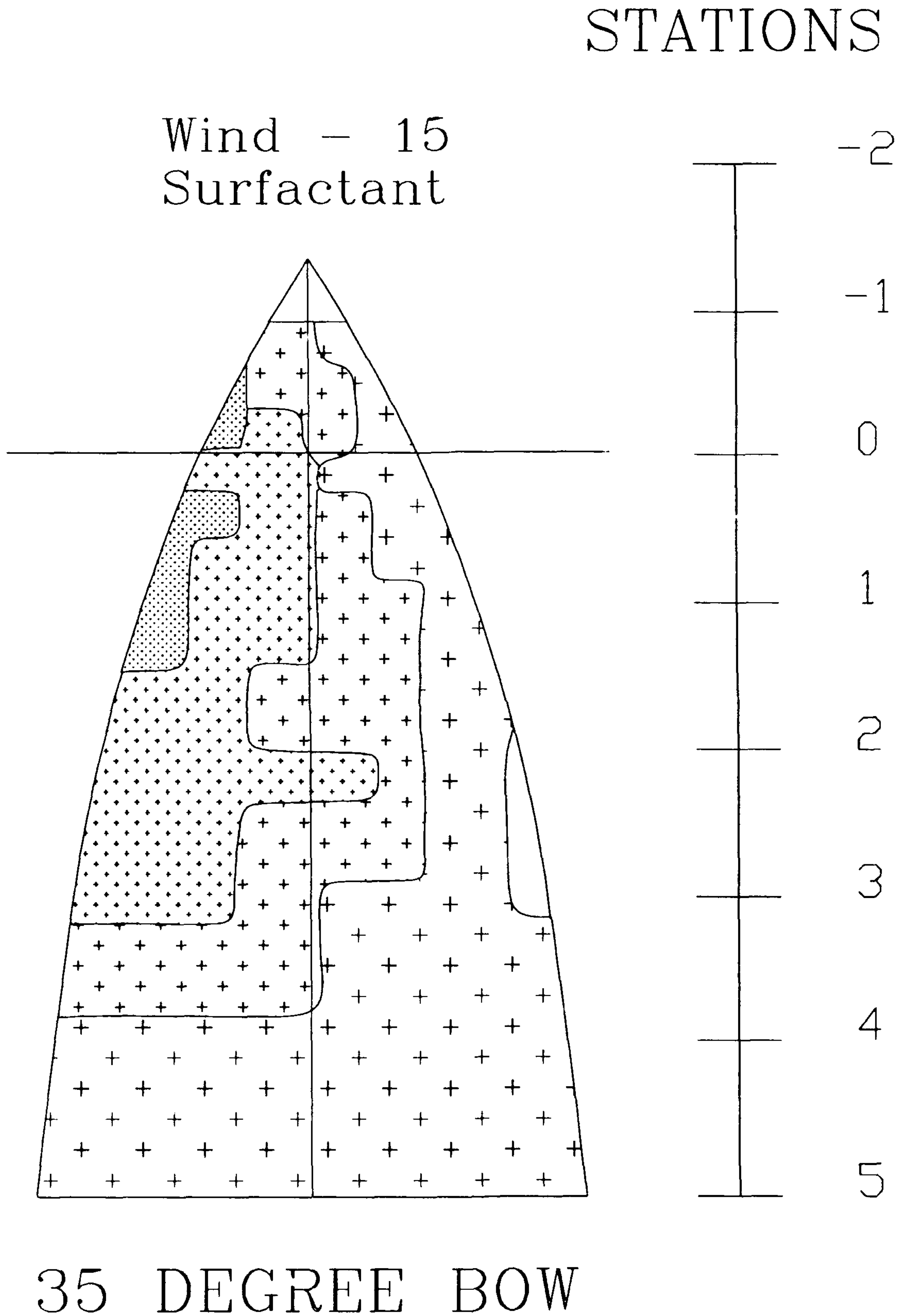
3
4
5
35 DEGREE BOW


STATIONS
Wind - 15
Surfactant
-2
-1
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3
4
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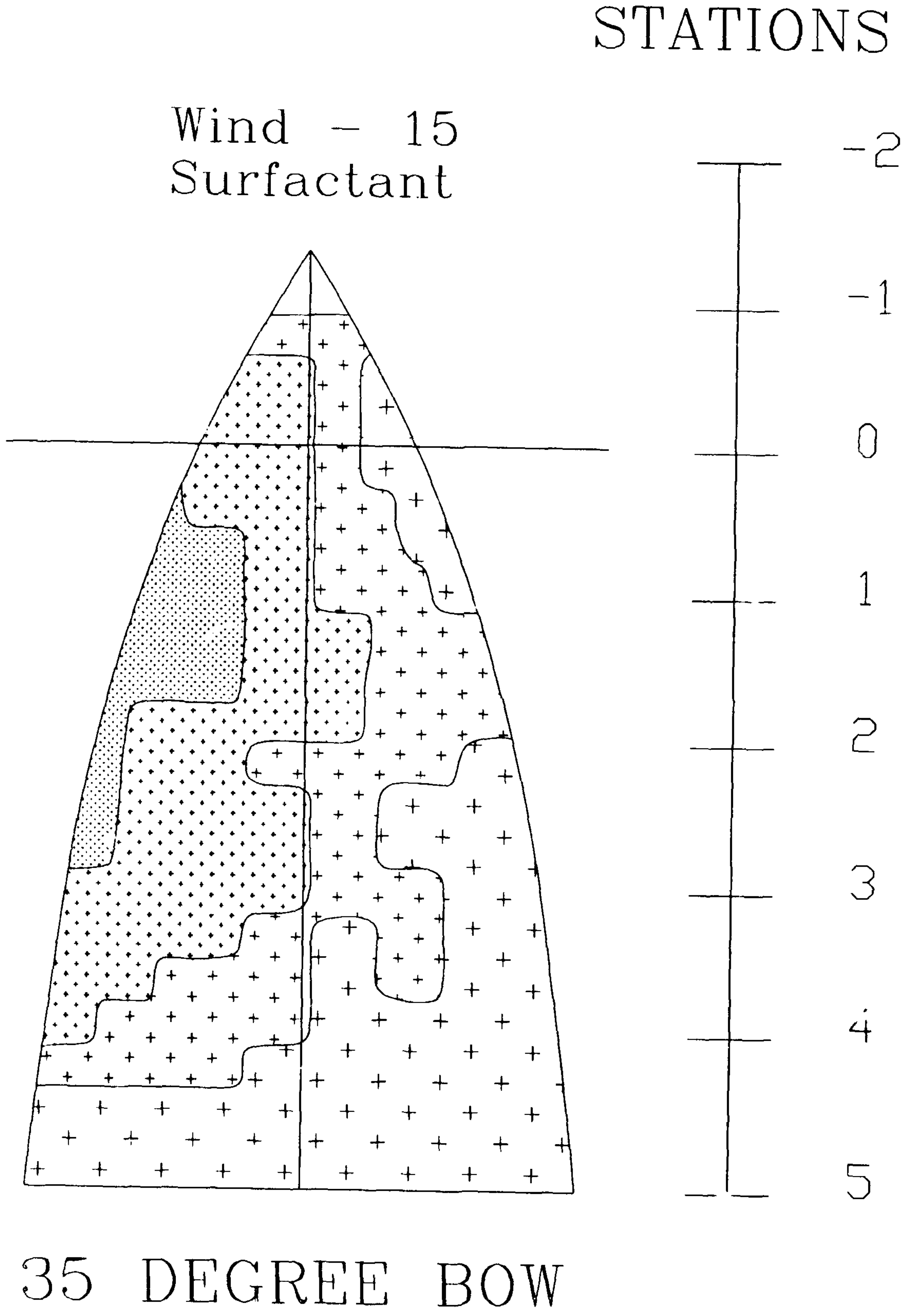
35 DEGREE BOW


STATIONS
Wind - 15
Surfactant
-2
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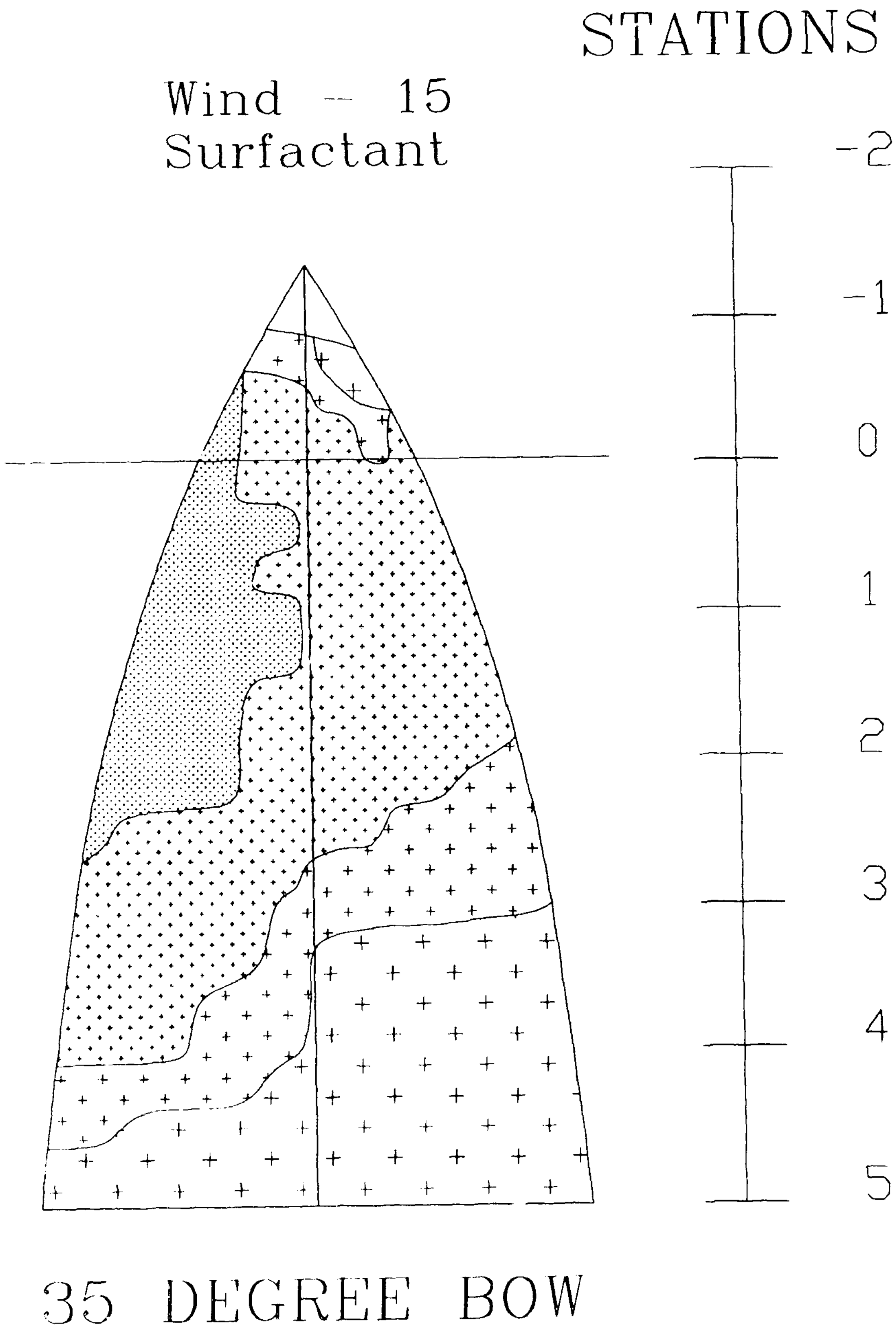
35 DEGREE BOW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Wind -- 15
Surfactant
-2
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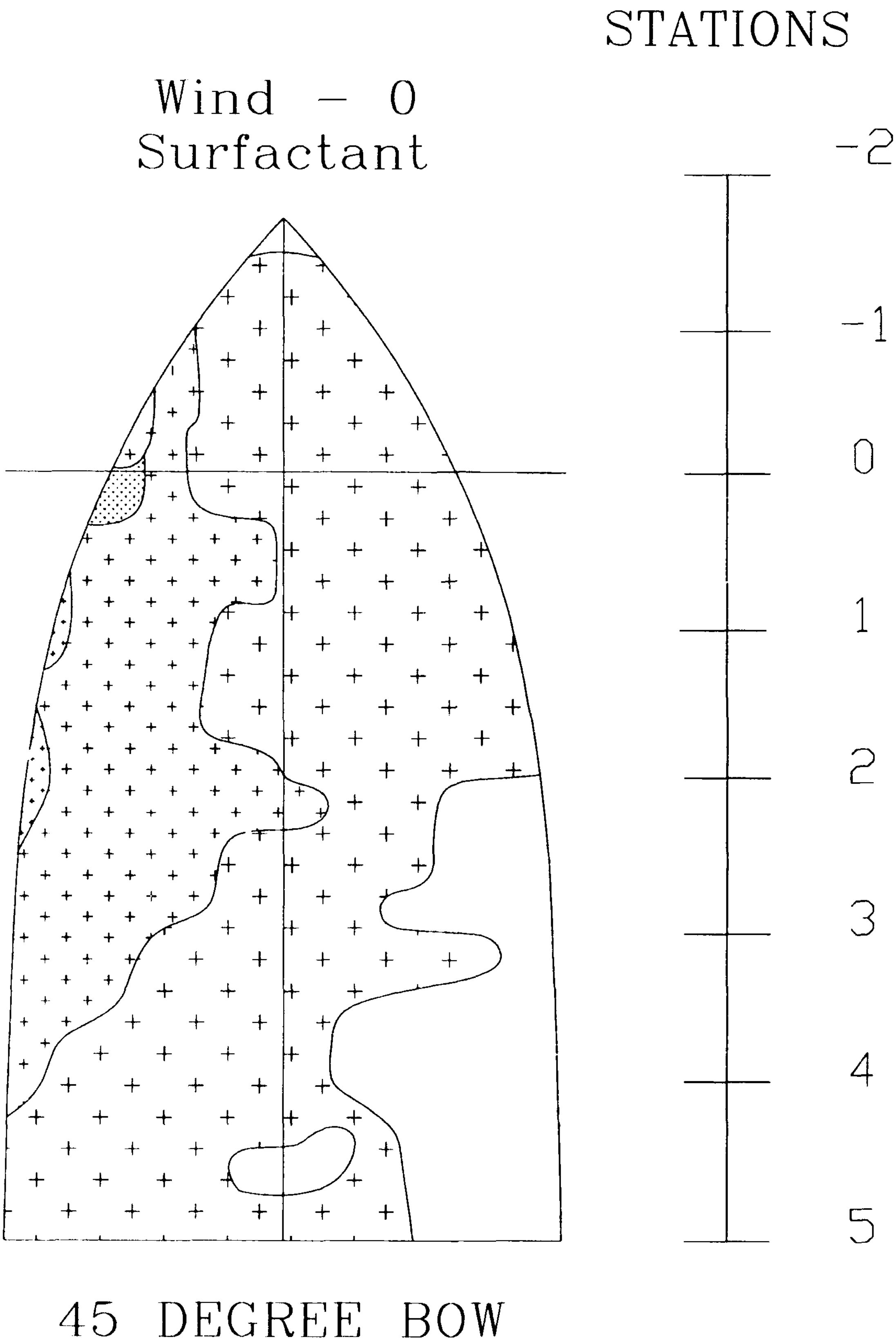
35 DEGREE BOW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Wind - 0
Surfactant
-2
-1
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1
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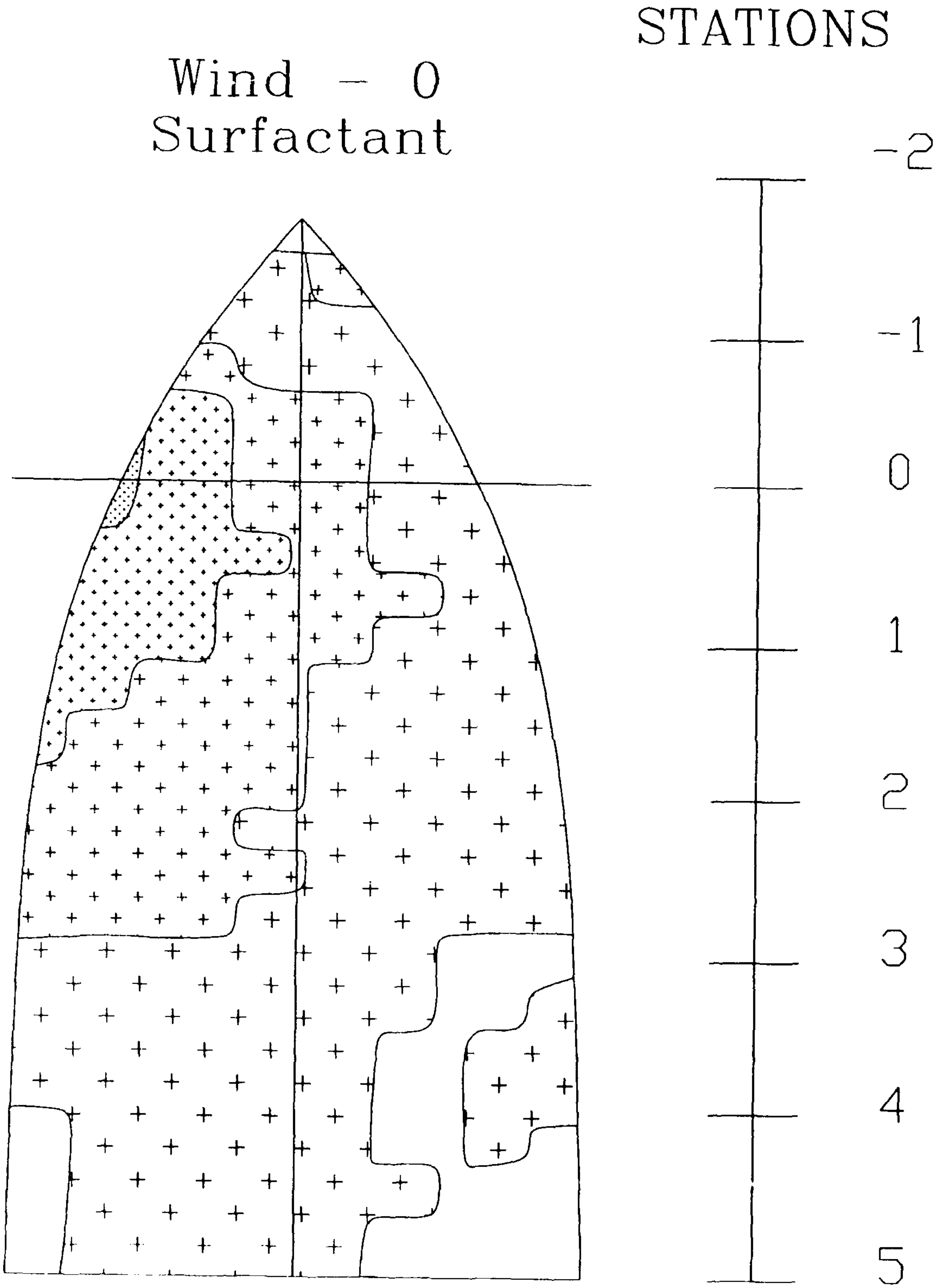
4
5
45 DEGREE BOW

