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SPACE SHUTTLE ENVIRONMENTAL EFFECTS: The First Five Flights

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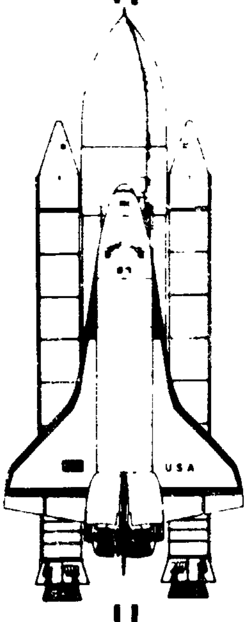

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December 14-16, 1982

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SPACE SHUTTLE ENVIRONMENTAL EFFECTS: THE FIRST FIVE FLIGHTS

A joint NASA-U.S. Air Force review held at the John F. Kennedy Space Center, Florida, December 14-16, 1982.

Andrew Potter, Editor

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16. Abstract

Environmental effects associated with the first five Space Shuttle flights were monitored by the National Aeronautics and Space Administration (NASA) and the U.S. Air Force (USAF). Results and interpretations from this effort were reported at the December 1982 joint NASA-USAF conference. The conference proceedings are presented in this document.

Most of the monitoring activity was focused on the launch cloud, emphasizing surface effects on the biota and air quality, model prediction of surface concentrations of HCl gas and Al_2O_3 dust, and airborne measurements of cloud composition. In general, assessments and predictions made in the April 1978 Final Environmental Impact Statement for the Space Shuttle Program were verified.

Fallout of acidic mist and dust within 3 mi to 5 mi of the launch pad was the only unexpected effect of the launch. Atomization of deluge water in the Shuttle exhaust is considered to be the most probable cause of this effect.

Sonic booms were monitored for several landings at Edwards Air Force Base, California; results agreed well with model predictions.

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PREFACE

The environmental impact of the Space Shuttle Program was addressed in the Final Environmental Impact Statement for the Space Shuttle Program published in 1978 (NASA TM-82278, Washington, D.C., April 1978).

In order to verify the 1978 assessments and to identify any unexpected results, environmental effects of the first five Space Shuttle flights were carefully monitored by National Aeronautics and Space Administration (NASA) and U.S. Air Force (USAF) experiment teams. In December 1982, a joint NASA-USAF conference was held for the purpose of collecting and documenting observations and interpretations of the environmental effects observed by NASA and the USAF during the first five Space Shuttle launches.

Major focus of the monitoring effort was on the exhaust clouds produced by the Space Shuttle launches. Sonic booms produced by the re-entry and landing of the Orbiter were also monitored.

The December 1982 conference proceedings are documented in this report. Several papers from other meetings are included in order to present a report as complete as possible and to provide a single reference document for the results of STS-1 through STS-5 monitoring activities.

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CONTENTS

MODELING OF THE EXHAUST CLOUD

SONIC BOOM

LONG-TERM MONITORING PLANS

ACRONYMS

AFGL	Air Force Geophysics Laboratory
BMP	Bi.'ogical monitoring plan
CCAFS	Cape Canaveral Air Force Station
CCN	Cloud condensation nuclei
CIFAFB	Central Instrumentation Facility Antenna Flight Building
DF	Direction finder
DIFFUS	A Lagrangian numerical model acquired by Western Space and Missile Center Safety Division
DRI	Data rate indicator
EIS	Environment Impact Statement
FSS	Fixed service structure
FWS	Fish and Wildlife Service
GEOMET	Earth/meteorological
HCl	Hydrogen chloride
HETAF	Heated Exhaust Toxic Area Forecast
IN	Ice nuclei
INS	Inertial Navigation System
JHW	J. H. Wiggins Company
KSC	John F. Kennedy Space Center
LC	Launch complex
LCC	Launch Control Center
LVE	Launch vehicle effluent
MLP	Mobile launch platform
MMDA	Martin-Marietta Denver Aerospace
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration

ACRONYMS (Concluded)

NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
OEHL	Occupational Environmental Health Laboratory
PMS	Particulate Monitoring Station
PPI	Pulse position indicator
PST	Pacific standard time
OCM	Quartz crystal microbalance
REED	Rocket Exhaust Effluent Diffusion
REEDM	Rocket Engine Exhaust Diffusion Model
RHI	Right hand indicator
SLC	Space Launch Complex (at VAFB)
SPL	Sound pressure level
SRB	Solid-rocket booster
SSME	Space Shuttle main engine
STS	Space Transportation System
TAS	True airspeed
TLL	Toxic limit line
TLV	Threshold limit value
TWA	Time-weighted average
USAF	U.S. Air Force
UCS	Universal camera site
VAB	Vehicle Assembly Building
VAFB	Vandenberg Air Force Base
WSMC/SE	Western Space and Missile Center/Safety Division
WTR	Western Test Range

ENVIRONMENTAL EFFECTS OF THE SHUTTLE LAUNCH CLOUD

- ENVIRONMENTAL EFFECTS OF STS-1 THROUGH STS-4 LAUNCHES: COMPREHENSIVE REPORT
  Knott et al.

- A SUMMARY OF GEOMET HCl DATA FROM STS-1 THROUGH STS-5
  Reed

- STS-5 EXHAUST PRODUCT GROUND DEPOSITION
  Swoboda

- CHEMICAL ANALYSIS OF ATMOSPHERIC GAS SAMPLES TAKEN AT THE STS-5 LAUNCH SITE
  Potter and Rippstein

- NEAR-FIELD EFFLUENT FALLOUT STUDY FOR STS-5
  Allen

- STS-5 FISH KILL, KENNEDY SPACE CENTER, FLORIDA
  Milligan

- EFFECTS OF ACIDIC DEPOSITION ON ECONOMIC PLANTS IN THE VANDENBERG AREA
  Granett

ENVIRONMENTAL EFFECTS OF STS-1 THROUGH STS-4 LAUNCHES: COMPREHENSIVE REPORT

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NASA-John F. Kennedy Space Center, Florida

and

John Puleo
Bionetics Corporation

1. INTRODUCTION

This report is a summary of the significant environmental effects measured and/or observed as part of the John F. Kennedy Space Center (KSC) Space Shuttle environmental monitoring program during the first four launches of the Space Transportation Systems (STS) [STS-1 through STS-4]. This report is restricted to those areas in which KSC personnel and contractors developed and implemented the tasks. KSC involvement included the following seven major areas of monitoring:

1. Launch cloud characteristics
2. Ground-level gaseous concentrations
3. Effects on water, sediment, and soils
4. Particulates and acid deposition
5. Acoustic noise effects
6. Biological effects
7. Personnel experiences

More detailed information on all environmental monitoring which was performed by KSC and contractor support personnel is available in reports on results from each launch.