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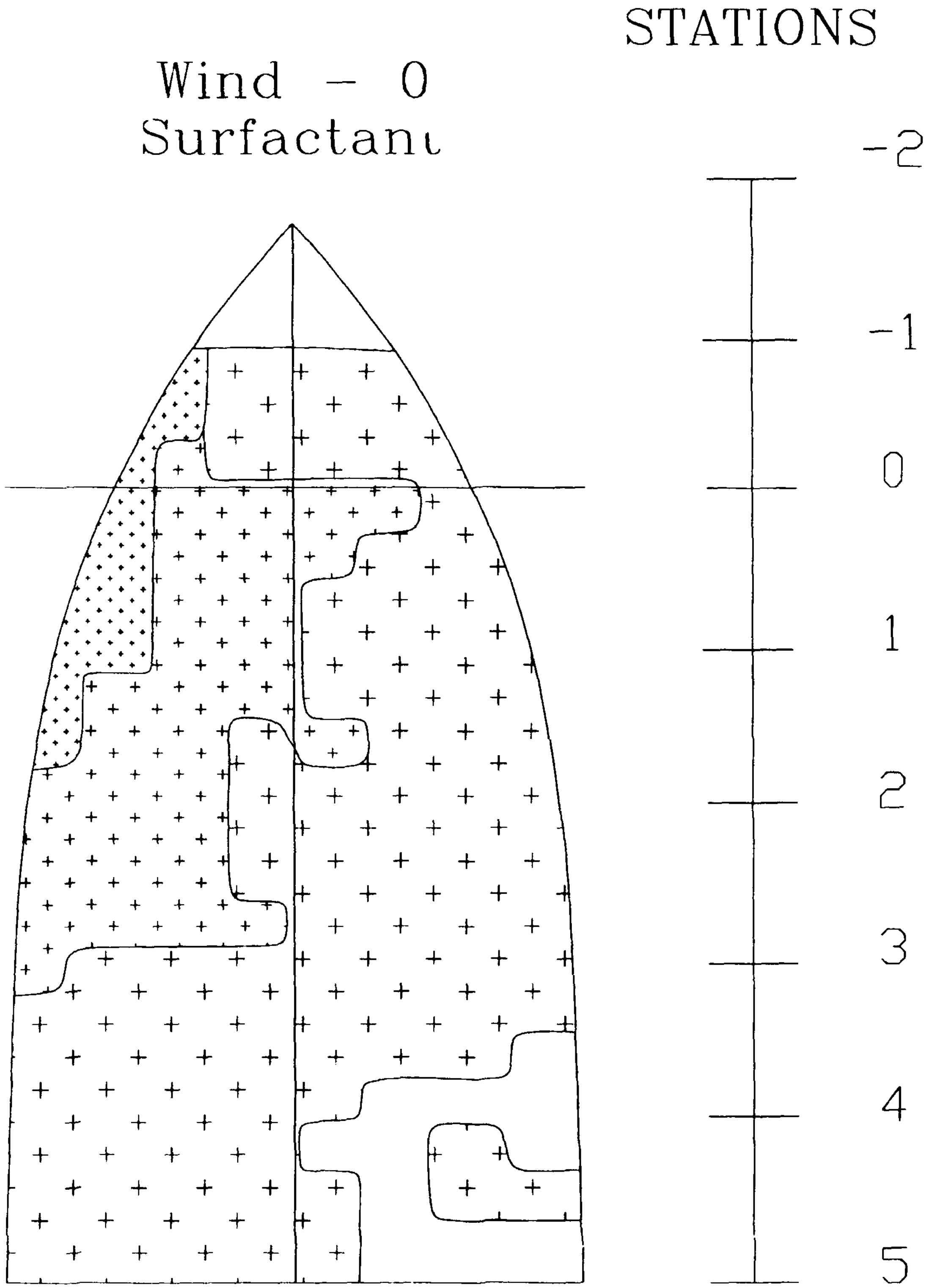


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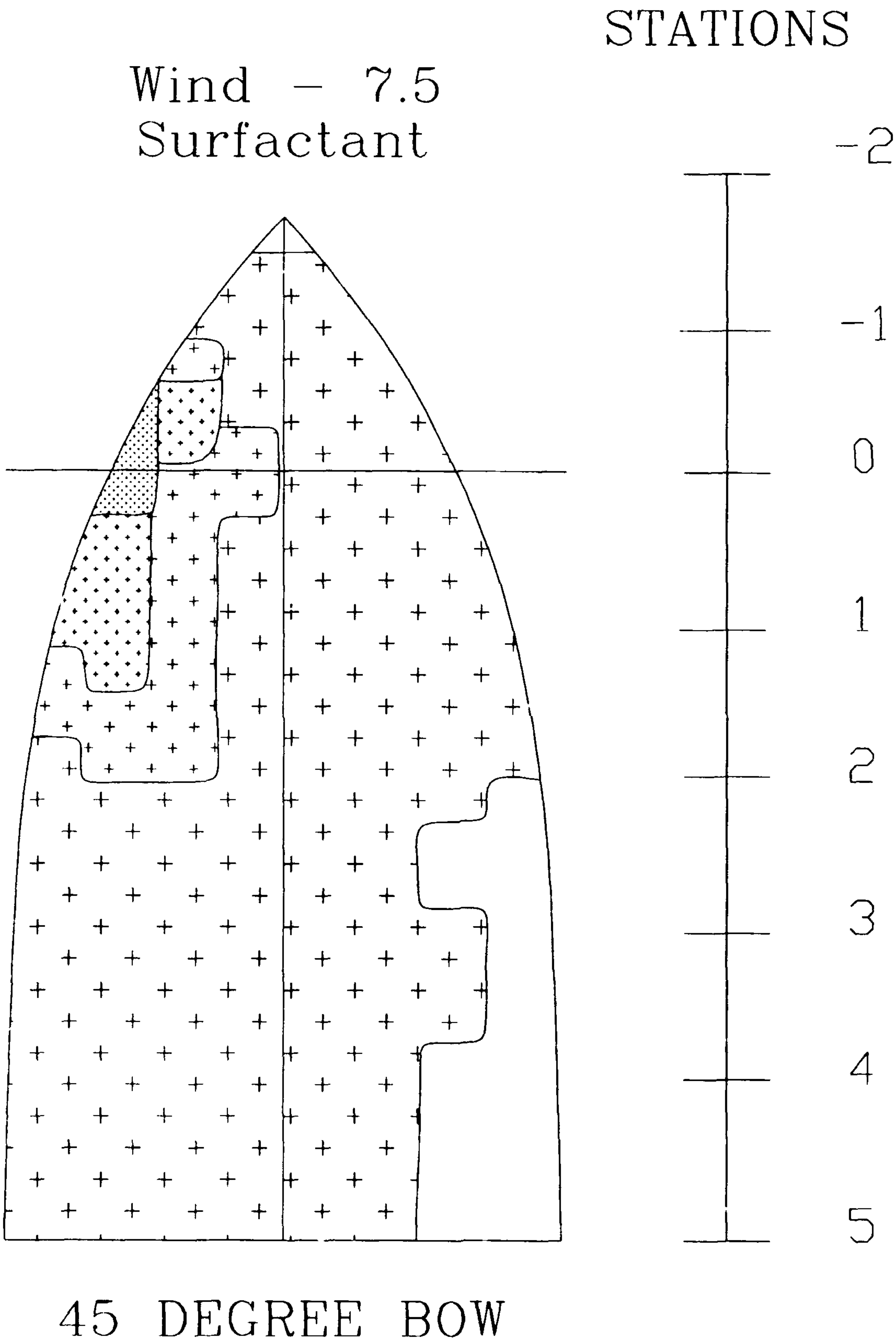
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Wind - 7.5
Surfactant
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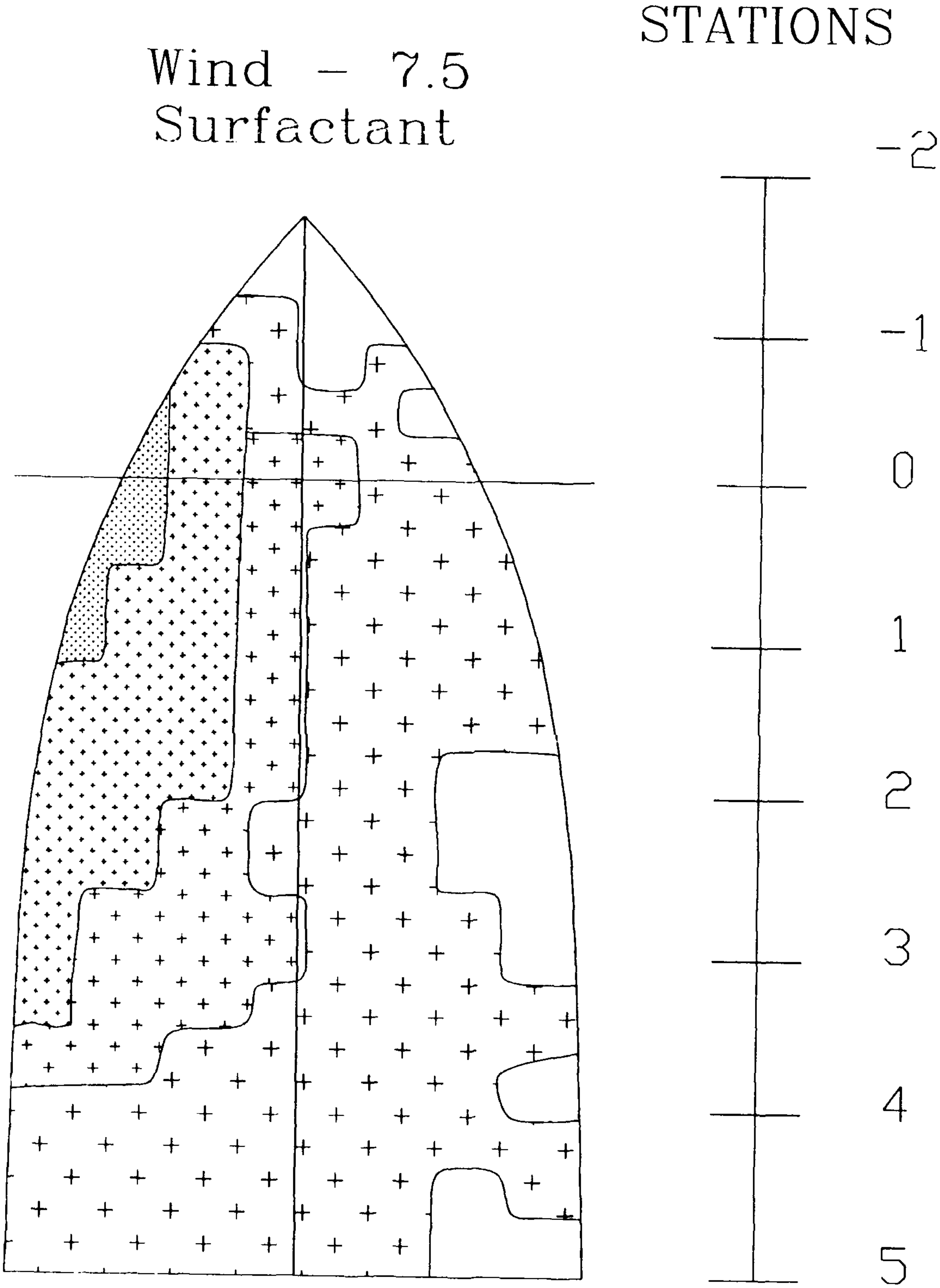
45 DEGREE BOW

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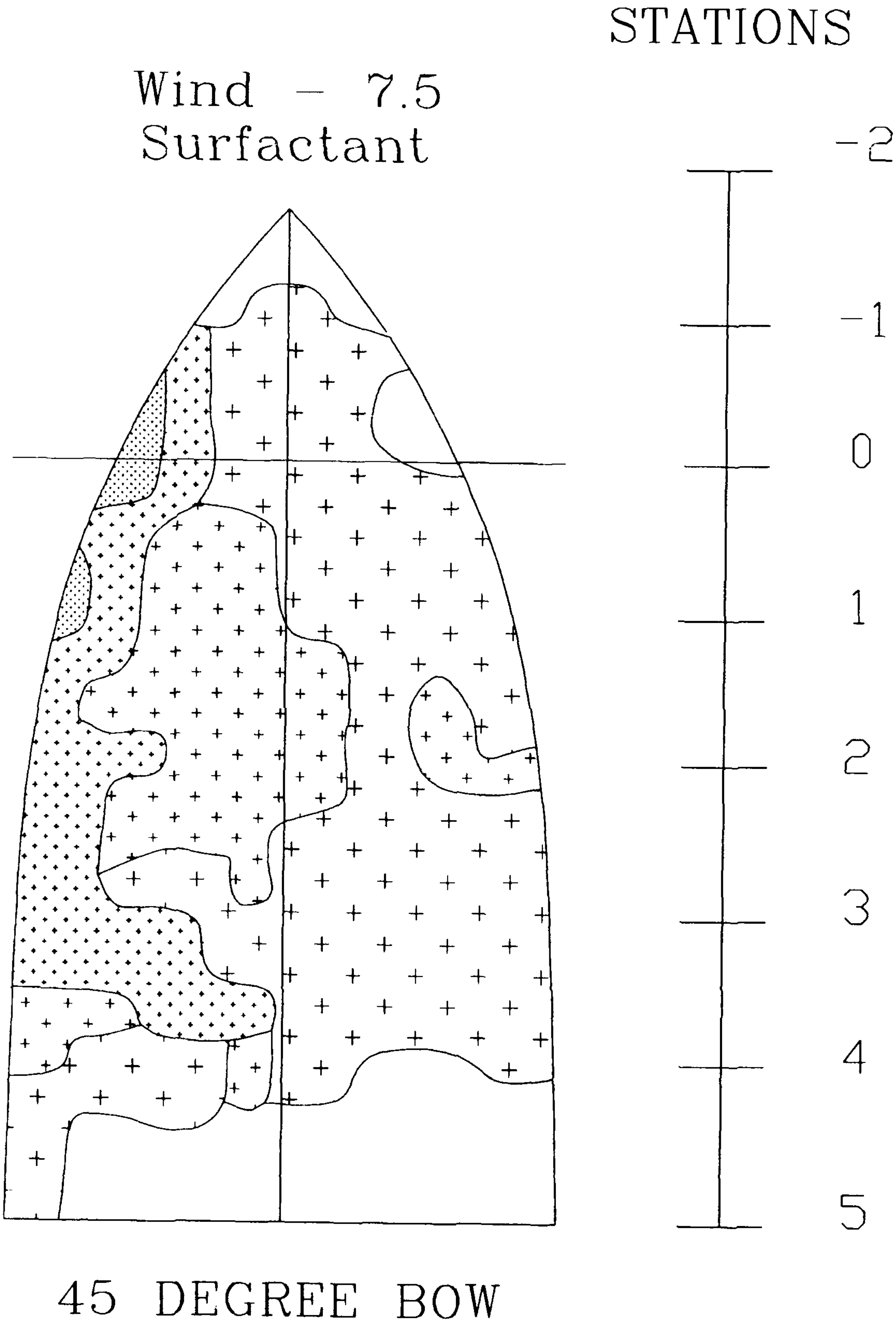
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Wind - 7.5
Surfactant
-2
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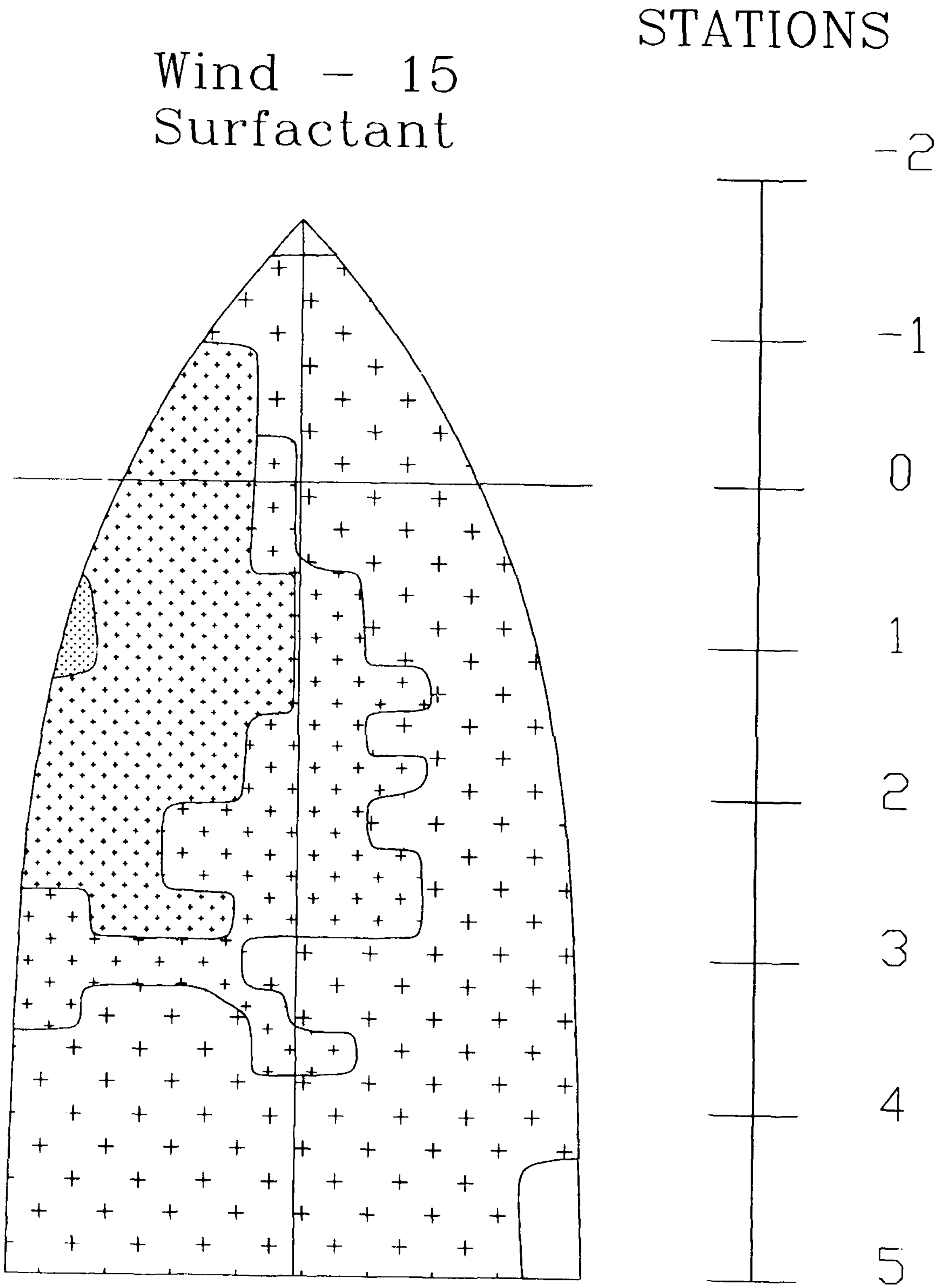


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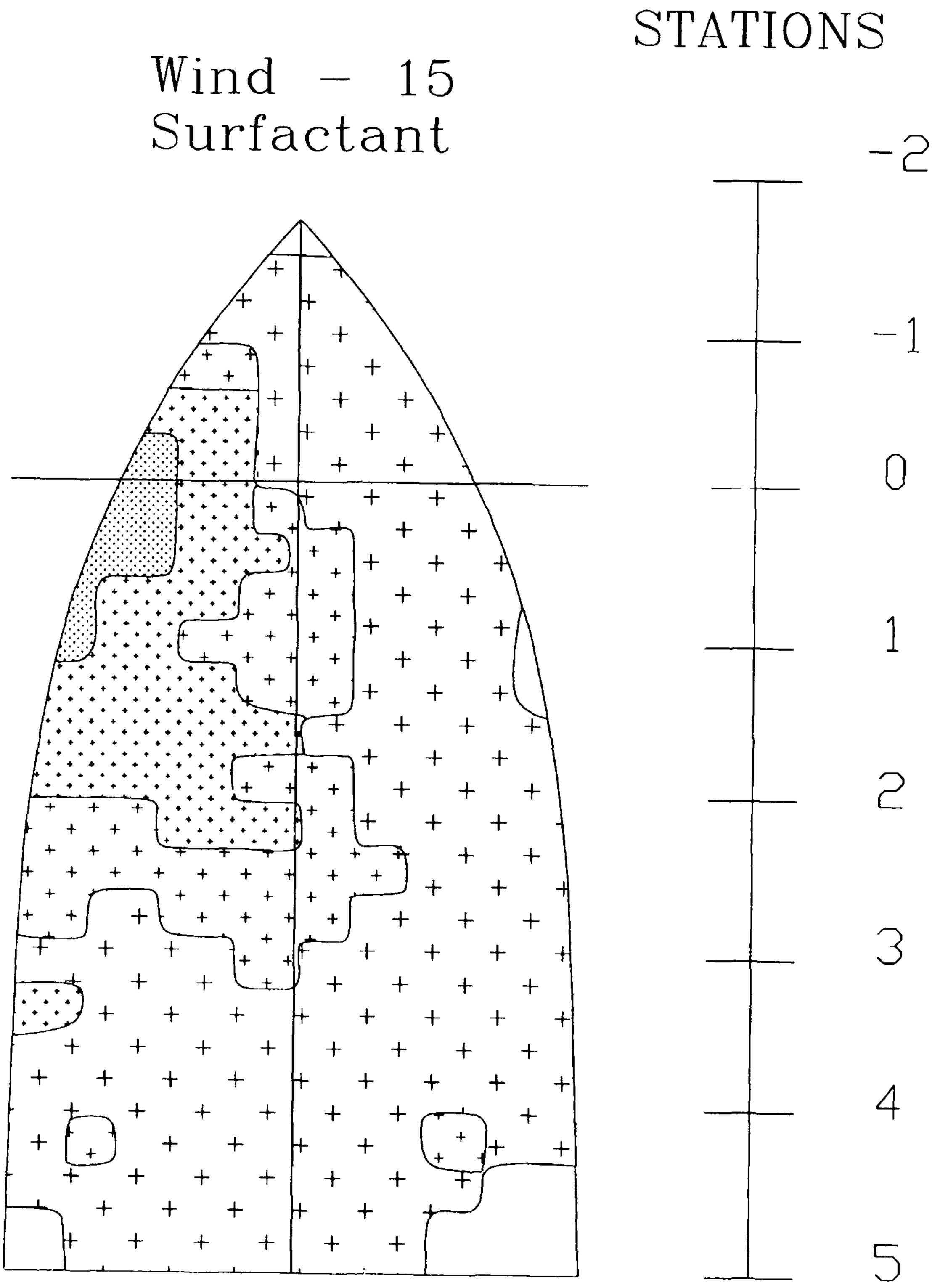