2. RESULTS

2.1 LAUNCH CLOUD CHARACTERISTICS

Each launch cloud that developed as a result of the ignition of the three Space Shuttle main engines (SSME's) and two solid-rocket boosters (SRB's) was composed of three distinct cloud formations. When ignited, the SSME's formed a very distinct, bright-white cloud that appeared from the southward-directed flame trench at Launch Complex (LC)-39A. This portion of the exhaust cloud rose quickly and rapidly dissipated.

Approximately 9 sec following the ignition of the SSME's, the SRB's were ignited with a subsequent exhaust cloud exploding out of the northward-directed flame trench. For the first four launches, this portion of the exhaust cloud covered a distance equal to or slightly less than 280 m in width and developed over the lagoon which is located 425 m north of the Fixed Service Structure (FSS). Once over the lagoon, this portion of the exhaust cloud soon rose as a result in a decrease in horizontal velocity. The color of a SRB cloud was distinctly different from the one produced by the SSME's. The exhaust cloud usually moves away from LC-39A by T + 2 min or sooner, as observed during STS-2 when high surface winds were present at the time of launch.

Finally, the third cloud component developed as the vehicle began to ascend (T-0) and is referred to as the column cloud. This portion of the exhaust cloud appears tan in color; the lower portion of which quickly mixes with the initial portion formed by the SRB's.

Maximum cloud volume of 70 x 10^6 m^3 at T + 2 to 2.5 min was determined from observations of photographs for STS-3 and STS-4. [According to Dr. Jeff Anderson of the George C. Marshall Space Flight Center (MSFC), this calculation is grossly underestimated, and cloud volume is of the magnitude of 70 x 10^9 m^3.] Wind conditions dictated whether the launch cloud remained as a single-formed cloud or split into more than one cloud as was observed for STS-1. Regardless, cloud stabilization occurred at an inversion or a theoretical level of approximately 1800 m, whichever was lower. The direction of the launch cloud migration from LC-39A was directly correlated to direction of prevailing winds at the height of cloud stabilization.

2.2 GROUND-LEVEL GASEOUS MEASUREMENTS

Based on data recorded by dosimeters and by geomets, hydrogen chloride (HCl) gas is present at the pad following areas north of the flame trench and situated in the plume zone. HCl gas has been measured at sites in these areas up to several hours postlaunch. This was best documented in the STS-5 findings. These data are not discussed within this section but are addressed in sections written by Major D. Reed of the United States Air Force (USAF) and Lt. Col. D. Naugle, USAF Occupational Environmental Health Laboratory (OEHL). No detectable HCl gas was measured at any far-field sites by KSC environmental monitoring teams for the first four STS launches.

From the onset of the STS environmental monitoring program, dosimetry was employed as a means of sampling gaseous HCl; from the conception, there were numerous problems, questions, and expressions of doubt concerning this methodology. A primary problem associated with the utilization of dosimeters involved the long prepa atory sequence for each tube. There were also problems with tube deployment. Tubes were extremely fragile and easily broken. Dosimeter tubes were easily contaminated if not handled with care and were very susceptible to moisture, a problem that is unavoidable in the highly humid environment at KSC. The constant salt spray from the adjacent Atlantic Ocean has also voided much data. Finally, in many instances, there were problems associated with proper paper activation-deactivation and/or pump performance hindering data collection. Regardless of the number of dosimeters deployed for any launch, there was, generally, a 33 percent failure rate due to one or more of the above problems. Based on the tremendous amount of effort expended for this method and the very limited amount of valid data obtained, KSC decided, after STS-4, not to use dosimeters in future efforts to gather information on HCl concentrations at determined sites.

2.3 WATER, SEDIMENT, AND SOIL CHEMISTRY

2.3.1 HOLDING PONDS

The discharge of deluge and firex water (during the launch of each Space Shuttle) resulted in the collection of water in two holding ponds, located northeast and northwest of the pad flame trench. Unkown volumes of water have splashed out and onto the field directly north of the flame trench or were vaporized into the launch cloud. A problem that has yet to be resolved involves the exact volume of water that ends up in the various locations. This information would be an asset in the formulation of models to describe cloud composition immediately after ignition.

The water retained by the two ponds has undergone numerous chemical analyses. Triplicate water samples from each pond were collected as soon after launch as safety permitted, a sampling problem that decreased with each launch. Each pond was again sampled between 8 and 11 days after launch. Nalgene bottles, either 500 ml or 1000 ml, were used in this sampling operation. Field measurements were conducted for water temperature, conductivity, pH, and water depth. With the exception of water temperature and depth, those parameters measured in the field were measured again in the laboratory as were concentrations (mg/l) of ammonia, total Kjeldahl nitrogen, nitrite, chlorides, phosphate, aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), silver (Ag),zinc (Zn). Table 2-1 shows the water chemistry concentrations in the lagoon holding pond.

The acidity, volume, and conductivity of the water in the two ponds have varied after each launch. Several hours after launch, average pH values ranged between 1.2 and 2.0. These values increased slightly to 2.5 to 3.5 within 2 weeks. Based on the analytical results for each pond following launch and the volume of water in each pond, the amounts of all measurable parameters were calculated. Analytical values for selected parameters of concern for the northeast holding pond, representative of both ponds, indicated that levels of chlorides, aluminum, iron, and zinc were present in substantial quantities (table 2-2). This calculation is important because this water was later pumped from the ponds onto the field and, therefore, was subjected to leaching and could pose a problem to the ground water supply.

2.3.2 GROUND WATER

Triplicate ground water samples taken on September 1, 1981; October 29, 1981; March 18, 1982; and May 22, 1982, from three wells at LC-39A were used to evaluate the effects of STS launches on the ground water at the pad (tables 2-3 and 2-4). Based on t values, comparing chloride-mean concentrations from each period, mean values for October 29, 1981, were proven to be significantly greater than that on September 1, 1981 (tables 2-4 and 2-5). Mean values of iron for June 22, 1982, were significantly higher than that for any of the three previous periods (table 2-6). According to the Florida Rules of the Department of Environmental Regulations, Chapter 17-3, all values of the 19 measurable parameters for any given period were within acceptable limits.