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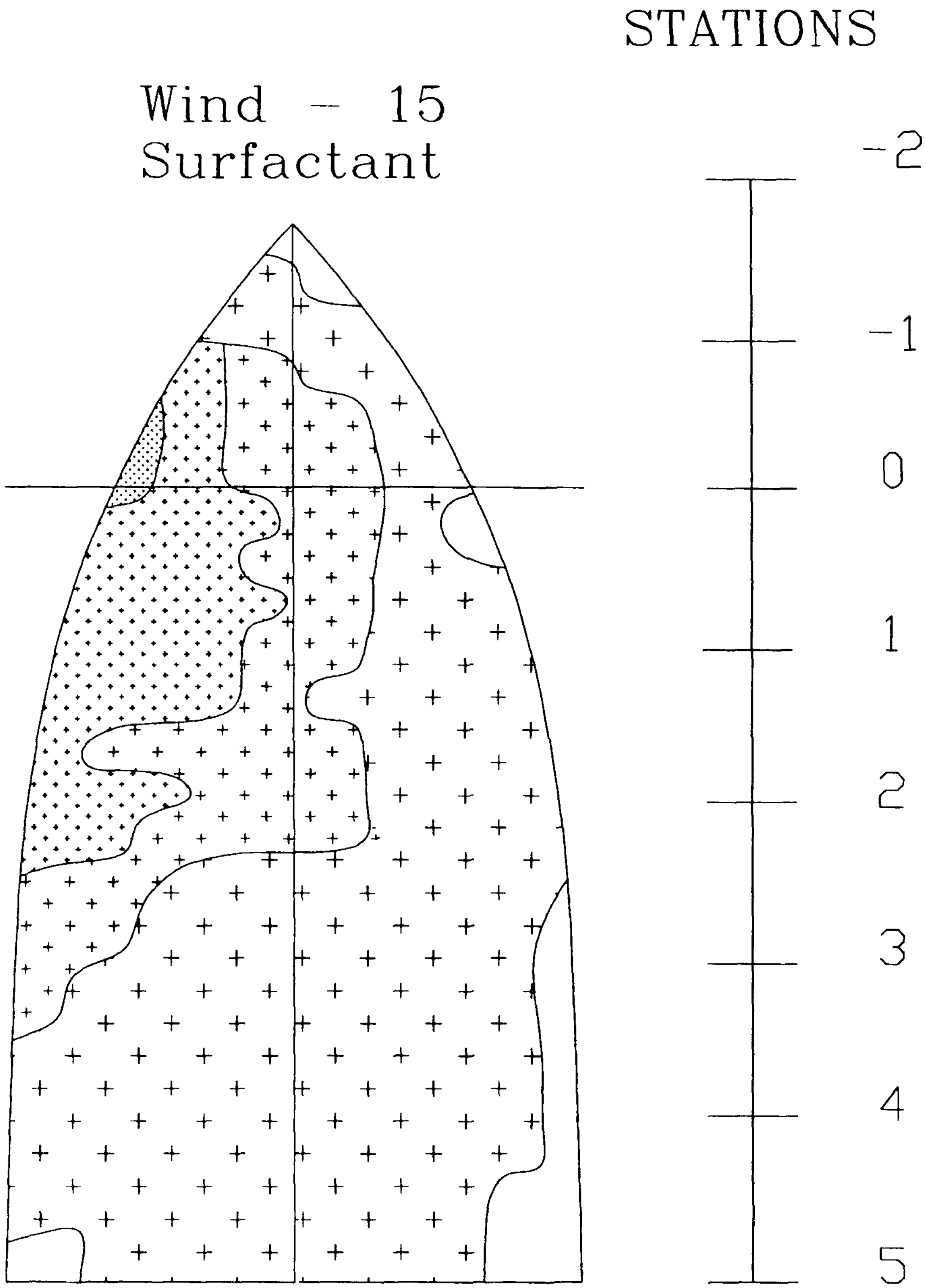


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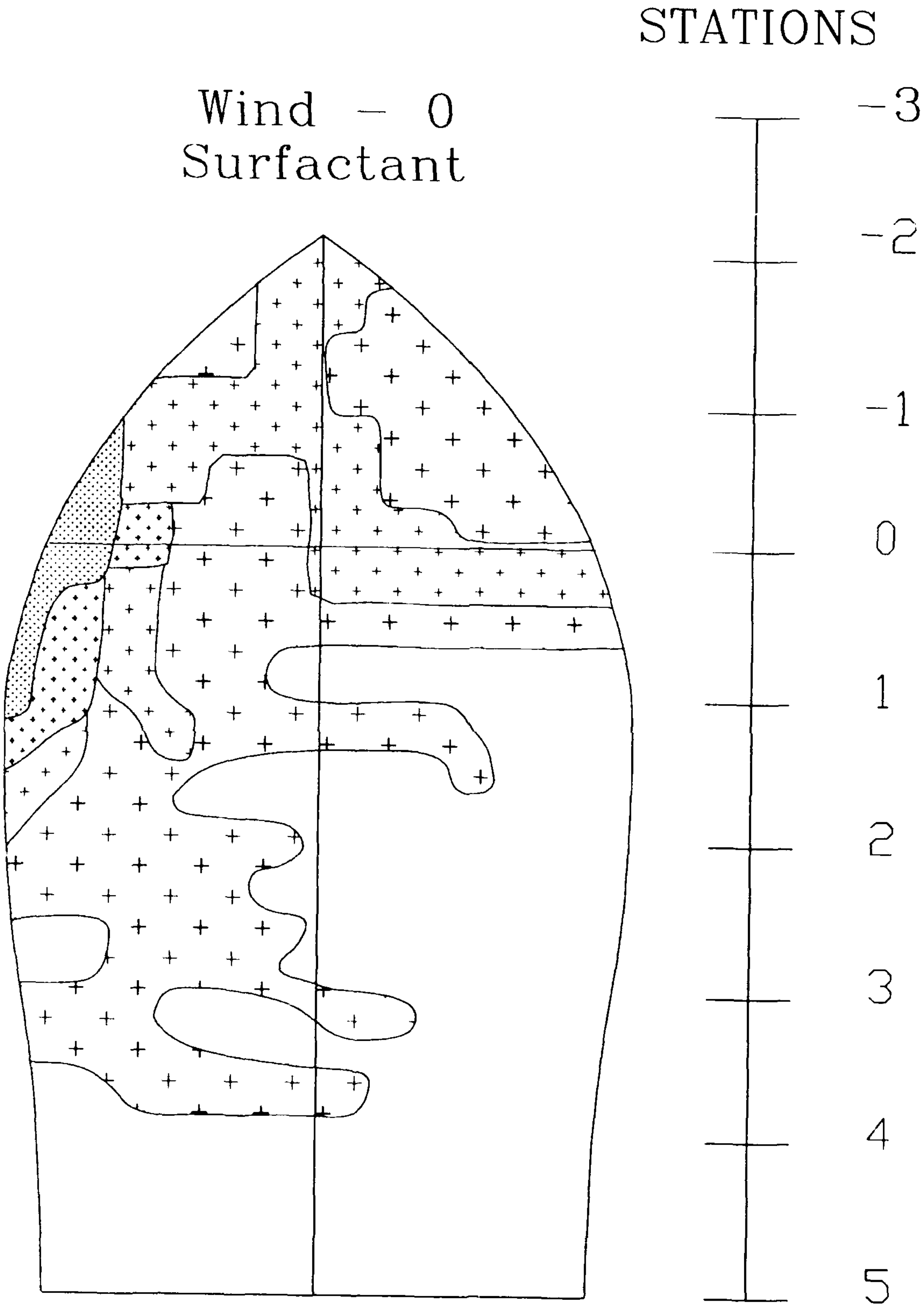


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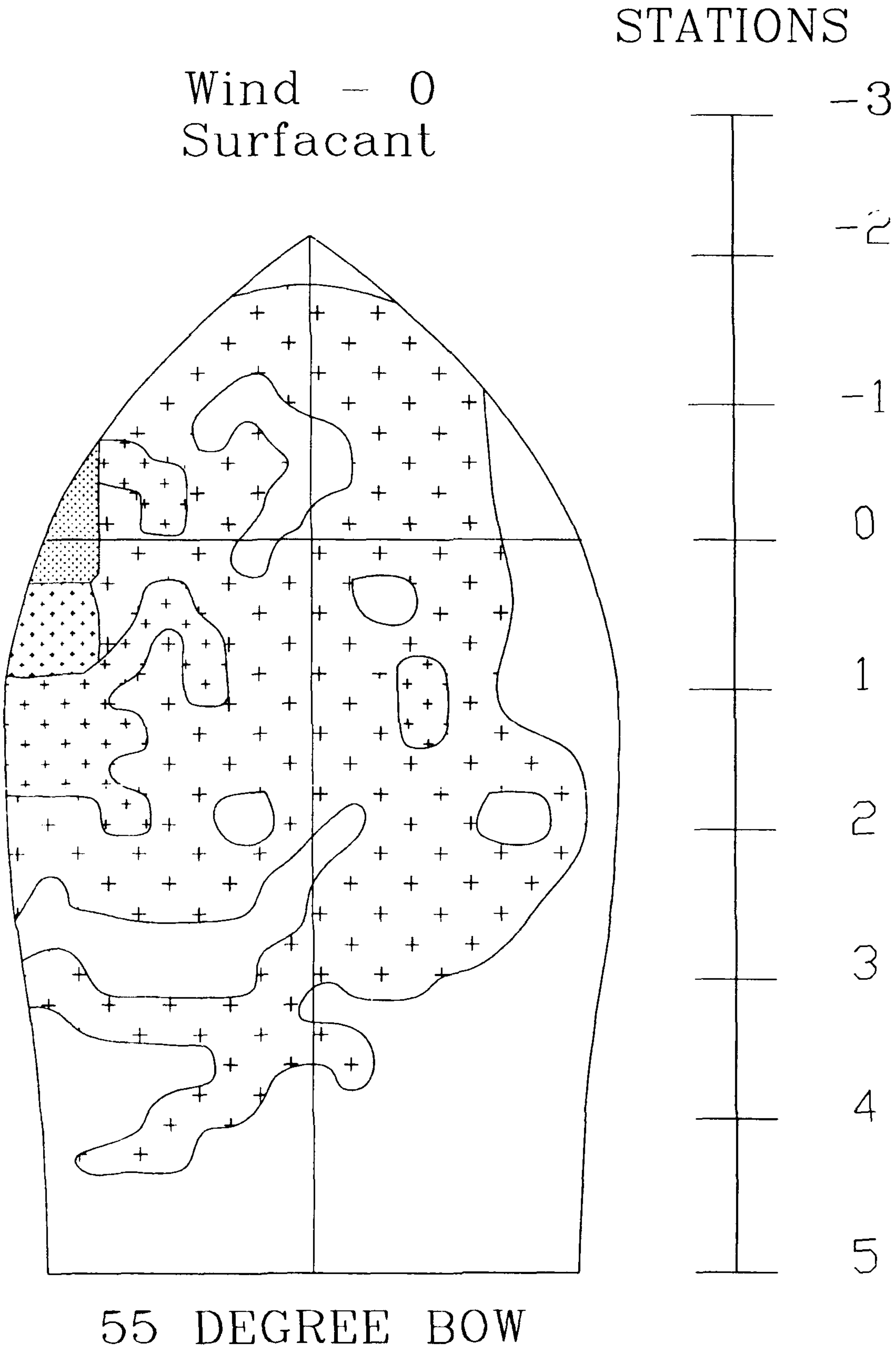
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Wind - 0
Surfacant
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-2
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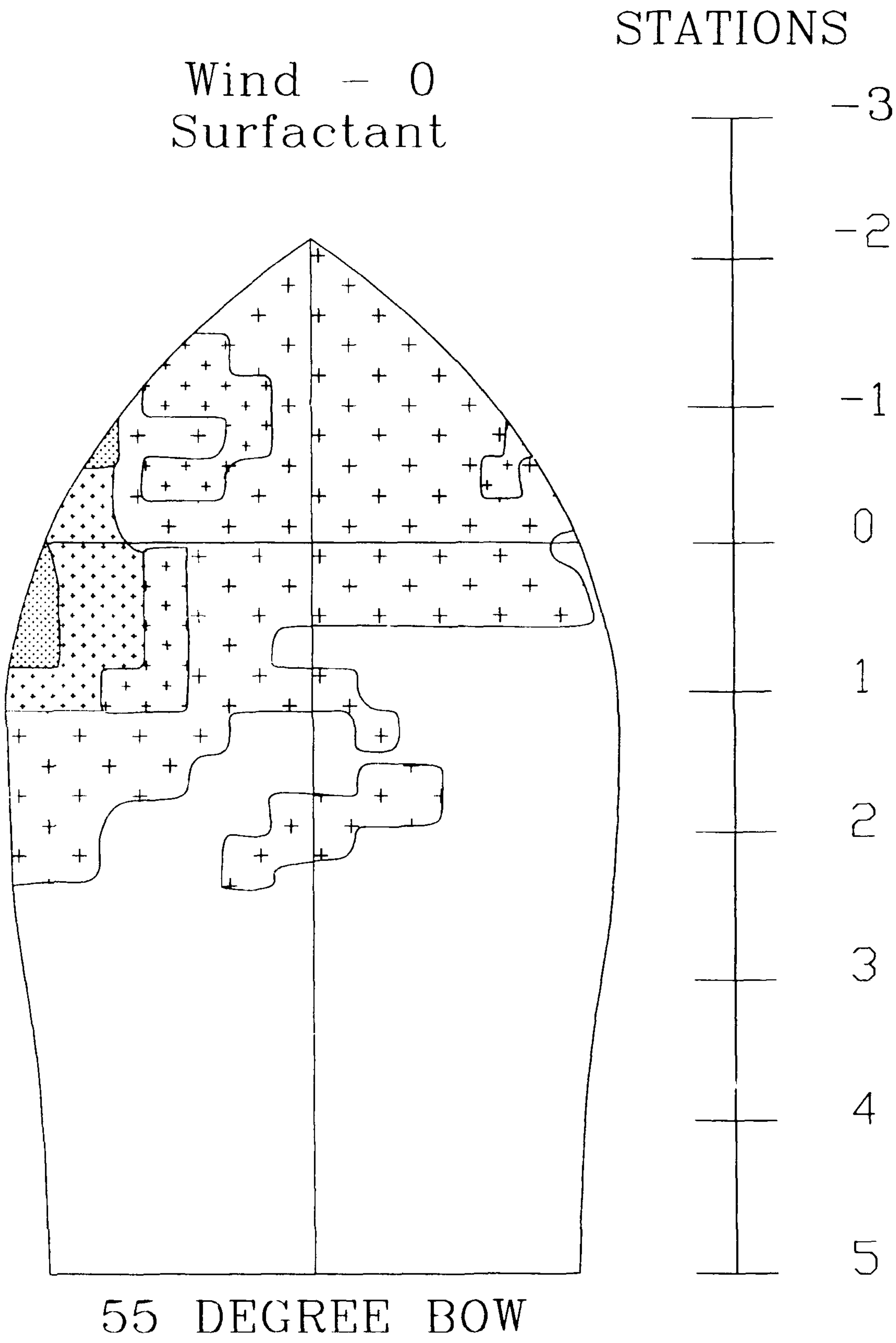
55 DEGREE BOW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Surfactant
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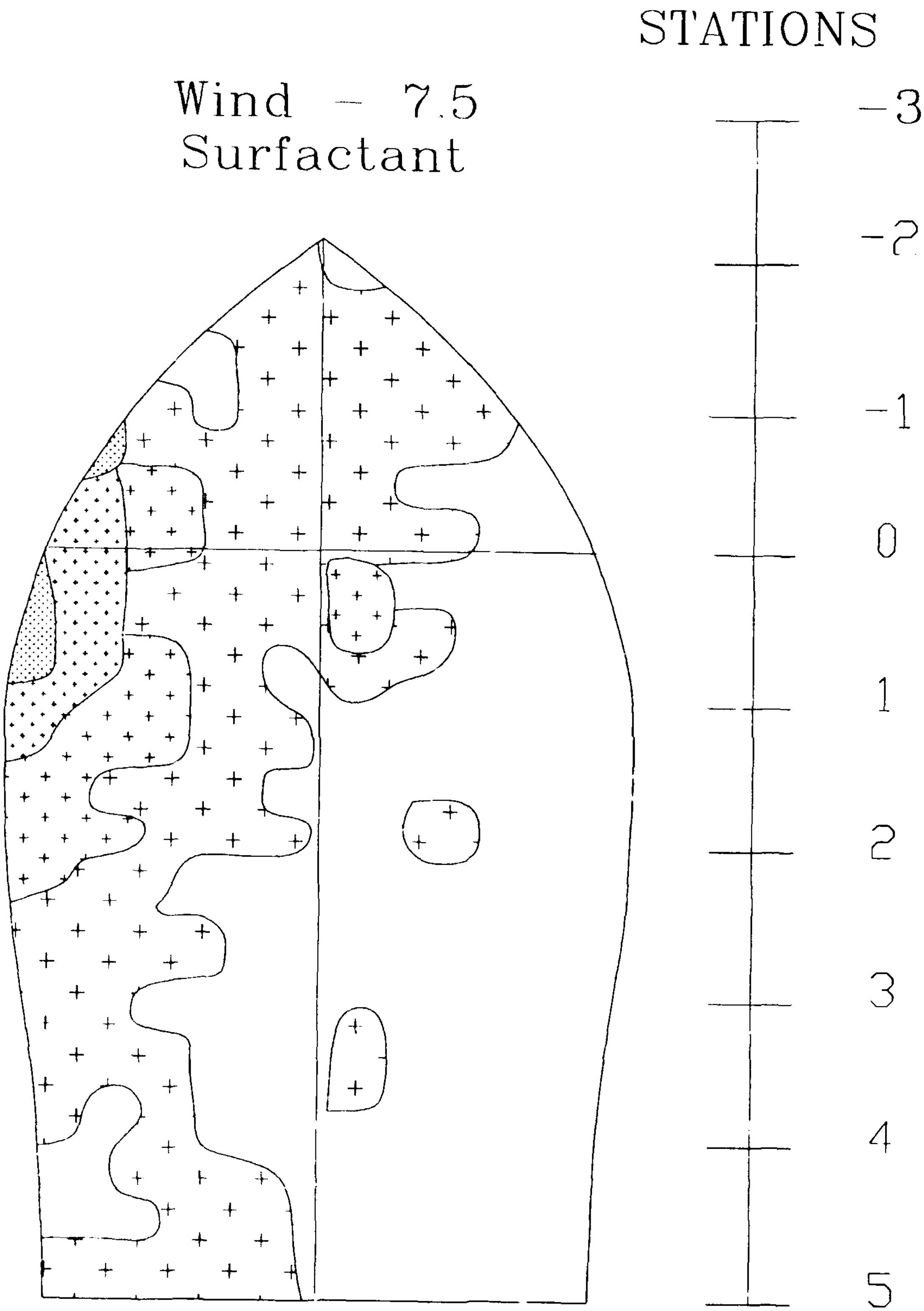
55 DEGREE BOW