2.3.3 LAGOONAL WATER

Lagoonal water samples were collected for each launch from six sites. These sites included two control sites and four experimental sites. Triplicate 500 ml water samples were collected at each site and analyzed for pH, conductivity, chlorides, nutrients, and selected metals. Water temperature, conductivity, and salinity measurements were measured in the field. Samples were obtained prior to each launch at L - 3 days and after each launch between T + 7 days and T + 15 days.

Based on the data obtained as a result of four launches, it appears that the variation in many parameters at control sites exceeds the variation in the same parameters at launch-affected sites. As a result, we cannot accurately assess any impact to the water quality due to the launches of the Space Shuttle at this time. Theoretically, the area that one would predict to be the most highly impacted by the launches, station 2, failed to reveal any trends in any of the measured parameters (table 2-7).

2.3.4 SEDIMENTS

Triplicate sediment samples were collected from the same six sites as were surface water samples. Samples, however, were not collected for STS-1, prelaunch or postlaunch. A polyvinyl chloride coring device, 2.5 cm in diameter, was pushed into the sediment to a depth of approximately 15 cm. Core samples were placed into separately labeled zip-lock bags and placed on ice for transport back to the laboratory. Simple trends in any of the measurable parameters are again difficult to find (table 2-8). However, in test for significant differences between the means of STS-2 prelaunch versus STS-4 postlaunch, a few anomalies are apparent (table 2-9). However, the degree of variation in several of the parameters at the two control sites exceeds the variation in the same parameters at the experiment sites. An accurate assessment of any impact to the water quality due to the launches of the Space Shuttle is not possible at this time.

2.3.5 SOILS

Replicate surface soil samples taken at the pad during STS-1 were analyzed for several parameters. Subsequently, STS-2 through STS-4 replicate soil samples from the pad were analyzed for different parameters, except for Al and pH. Since different sites and different parameters were measured, STS-1 data cannot be compared to that of the other three launches. Assessment of trends is, therefore, restricted to launches of STS-2, STS-3, and STS-4 (table 2-10). Of the ten parameters analyzed, Al, Cd, Cr, and Mn showed a significant increase (table 2-11). Iron revealed a significant decrease.

The character of the pad soil is apparently changing as a result of launch operations. The long-term impact of such is not readily apparent and deserves further study.

2.4 PARTICULATES AND DEPOSITION MEASUREMENTS

Acidic deposition was detected on pH paper at all four STS launches. Twenty-nine sites were instrumented for

STS-1, fifty-one sites for STS-2 and STS-3, and forty-seven sites for STS-4. Papers were visually analyzed in the field at each site and pH values recorded when deposition occurred. Papers were also analyzed in the laboratory.

In addition to the pH paper, copper plates supplied by MSFC were used in STS-2 through STS-4 launch monitoring. Prior to deployment, plates were buffed, degreased with perchlorethylene, and sealed in airtight plastic bags. For STS-2, fifty-one plates, 27 cm x 30 cm with a stamped identification number, were deployed at sites with pH paper. Copper plates and pH paper which had recorded acidic deposition were photographed in the field. Subsequent laboratory analyses of copper plates were performed by MSFC. Fifty-one sites were equipped with plates during STS-3 and forty-seven sites during STS-4. These sites were synonymous to sites instrumented with pH paper.

Pad deposition for the first four launches was fairly consistent from launch to launch. Those areas which received the greatest deposition were: (1) generally close to the apron of the pad, (2) positioned in the path of the launch cloud migration or (3) positioned north of the flame trench. Vapors having a pH less than 1.0 were common at LC-39A, and acidic deposition, both on the pad and downfield, exhibited a pH of at least 1.0. Aluminum oxide (Al_2O_3) was common at most pad sites but was minimal at far-field sites. Other primary pad particulates were iron and zinc. Most deposition appeared to take place within a 15-min period with deposition characteristically being discontinuous under the cloud track.

For the first four STS launches, much of the deposition occurred over water (Atlantic Ocean and Banana River). During STS-1, deposition was observed from LC-39A northwest and extended as far north as the Universal Camera Site (UCS)-9. At this point, the cloud drifted northerly and out to sea. Deposition failed to occur more than 1.5 km west of the primary coastal dune line. The estimated boundary for STS-1 deposition is shown in figure 2-1. For STS-2, heaviest deposition to occur on land was located approximately 100 m southeast of the pad perimeter and at the Titan Industrial Complex, located 8.5 km south-southeast of LC-39A. Much of the deposition was thought to occur over isolated land spits, as well as the waters and spoil islands of the Banana River. The boundary for STS-2 acidic deposition is shown in figure 2-2. Prior to the launch of STS-3, winds were from the west. As a result, the exhaust cloud drifted almost directly east of the pad, thus, influencing very little land area with deposition. Figure 2-3 illustrates the percentage of deposition on native flora near the pad for STS-3. Figure 2-4 depicts the total area affected by STS-3 deposition. The STS-4 launch cloud drift was very similar to that of STS-3. The STS-4 cloud drifted in a more northeasterly direction, with the heaviest deposition on land occurring at a distance of 0.7 km northeast of the launch complex. Deposition was not recorded north of a point east and parallel to LC-39B on Beach Road. The total area affected by STS-4 deposition is shown in figure 2-5.

Generally, acidic deposition can be expected to occur at each launch. The deposition pattern and direction will be highly dependent on ambient meteorological conditions at the time of launch.

2.5 ACOUSTIC NOISE MEASUREMENTS

For STS-1 activities, environmental noise was recorded at 15 sites using 15 metrosonic decibels (dB) and 652 devices. A GR-1982 Precision Sound Level meter was used at the VAB roof. The metrosonic devices were placed 4.8 km to 22.5 km from LC-39A. Four samples per second were taken and integrated over 1 min.

Most of the metrosonic instrumentation was activated 6 hours prior to launch and possessed the capability of storing data up to 8 hours. All instruments were picked up and deactivated; instruments and data were returned to the laboratory following launch. Six sites (P4, P5, P8, VAB roof, Eagle's nest, and the Glass Bank in Cocoa Beach) were equipped to monitor far-field acoustics. Three of these sites, P4, P8, and the VAB roof, were also equipped to monitor environmental noise. Twelve additional environmental sites were instrumented. Five sites were monitored by Fish and Wildlife Service (FWS) personnel to assess effects on wildlife.

The STS-2 far-field acoustic data (except VAB roof) were recorded using type 1551-C sound-level meters with a flat frequency response of 20 Hz to 20 Hz; 8 Hz attentuated approximately 9 dB, 4 Hz attenuated approximately 14 dB, and 2 Hz attenuated approximately 19 dB. Before and after launch, background levels were obtained from six far-field sites. Unweighted peak noise levels were recorded from the Central Instrumentation Facility Antenna Flight Building (CIFAFB) roof, Tico Airport, Wildlife Refuge, Glass Bank in Cocoa Beach, Titan Industrial Complex, and the VAB roof. As a result of a malfunction to a tape recorder positioned on the VAB roof, data were not available from this site past 19.5 sec.

STS-3 noise measurements were conducted by R. W. Young (Consultant for Acoustics), using an Environmental Noise Analyzer No. 387059 set for a weighted sound level in the range of 55-145 dB. A GR 1971-9601 microphone No. 44422 was positioned in an 18 cm diameter foam windball, horizontally supported 3.6 m above the ground on an aluminum mast located near the VAB Turn Basin. Measurements were printed automatically by the EFL-162 SEL. The same measurements previously outlined for STS-2 were made at the VAB roof, CIFAFB roof, Wildlife Laboratory, Tico Airport, Glass Bank, and the Titan Industrial Complex. Measurements as outlined for STS-2 were conducted for STS-4 from the VAB roof and the CIFAFB roof.

The effects of STS launch noise levels on humans and wildlife were intensively monitored for STS-1. Findings from this monitoring and subsequent data from STS noise monitoring indicate the following: based on the Department of Labor standards for maximum exposure (90 dBA as the limit for 8 hours of exposure per day), the noise levels at all sites for all four launches were within the limits due to the very short exposure times. An exposure of 15 min or less is permissible for 115 dBA slow response. Figure 2-6 illustrates the mean sound pressure levels (SPl's) at a varying distance from LC-39A for STS-1 through STS-4. Instruments at the VAB consistently recorded the highest SPL, however, 115 dBA was never reached.

2.6 BIOTA

2.6.1 VEGETATION

Two greenhouse-reared indicator plant species were used to assess the effects of STS-1 exhaust effluents on native vegetation. *Hydrocotyle umbellata* (pennywort) and *Raphanus sativus* ('commet' radish) were cultivated approximately 5 weeks prior to STS-1. In addition, some native vegetation was tagged at selected sites including such species as *Baccharis halmifolia* (groundsel), *Borrichia frutescens* (sea daisy), *Iva frutescens* (marsh elder), *Myrica cerifera* (wax myrtle), and *Salix caroliniana* (swamp willow).

During STS-1 activities, greenhouse-reared plants were positioned at

30 sites. Natural vegetation was tagged at 34 sites. Following STS-1 launch, samples of impacted *M. cerifera* collected from an area north of the pad and samples of the same species collected from an area southwest of LC-39A were obtained. Twenty grams of each sample were washed with 200 ml of deionized water, filtered, and analyzed.

Indicator plant species, both greenhouse-reared and native, were utilized in the assessment of the STS-2 launch. Only native vegetation was used in assessing launch impacts for STS-3 and STS-4. Photographs of the first four launches were taken of selected areas for both prelaunch and postlaunch in an effort to help document and assess STS impact.

The impact of Space Shuttle launches on the flora in the vicinity of LC-39A because of the launch exhaust plume has been clearly evident in an area north of the pad perimeter fence (fig. 2-7). The amount of severely impacted area ranged from 5.5 ha following the launch of STS-3 to 9.1 ha following the launch of STS-4. For the first four launches, the mean number of hectares impacted by the plumes was 7.2. Those major plant species continuously subjected to this impact included the following: *Avicennia germinans* (black mangrove), primarily concentrated on the northern shore of the lagoon and along the south side of the dike road; *M. cerifera*, found throughout the impact zone; *B. frutescens*, very common along the east and west banks of the lagoon; *Opuntia compressa* (prickly pear), common throughout the zone; *B. halmifolia*, very common throughout; and *Sabal palmetto* (cabbage palm), present in just a few locations. A survey of this plume zone, prior to STS-4, showed little plant community composition change. However, certain individual plants which had been severly impacted by the exhaust cloud after each launch have either died or exhibit stunted growth. Based on a survey of this area on November 9, 1982, and use of 1979 infrared aerial imagery, a change in plant composition, occurring along the western bank, had been documented. *B. frutescens* which was the dominant plant species on the bank is stunted, clearly a result of the launch plumes, and has been displaced by *Phytolacca americana* (pokeweed) and *Rivina humilis* (rouge plant). Natural vegetation in the immediate launch impact zone has been mostly replaced by ruderal vegetation.

The effect of deposition on plant communities downrange from the launch pad is not readily apparent. Deposition tends to be very spotty rather than a continuous (fig. 2-8) gradient from the pad. Acute effects appear as spotting, observed on many native species downrange; however, the degree of damage appears minimal and short term. Chronic effects may or may not be a problem.

2.6.2 FISH

A fish-kill was observed in the lagoon north of LC-39A immediately after STS-3. Species encountered were *Gambusia affinis* (mosquito fish), *Poecilia latipinna* (sailfin molly), *Mugil* spp. (mullet), *Floridichthys carpio* (gold-spotted killifish), *Anchoa mitchilli* (bay anchovy), and *Fundulus grandis* (gulf killifish). Approximately 400 individuals were observed dead. An experiment was implemented during STS-4 to determine if fish-kills were launch-related. Four (14.6 l) buckets were deployed at the pad perimeter fence and in direct line with the flame trench the evening prior to STS-4 launch. Two of the buckets contained fish collected from the Molly Pond (a control site), and two possessed fish collected from the lagoonal complex north of LC-39A. Two buckets (one control and one experimental) were emplaced without a lid thereby exposing the water to the ambient air at launch. The other two buckets were covered. The pH was recorded in each bucket following launch. Notes were made of each container. All specimens were preserved in 10 percent formalin solution for necropsy and sent to Dr. R. M. Overstreet, the Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

The control tissues of two species (Gambusia affinis and Poecilia latipinna) did not exhibit damage attributable to toxicant exposure. Four of the exposed specimens had apparently experienced severe gill damage. In exposed specimens exhibiting severe gill damage, the pericardial cavity was filled with fluid. In summary, the fish had been exposed to a drastic environmental alteration possibly due to pH change or metal intoxication. A more extensive experimental design was proposed for STS-5 to try and pinpoint the cause of fish mortality.