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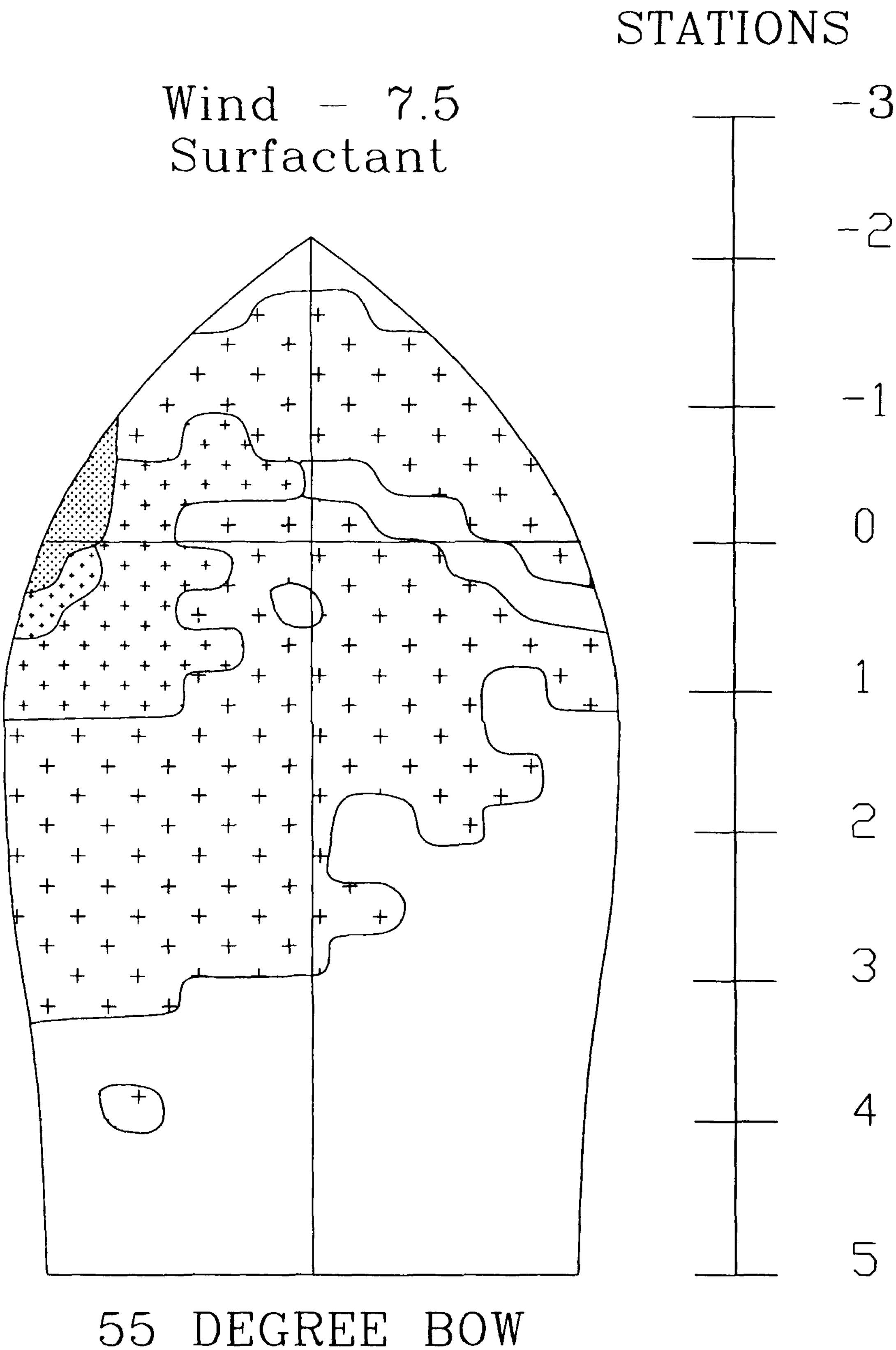
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Surfactant
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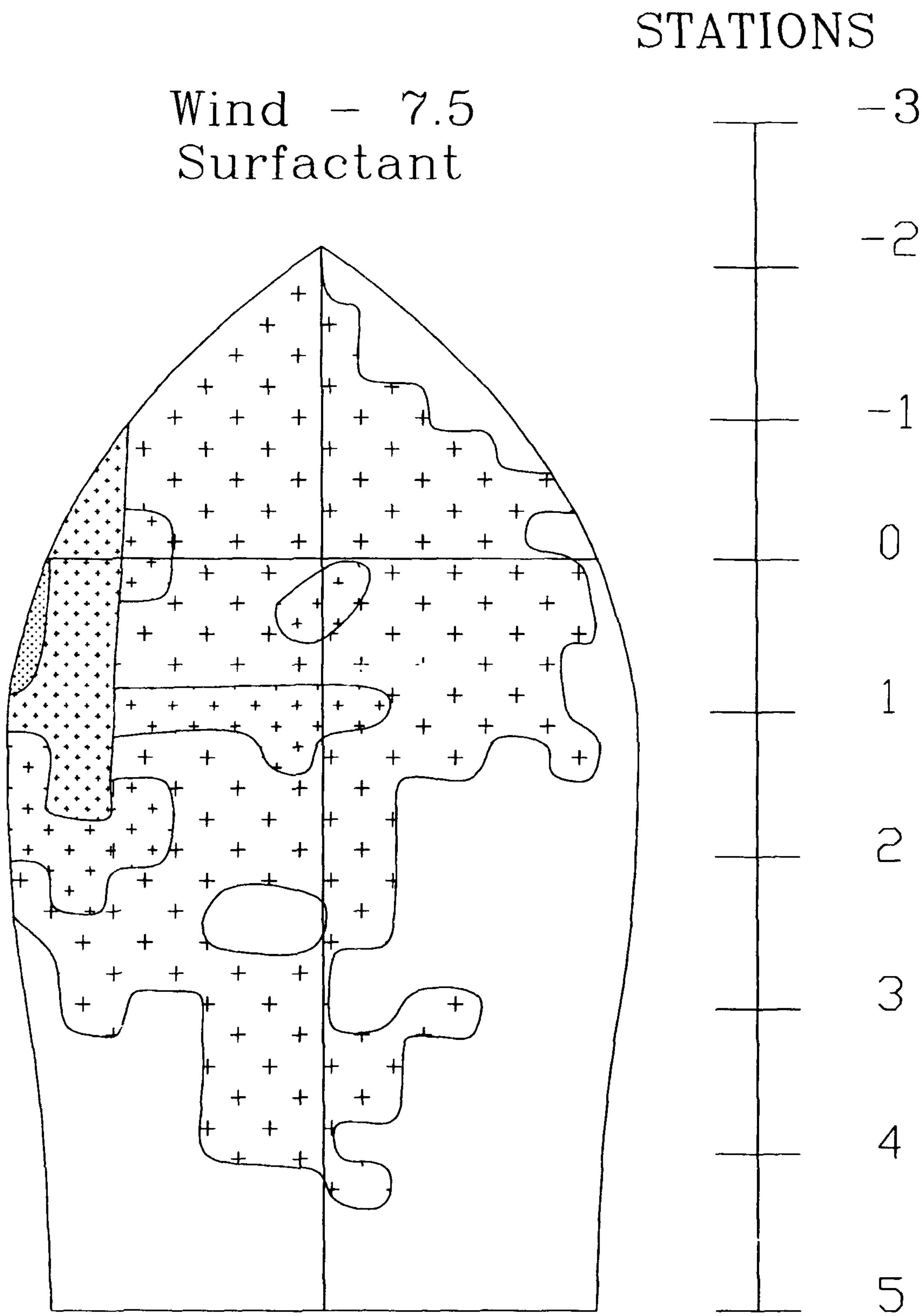
55 DEGREE BOW