2.6.3 WILDLIFE

Based on the environmental noise data obtained for STS-1 through STS-4, one can expect most wildlife located within 10 km to 15 km of LC-39A to exhibit a startle response to STS launches at the time when peak noise levels occur. Normal routines should be resumed within a few minutes after peak noise levels have subsided. It is too early to determine or accurately predict what the cumulative effect will be on wildlife, once the Space Shuttle launches become more frequent.

2.6.4 BENTHIC

Benthic samples have been collected at four sites in the Space Shuttle monitoring program. One year of baseline data was taken prior to any launches. Beginning with the second STS launch, four stations were sampled, station 2, 5, 6, and 10. Only station 2 was sorted, identified, and enumerated. Samples were taken prelaunch (L - 3 days) and postlaunch between T + 7 days and T + 15 days. Samples were collected via an Ekman dredge (15.24 x 15.24 x 15.24 cm). Triplicate samples were collected from each station and the volume of each recorded. Samples were independently sieved in the field using a 500µm bronze mesh sieve. Samples were then funneled into a labeled 500 ml nalgene jar and fixed with a 10 percent solution of formalin. Samples were transferred to 70 percent isopropyl alcohol within 72 hours.

The postlaunch number of different species or richness of the benthic community at this station, the station most directly affected by the exhaust cloud, is consistent (table 2-12) with the prelaunch data. The immediate (few days) prelaunch and postlaunch similarity is relatively high (e.g., 03/19/82 and 03/31/82), indicating that the acute effects of the launch cloud are minimal. The ecological significance of the change in species composition is poorly understood at this time and needs further evaluation. There is apparently no change in species numbers as a result of launch effects. However, if the actual species are examined (tables 2-13 and 2-14), there is no apparent shift in the species composition over time even though the total number is fairly constant. This is readily apparent when comparing the similarity of station 2 samples at essentially the same time of year (e.g., 03/28/80, table 2-15).

2.7 PERSONNEL EXPERIENCES

Acidic deposition from the launch cloud has been attributed to minor skin irritations. With the exception of the deposition that occurred on forward observers at UCS-4 following the launch of STS-1 and at the Titan Industrial Complex following the launch of STS-2, there have been no major incidences where acidic deposition posed a problem to KSC and Cape Canaveral Air Force Station (CCAFS) workers or spectators. In the future, this problem can be avoided by wearing clothing which covers the majority of the exposed skin or positioning oneself far enough downrange of the launch cloud where deposition has a very small chance of occurring. The effects of the deposition on the skin are easily removed by simply rinsing with water. There are no lasting effects.

Acidic deposition may be more detrimental to sensitive metal surfaces or paints. Permanent effects to chrome on cars have been documented. Personnel whose cars are parked within the impact area are supplied with car covers.

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TABLE 2-1.- LAGOON HOLDING POND WATER CHEMISTRY CONCENTRATIONS FOR STS-1 THROUGH STS-4

Parameters	STS-1		STS-2		STS-3		STS-4	
	L + 8 hours	L + 8 days	L + 6 hours	L + 11 days	L + 4 hours	L + 11 days	L + 4 hours	L + 11 days
pH	1.6	3.4	1.6	2.3 ± 0.0	1.88 ± 0.01	2.6 ± 0.0	1.92 ± 0.07	3.20 ± 0.00
Conductivity	647 ± 31	-	17,300 ± 4,900	4,973 ± 225	8,600 ± 200	2,000 ± 0.0	5,500 ± 0.00	3,100 ± 0.00
NH_3	0.26 ± 0.01	0.63 ± 0.01	0.27 ± 0.08	0.43 ± 0.06	0.42 ± 0.23	0.52 ± 0.006	0.13 ± 0.01	0.29 ± 0.05
TKN	3.0 ± 0.07	3.4 ± 0.80	0.38 ± 0.10	2.1 ± 0.50	0.64 ± 0.14	1.7 ± 0.2	<0.5	0.80 ± 0.00
NO_2	0.04 ± 0.01	<0.02	-	-	<0.02	0.034 ± 0.008	<0.02	0.05 ± 0.00
NO_3	8.8 ± 1.0	11.5 ± 3.4	433 ± 176	106 ± 6	0.6 ± 0.0	0.4 ± 0.0	0.87 ± 0.06	0.37 ± 0.006
Bromides	-	-	-	-	-	-	-	-
Chlorides	2,200 ± 173	2,200 ± 100	4,200 ± 200	1,300 ± 0.0	1,500 ± 100	1,067 ± 58	1,004 ± 91	1,056 ± 117
Phosphate	11.0 ± 1.0	-	24.6 ± 0.80	3.6 ± 0.30	1.6 ± 0.15	0.7 ± 0.1	0.63 ± 0.15	<0.5
Al	23.9 ± 0.2	27.6 ± 0.6	39 ± 1.0	30 ± 2.0	20 ± 2.0	11 ± 1.0	5.9 ± 0.40	10.27 ± 0.16
Cd	0.13 ± 0.0	0.13 ± 0.01	0.11 ± 0.01	0.05 ± 0.0	0.07 ± 0.02	0.08 ± 0.01	0.03 ± 0.00	0.04 ± 0.01
Cr	0.2 ± 0.0	0.12 ± 0.01	0.59 ± 0.05	[a]0.03 ± 0.01	0.23 ± 0.0	0.18 ± 0.00	0.13 ± 0.01	0.11 ± 0.00
Cu	0.22 ± 0.03	0.23 ± 0.01	0.35 ± 0.02	0.20 ± 0.006	<0.05	0.10 ± 0.03	0.09 ± 0.00	0.10 ± 0.01
Fe	10 ± 0.0	9.95 ± 0.5	41 ± 0.0	24 ± 2.0	15 ± 0.6	14 ± 0.6	10.37 ± 1.42	12.53 ± 0.15
Pb	0.8 ± 0.1	0.63 ± 0.08	1.3 ± 0.1	0.70 ± 0.02	0.4 ± 0.1	0.48 ± 0.006	0.28 ± 0.02	0.29 ± 0.00
Mn	0.75 ± 0.0	0.741 ± 0.012	0.78 ± 0.02	0.49 ± 0.02	0.34 ± 0.02	0.26 ± 0.01	0.33 ± 0.01	0.48 ± 0.15
Ni	0.60 ± 0.1	0.12 ± 0.15	1.2 ± 0.06	0.41 ± 0.04	0.69 ± 0.05	0.17 ± 0.03	0.32 ± 0.01	0.28 ± 0.00
Ag	<0.05	0.55 ± 0.02	<0.05	<0.05	-	-	-	-
Zn	180 ± 2.0	161 ± 1.0	280 ± 10	113 ± 6.0	93 ± 3.0	86 ± 14	66 ± 3.46	55 ± 1.00

Symbol definition:

L = launch
TKN = Total Kjeldahl nitrogen

[a]One-half of < value, [t](mg/1).

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TABLE 2-2.- AMOUNT OF SELECTED PARAMETERS IN HOLDING POND WATERS FOR STS-1 THROUGH STS-4[a]

Parameter	Flight number and station name or number								Total	
	STS-1		STS-2		STS-3		STS-4			
	Lagoon Pond, kg	Gator Hole Pond, kg	Lagoon Pond, kg	Gator Hole Pond, kg	Lagoon Pond, kg	Gator Hole Pond, kg	Lagoon Pond, kg	Gater Hole Pond, kg	kg	(lb)
NH_3	0.33	0.32	0.15	0.17	0.32	0.26	0.24	0.08	1.87	(4.12)
TKN	2.37	1.30	0.52	0.43	0.80	0.60	0.59	0.43	7.04	(15.52)
NO_3	7.52	5.68	112.21	40.59	0.34	0.31	0.69	0.62	167.96	(370.35)
Chlorides	1,630.70	1,205.30	1,144.96	728.61	881.74	839.13	1,153.41	935.83	8,519.68	(18,785.89)
PO_4	8.15	5.07	5.87	3.48	0.79	1.45	0.49	0.73	26.03	(57.39)
Al	19.09	12.78	14.36	7.49	10.65	10.91	9.07	7.60	91.95	(202.74)
Cd	0.10	0.10	0.03	0.03	0.05	0.11	0.04	0.07	0.53	(1.16)
Cr	0.12	0.21	0.13	0.09	0.14	0.32	0.13	0.31	1.45	(3.19)
Cu	0.17	0.50	0.11	0.14	0.04	0.29	0.11	0.57	1.93	(4.25)
Fe	7.41	5.98	13.53	6.50	9.96	6.15	12.83	6.86	69.22	(152.63)
Pb	0.53	0.63	0.42	0.28	0.30	0.73	0.32	0.55	3.76	(8.29)
Mn	0.55	0.59	0.26	0.16	0.21	0.20	0.45	0.25	2.67	(5.88)
Ni	0.27	0.35	0.34	0.21	0.30	0.34	0.34	0.26	2.41	(5.31)
Zn	126.38	113.87	81.81	53.29	61.48	74.68	67.78	100.15	679.44	(1,498.16)
Liters of H_2O in pond										
	741,229 liters	634,366 liters	416,350 liters	416,350 liters	686,978 liters	559,423 liters	1,120,360 liters	927,325 liters	5,502,381 liters	(1,453,729 gal)

Symbol definition:

TKN = Total Kjeldahl nitrogen

[a]Based on mean concentrations of each parameter computed from two sample periods.

TABLE 2-3.- GROUND WATER ANALYTICAL RESULTS FROM THESE WELLS

Parameter (a)	Date, month/day/year											
	September 1, 1981			October 29, 1981			March 18, 1982			June 22, 1982		
pH	7.8	8.2	7.6	7.2	7.4	7.2	7.0	7.0	7.3	7.0	7.0	7.0
Conductivity	600	780	790	760	1,200	1,200	700	700	700	430	900	800
Chloride	10	25	35	240	150	120	45	40	170	12	220	37
[b]Nitrate	0.40	0.39	0.43	0.64	0.69	0.40	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
[b]Nitrite	0.02	0.02	0.02	<0.02	<0.02	<0.02	0.05	0.03	0.02	<0.02	<0.02	<0.02
[b]Ammonia	0.36	0.36	0.52	0.15	0.60	0.08	0.11	0.14	0.28	0.34	0.10	0.14
[b]TKN	0.90	1.0	0.90	0.33	0.40	0.11	0.60	0.60	0.90	<0.50	<0.50	<0.50
[c]Total phosphorus	<0.50	0.50	0.50	<0.50	<0.50	<0.50	0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Ag	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Al	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.10	<0.10	<0.10
Cd	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cu	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fe	<0.05	<0.12	<0.15	<0.34	<0.22	<0.12	<0.16	<0.17	<0.22	<1.1	<0.47	<0.90
Mn	<0.05	0.05	<0.05	0.08	0.07	0.08	0.11	0.11	0.06	<0.05	<0.05	<0.05
Ni	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.12	0.08	0.09	<0.05	<0.05	<0.05
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.005	<0.005	<0.005
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.02	<0.02	0.01	0.01	0.02
B	0.20	0.20	0.20	0.10	0.20	0.20	<0.10	<0.10	0.60	<0.10	<0.10	<0.10

Symbol definition:

TKN = Total Kjeldahl nitrogen

[a]mg/l except where indicated, and for pH and conductivity (μmhos).

[b]mg/l N

[c]mg/l PO_4

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TABLE 2-4.- MEAN AND STANDARD DEVIATIONS OF SELECTED GROUND WATER PARAMETERS

Parameter	Sample date, month/day/year			
	9/1/81	10/29/81	3/18/82	6/22/82
[a]Conductivity	723 ± 107	1,053 ± 254	700 ± 0	710 ± 248
[b]Fe	0.09 ± 0.06	0.22 ± 0.11	0.18 ± 0.03	0.82 ± 0.32
[b]Chloride	23 ± 13	170 ± 62	85 ± 74	90 ± 114

[a]µmhos

[b]mg/l

TABLE 2-5.- MATRIX OF t VALUES COMPARING THE MEAN CONCENTRATIONS (mg/l) OF CHLORIDES IN GROUND WATER SAMPLES (N = 3)

Sample date, month/day/year	Sample date, month/day/year		
	10/29/81	3/18/82	6/22/82
09/01/81	[a]3.98	1.42	1.52
10/29/81		0.24	0.11
03/18/82			0.05

[a]Significant at $\alpha = 0.10$.