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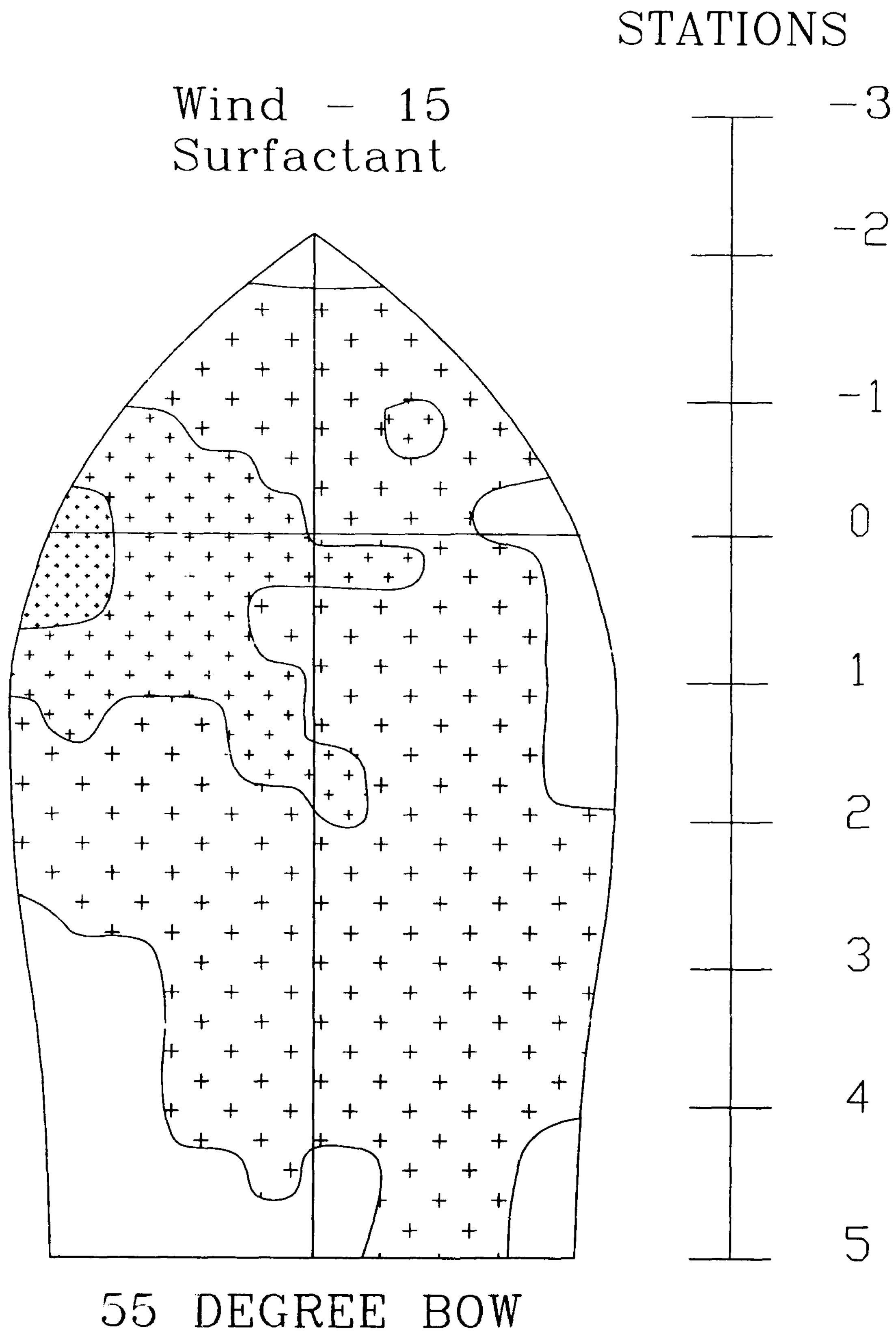
STATIONS
Wind - 15
Surfactant
-3
-2
-1
0
1
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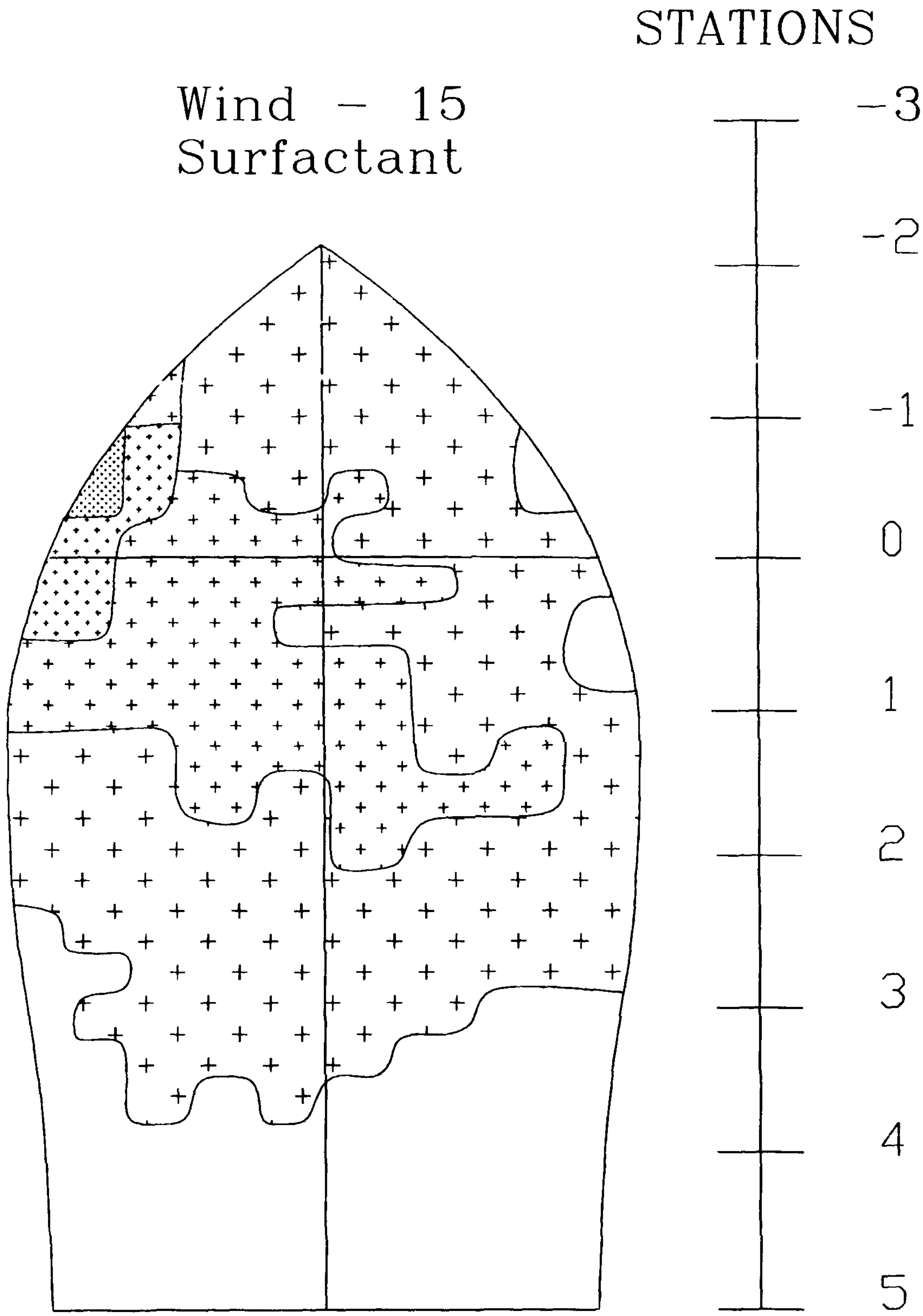
4
5
55 DEGREE BOW

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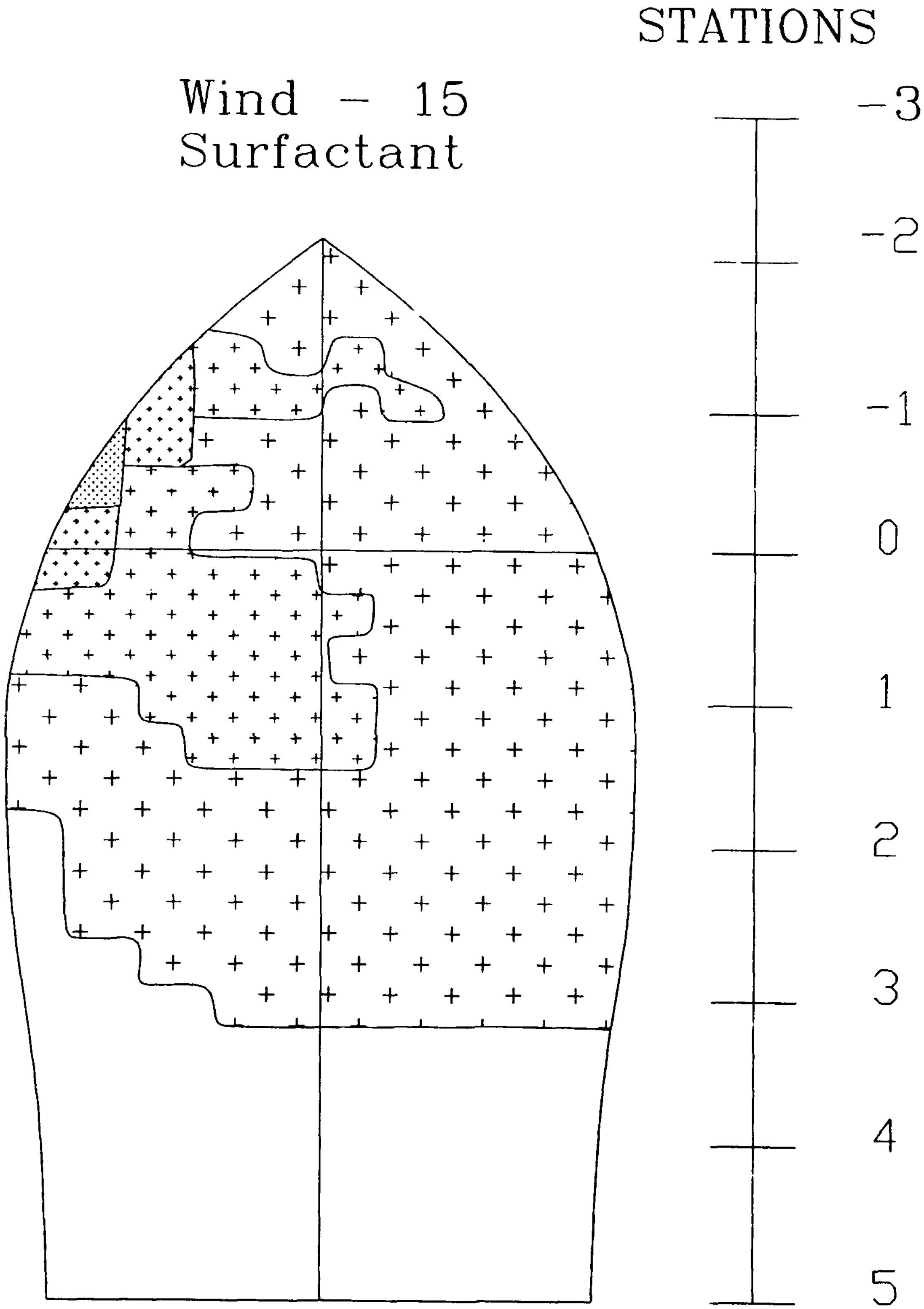

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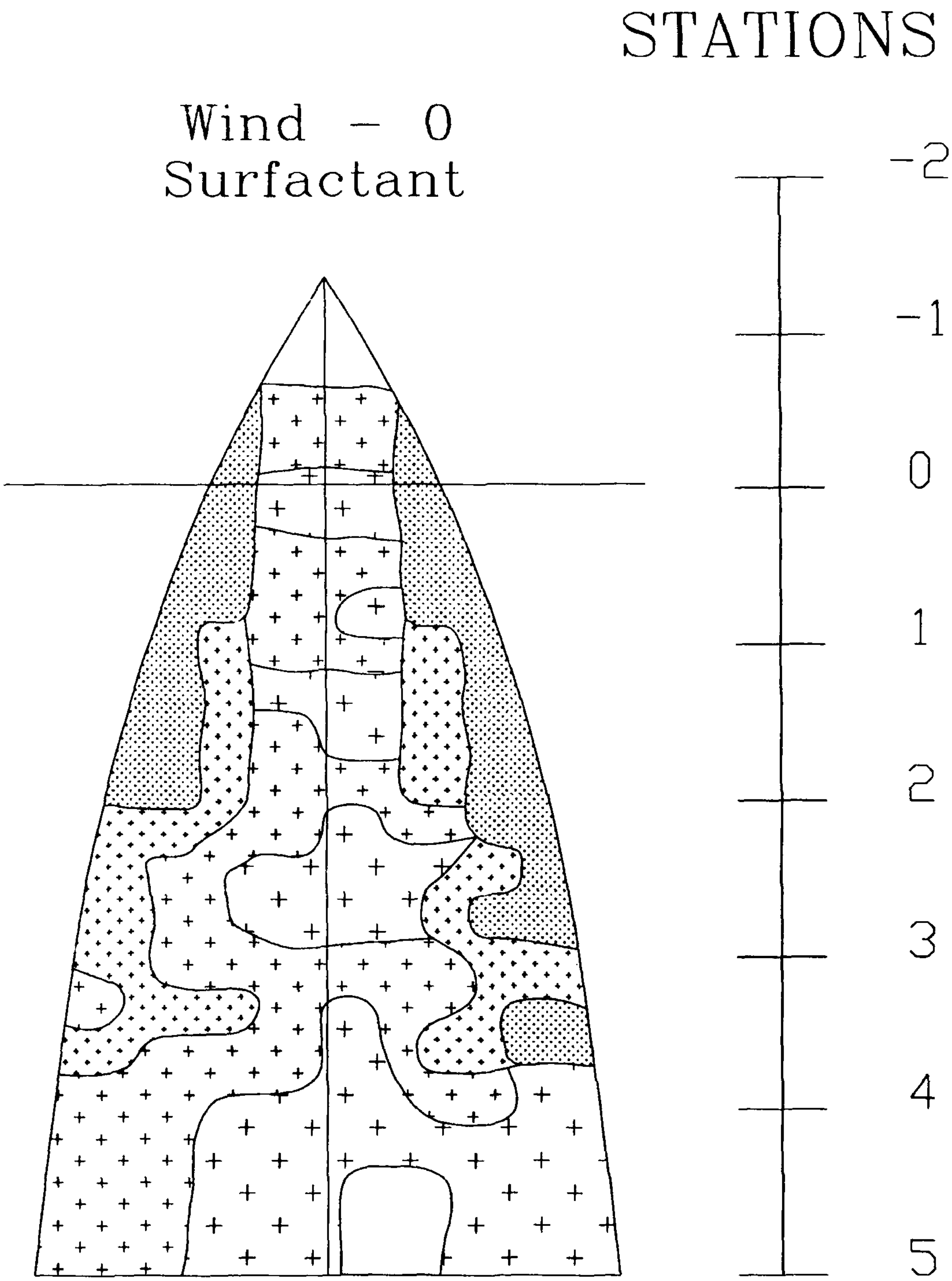
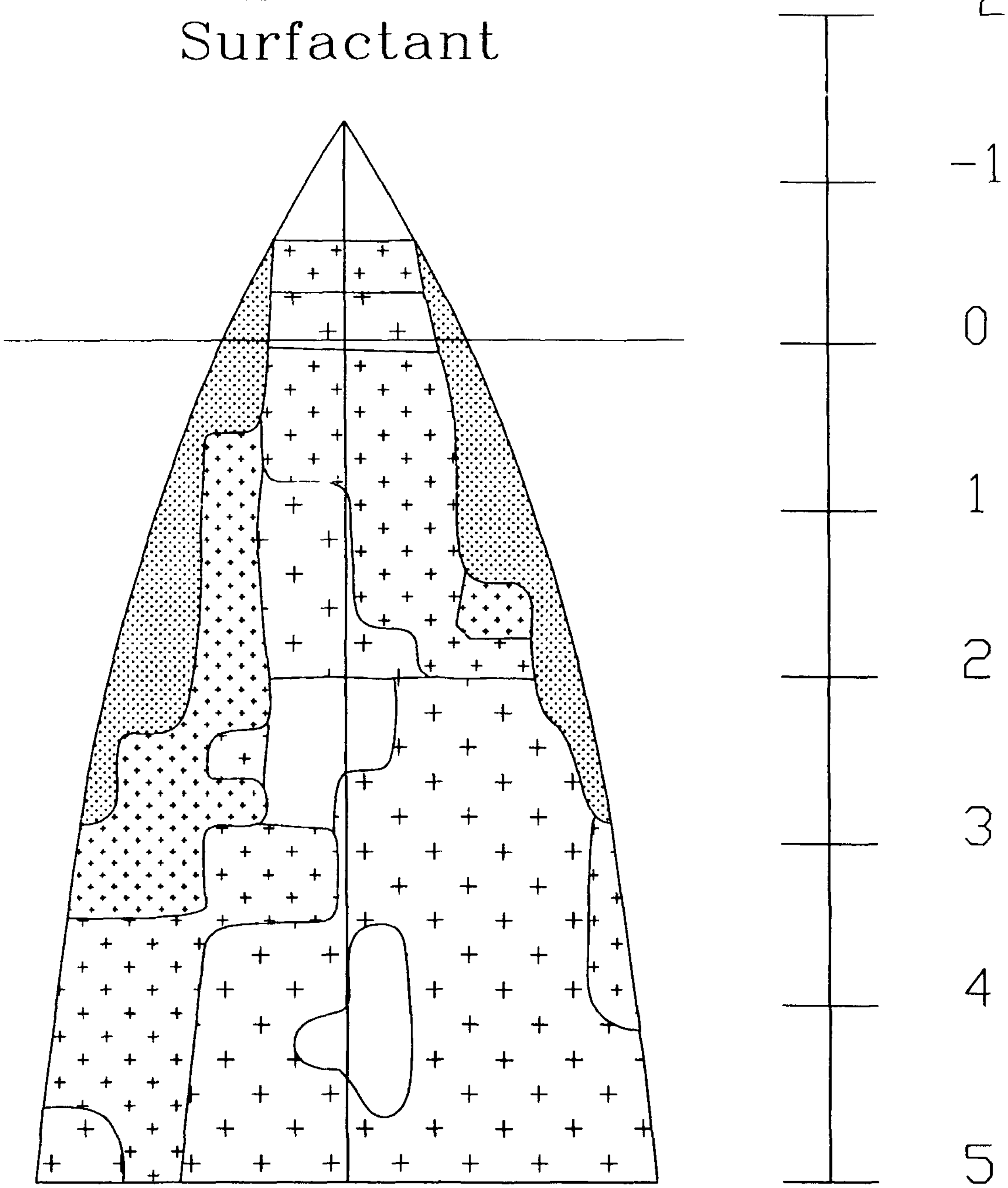