TABLE 2-6.- MATRIX OF t VALUES COMPARING THE MEAN CONCENTRATIONS (mg/l) OF IRON GROUND WATER SAMPLES (N = 3)

Sample date, month/day/year	Sample date, month/day/year		
	10/29/81	03/18/82	06/22/82
09/01/81	1.73	2.02	[a]3.82
10/29/81		0.65	[a]3.03
03/18/82			[a]3.42

[a]Significant at $\alpha = 0.10$.

TABLE 2-7.- MEAN AND STANDARD DEVIATION OF WATER CHEMISTRY PARAMETERS FROM STATION NUMBER 2

Parameter	Prelaunch STS-1	Postlaunch STS-1	Prelaunch STS-2	Postlaunch STS-2	Prelaunch STS-3	Postlaunch STS-3	Prelaunch STS-4	Postlaunch STS-4
pH	8.1	8.0	8.0 ± 0	8.0 ± 0	8.8 ± 006	8.2 ± 0	8.4	8.0 ± 0.1
Conductivity	15,000 ± 1,000	-	29,000 ± 0	25,000 ± 0	16,567 ± 208	17,000 ± 0	17,000	22,000 ± 0
NH_3	0.02 ± 0.01	0.16 ± 0.09	0.17 ± 0.08	0.19 ± 0.04	<0.03	0.05 ± 0	<0.03	<0.03
TKN	1.1 ± 0.1	1.0 ± 0.7	2.5 ± 0.3	2.2 ± 0.36	2.3 ± 0.7	3.6 ± 0.3	[a]0.4 ± 0.26	<0.5
NO_2	0.02 ± 0.01	0.02 ± 0.01	-	-	0.070 ± 0.01	0.03 ± 0.006	<0.02	0.03 ± 0.01
NO_3	55 ± 5	69 ± 11	1,647 ± 315	490 ± 36	<0.1	0.2 ± 0	0.2 ± 0	0.4 ± 0.1
Cl	17,000 ± 2,000	12,000 ± 0	14,000 ± 1,732	13,000 ± 1,000	12,667 ± 1,528	12,667 ± 577	11,000 ± 0	10,333 ± 577
PO_4	0.3 ± 0.1	1 ± 1	0.7 ± 0.1	[a]1.3 ± 1.3	<0.5	<0.5	<0.5	<0.5
Al	<1.0	<1.0	<1.0	<1.0	2 ± 0	<1.0	<0.2	[a]0.3 ± 0.17
Cd	0.035 ± 0.004	0.035 ± 0.001	0.06 ± 0.006	0.03 ± 0.006	0.14 ± 0.06	0.01 ± 0	0.07 ± 0.01	0.08 ± 0
Cr	<0.05	<0.05	<0.05	<0.05	[a]0.04 ± 0.02	<0.05	<0.05	<0.05
Cu	0.04 ± 0	0.05	[a]0.03 ± 0.01	<0.05	0.06 ± 0.01	0.07 ± 0.02	0.05 ± 0.01	0.05 ± 0
Fe	0.19 ± 0.01	0.22 ± 0.02	1.2 ± 1.8	<0.05	0.4 ± 0	0.69 ± 0.07	0.44 ± 0.01	0.39 ± 0.01
Pb	<0.01	0.2 ± 0.1	0.32 ± 0.01	0.26 ± 0.01	0.2 ± 0	0.41 ± 0.02	0.31 ± 0.01	0.27 ± 0.02
Mn	<0.05	0.266 ± 0.417	[a]0.08 ± 0.08	[a]0.03 ± 0.01	0.10 ± 0.06	0.11 ± 0.006	0.06 ± 0.01	0.07 ± 0
Ni	0.17 ± 0.03	0.17 ± 0.1	0.31 ± 0.06	0.14 ± 0.02	0.42 ± 0	<0.05	<0.05	<0.05
Ag	<0.05	<0.05	[a]0.04 ± 0.03	<0.05	-	-	-	-
Zn	<0.01	<0.01	[a]0.02 ± 0.02	0.08 ± 0.006	0.06 ± 0	0.43 ± 0.02	0.05 ± 0.01	0.09 ± 0.01

Symbol definition:

TKN = Total Kjeldahl nitrogen

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TABLE 2-8.- MEAN AND STANDARD DEVIATIONS OF PRELAUNCH STS-2 VERSUS POSTLAUNCH STS-4 SEDIMENT ANALYSES

Parameter	Station name or number					
	Max Hoeck Creek	Banana Creek	2	5	6	10
pH	7.66 ± 0.61	[a]8.33 ± 0.05	7.66 ± 0.61	8.26 ± 0.05	[b]8.26 ± 0.05	8.3 ± 0.0
	7.36 ± 0.15	7.80 ± 0.1	7.73 ± 0.05	7.86 ± 0.25	7.66 ± 0.05	7.63 ± 0.05
Al	[b]2,200 ± 2,645.75	[b]2,266.66 ± 251.66	[b]756.66 ± 81.44	[b]2,600 ± 964.36	[b]353.33 ± 15.27	[b]213.11 ± 51.31
	33,666.66 ± 3,785.93	6,133.33 ± 1,006.64	1,500.0 ± 100.0	13,000 ± 1,732.05	576.66 ± 87.36	506.66 ± 40.41
Cd	[a]0.5 ± 0.0	[a]0.5 ± 0.0	[a]0.5 ± 0.0	[a]0.5 ± 0.0	[a]0.05 ± 0.0	[a]0.5 ± 0.0
	1.37 ± 0.06	0.67 ± 0.06	1.2 ± 0.44	2.77 ± 0.75	1.47 ± 0.06	[a]0.6 ± 0.51
Cr	47.0 ± 7.54	[b]11.33 ± 1.15	6.50 ± 0.86	[b]12.16 ± 3.75	2.5 ± 0.0	[a]4.0 ± 2.5
	63.33 ± 3.21	18.0 ± 2.0	7.33 ± 0.57	34.33 ± 2.88	4.0 ± 0.0	2.7 ± 0.5
Cu	6.96 ± 1.64	[a]2.5 ± 0.0	[a]2.5 ± 0.0	[a]2.5 ± 0.0	[a]2.5 ± 0.0	[a]1.5 ± 0.0
	0.23 ± 0.02	6.0 ± 1.73	3.0 ± 1.0	5.67 ± 0.58	2.33 ± 1.53	2.7 ± 0.6
Fe	19,000 ± 1,000	[b]2,700 ± 200.0	873.33 ± 111.4	3,933.33 ± 140.18	493.33 ± 75.05	386.66 ± 68.06
	20,766.66 ± 1,965.53	4,466.66 ± 642.91	1,133.33 ± 57.73	6,933.33 ± 5,054.04	603.33 ± 45.09	556.66 ± 104.08
Pb	[b]25.33 ± 8.50	[a]8.33 ± 2.88	[a]8.33 ± 2.89	12.66 ± 4.61	[a]6.33 ± 2.3	17.66 ± 0.57
	35.33 ± 1.15	12.0 ± 1.0	10.67 ± 0.58	20.66 ± 1.15	8.33 ± 5.77	9.66 ± 4.04
Mn	260.0 ± 10.0	[b]13.0 ± 1.0	[b]6.56 ± 1.18	[b]22.66 ± 7.23	[a]4.86 ± 4.45	3.66 ± 2.02
	206.0 ± 11.54	34.66 ± 2.30	30.00 ± 2.00	54.33 ± 4.50	10.0 ± 0.0	10.66 ± 2.51
Zn	33.33 ± 5.50	[a]0.5 ± 0.0	[a]1.90 ± 1.31	[b]3.70 ± 4.30	[a]0.5 ± 0.0	[a]0.5 ± 0.0
	42.66 ± 3.51	27.67 ± 33.2	97.33 ± 120.23	25.0 ± 5.29	4.0 ± 1.0	1.6 ± 0.0