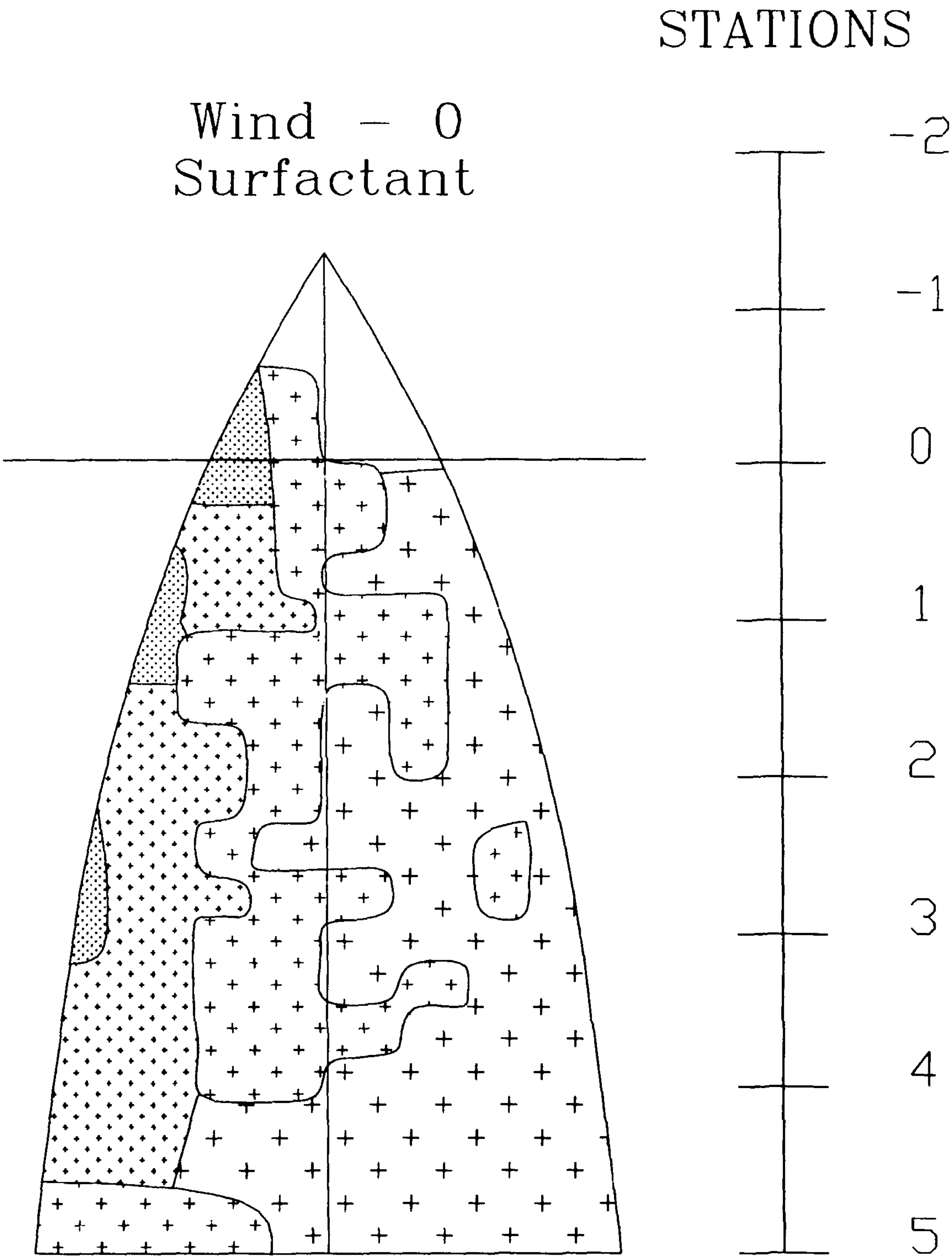

35 DEGREE BOW KNUCKLE

STATIONS

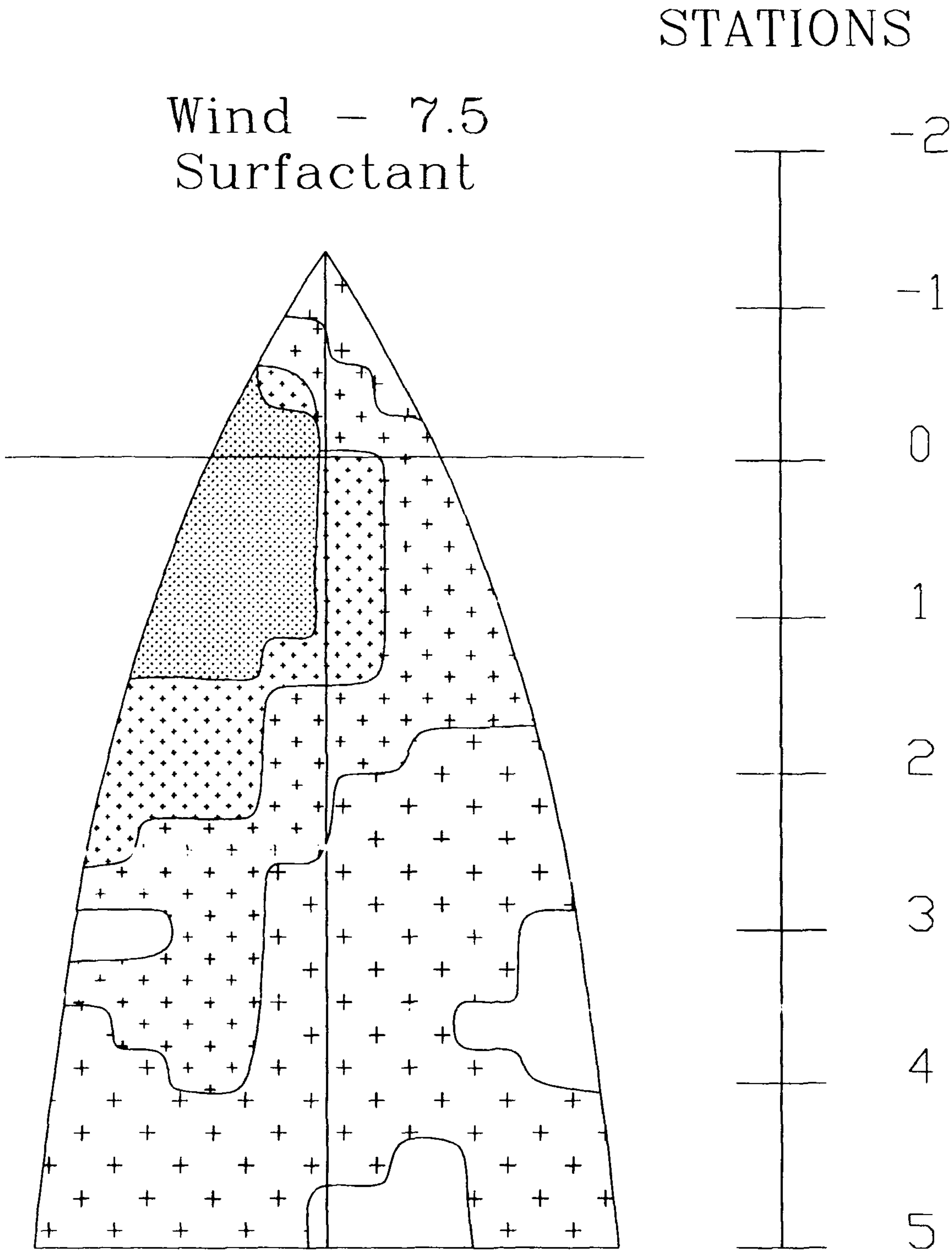
Wind - 0
Surfactant



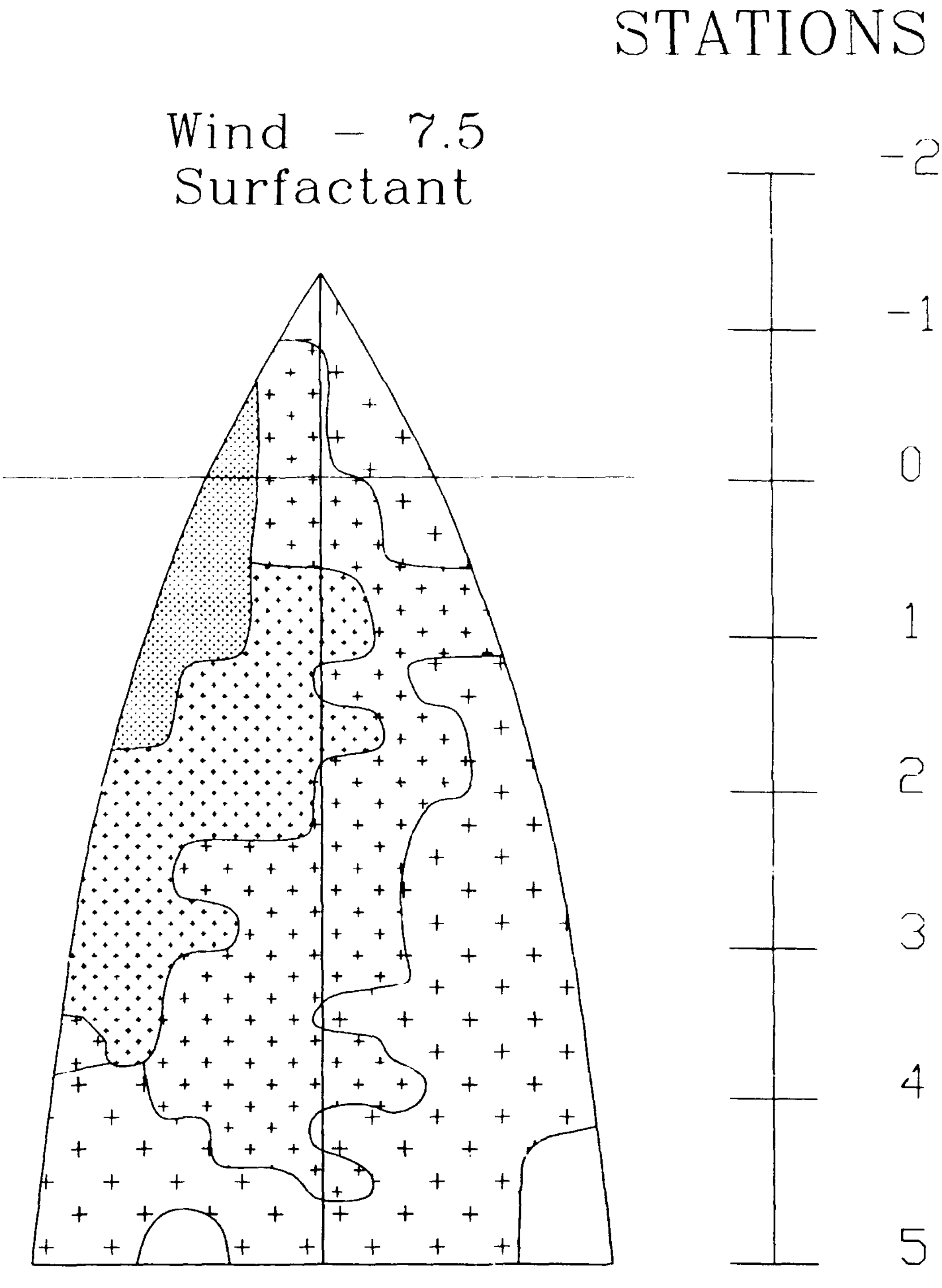

35 DEGREE BOW
KNUCKLE



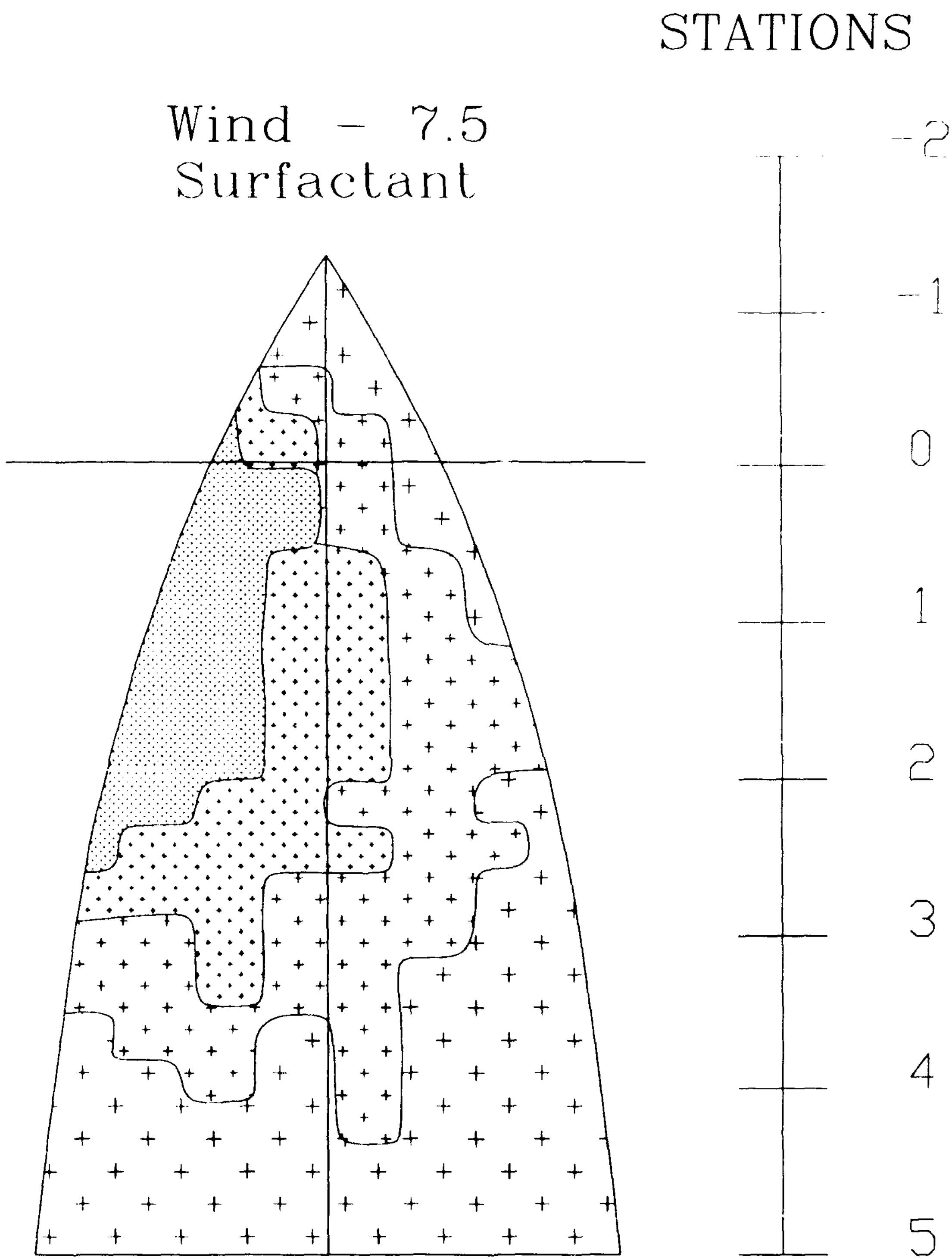

35 DEGREE BOW
KNUCKLE



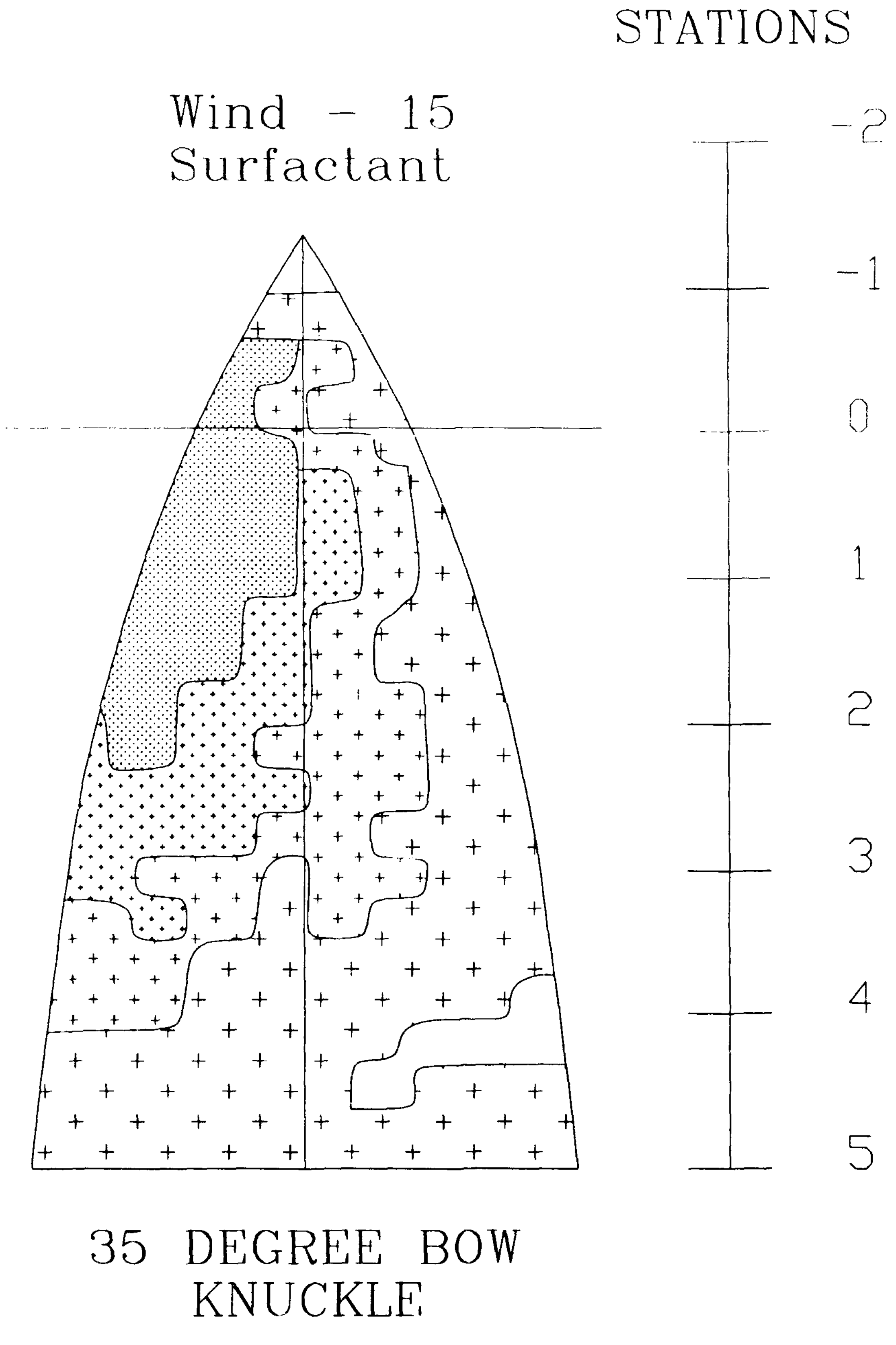

35 DEGREE BOW
KNUCKLE



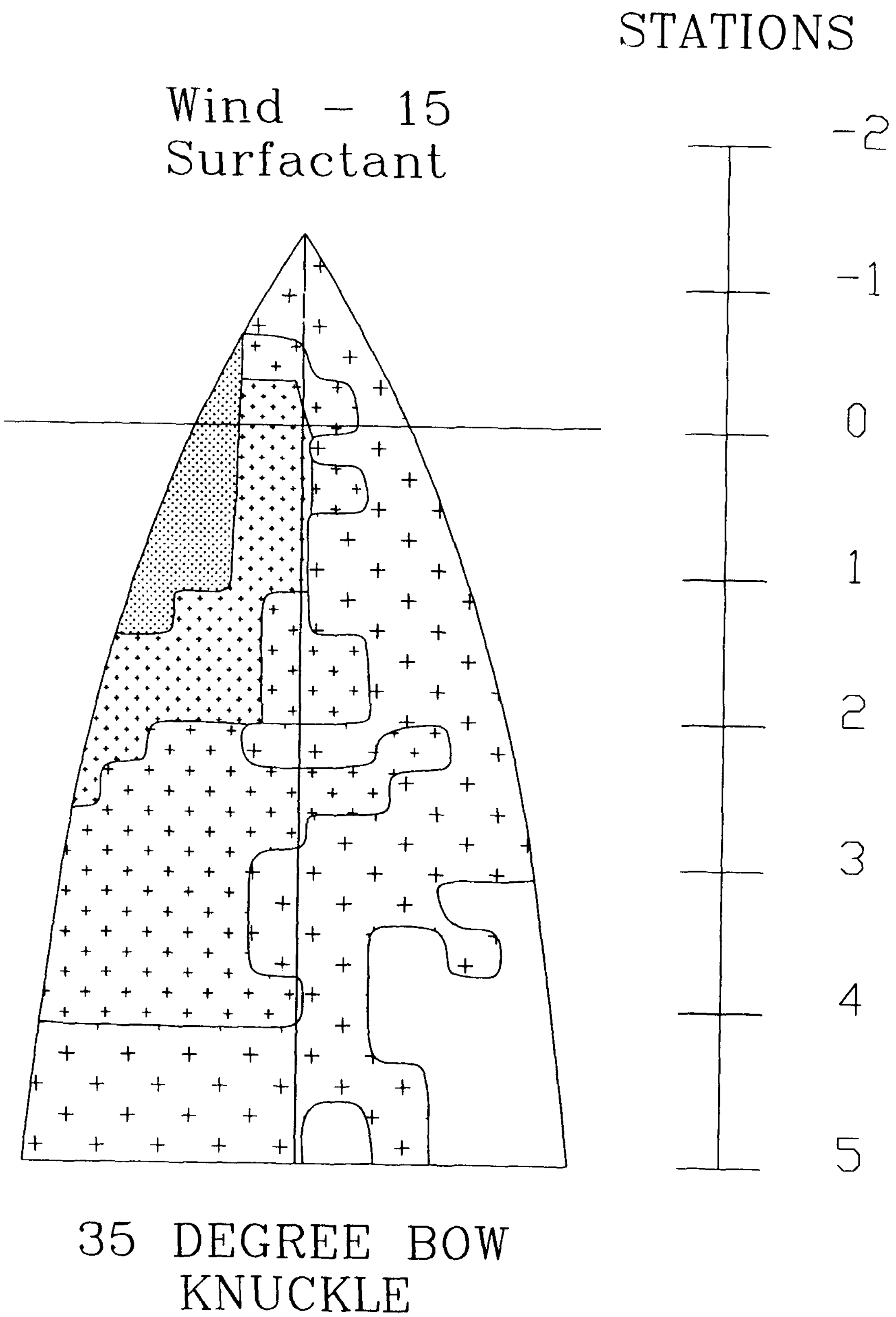

35 DEGREE BOW
KNUCKLE




35 DEGREE BOW KNUCKLE



STATIONS
Wind - 15
Surfactant
-2
-1
0
1
2
3
4
5
35 DEGREE BOW
KNUCKLE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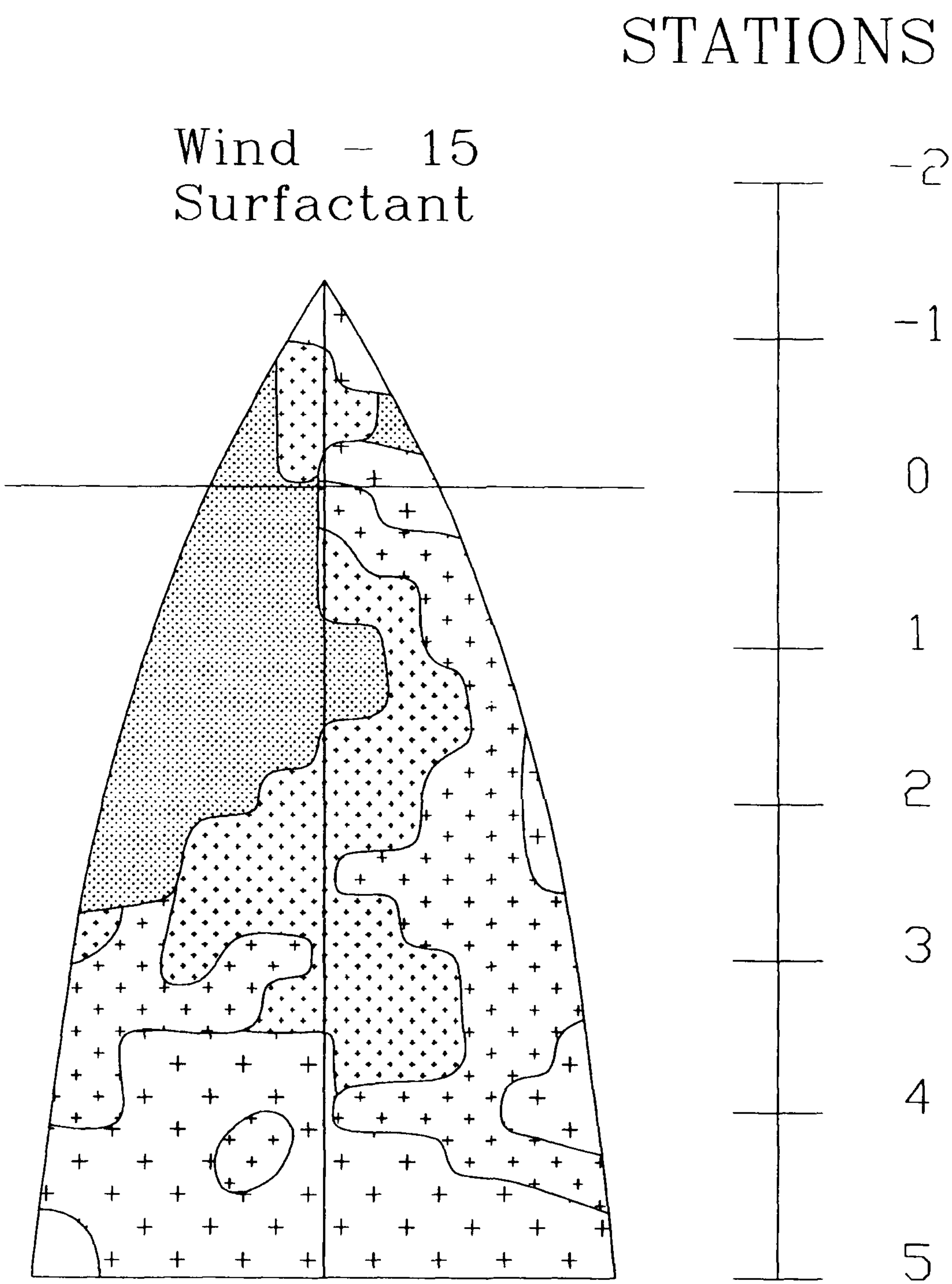


35 DEGREE BOW KNUCKLE