[a]One-half value.

[b]Significantly different at $\alpha = 0.05$ (t-test).

TABLE 2-9.- COMPARISON OF PRELAUNCH STS-2 AND POSTLAUNCH STS-4 FOR SIGNIFICANT CHANGES IN SELECTED SEDIMENT PARAMETERS

Parameter	Station name or number					
	Max Hoeck Creek	Banana Creek	2	5	6	10
pH		-			-	
Al	+		+	+	+	+
Cd						
Cr		+	+			
Cu	-					
Fe		+				
Pb	+					
Mn	-	+	+	+		
Zn				+		

Symbol definition:

+ = significant increase
- = significant decrease

[a]Significant at $t_{0.05}$.

TABLE 2-10.- MEAN VALUES OF SELECTED SOIL PARAMETERS FROM THREE-SAMPLE SITES FOR STS-2, STS-3, AND STS-4

Parameter	STS-2 sites			STS-3 sites			STS-4 sites		
	1	2	3	1	2	3	1	2	3
pH	7.0 ± 0.7	7.6 ± 0.5	7.9 ± 0.7	6.4 ± 0.1	6.3 ± 0.2	6.3 ± 0.1	7.2 ± 0.3	7.4 ± 0.1	7.2 ± 0.5
Al	1,733 ± 666	1,200 ± 264	1,227 ± 361	797 ± 181	587 ± 248	663 ± 326	3,900 ± 1,562	2,233 ± 153	2,100 ± 100
Cd	<1.0	<1.0	0.9 ± 0.4	<1.0	<1.0	1.4 ± 0.3	1.4 ± 0.1	1.9 ± 0.2	1.5 ± 0.1
Cr	9.0 ± 1.0	7.4 ± 2.0	7.2 ± 0.7	6.0 ± 4.0	<5.0	6.0 ± 4.0	16.0 ± 3.5	17.3 ± 2.9	12.0 ± 3.0
Cu	5.0 ± 5.0	3.9 ± 2.4	9.6 ± 8.5	6.3 ± 3.0	<5.0	14.0 ± 5.0	5.0 ± 1.0	12.8 ± 5.8	6.3 ± 0.6
Fe	2,467 ± 208	2,467 ± 289	2,533 ± 378	1,833 ± 551	1,500 ± 173	2,233 ± 814	1,933 ± 580	1,833 ± 252	1,800 ± 100
Pb	19.0 ± 12.0	19.7 ± 5.5	33.0 ± 1.0	12.0 ± 3.0	27.0 ± 3.0	51.0 ± 10.0	20.0 ± 4.0	26.7 ± 3.0	44.0 ± 16.0
Mn	16.0 ± 0.5	22.0 ± 6.0	22.0 ± 6.0	34.0 ± 7.0	33.0 ± 7.0	41.0 ± 4.0	47.0 ± 2.0	39.0 ± 3.0	24.0 ± 3.0
Ni	18.0 ± 3.0	18.0 ± 14.0	22.0 ± 9.0	<5.0	5.0 ± 4.0	13.0 ± 6.0	22.0 ± 7.0	12.0 ± 2.0	11.0 ± 1.0
Ag	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	-	-	-
Zn	109.0 ± 64.0	121.0 ± 16.0	939.0 ± 805.0	154.0 ± 124.0	90.0 ± 66.0	240.0 ± 87.0	153.0 ± 35.0	71.0 ± 28.0	100.0 ± 35.0

TABLE 2-11.- COMPARISON OF STS-2 AND STS-4 SOIL PARAMETERS FOR SIGNIFICANT CHANGES (N = 9)

Parameter	STS-2, mean ± standard deviation	STS-4, mean ± standard deviation	t
pH	7.48 ± 0.66	7.24 ± 0.32	0.99
Al	1,386.66 ± 478.12	2544 ± 634.64	4.37
Cd	0.63 ± 0.26	1.60 ± 0.25	[a]7.82
Cr	8.05 ± 1.58	15.22 ± 3.59	[a]5.46
Cu	6.27 ± 5.66	8.00 ± 4.38	0.72
Fe	2,488.88 ± 261.93	1,855.55 ± 150.92	[a]6.28
Pb	24.00 ± 9.59	30.11 ± 13.55	1.10
Mn	20.22 ± 4.96	36.77 ± 10.10	[a]4.40
Ni	19.22 ± 8.57	15.00 ± 6.50	.23
Zn	389.66 ± 582.68	108.11 ± 46.01	1.44

[a]Significantly different at $\alpha = 0.05$, $t_{0.05(8)} = 2.31$.

TABLE 2-12.- NUMBERS OF BENTHIC SPECIES PRESENT AT STS MONITORING STATIONS

Date, month/day/year	Station number			
	2	5	6	10
12/06/79	19	24		
03/28/80	22	22	24	
04/04/80				35
07/07/80		26	22	
07/09/80	22			23
09/23/80		11	17	
09/24/80	19			36
12/11/80	18			
12/10/80		16	18	49
STS-1				
04/09/81	21			
04/20/81	22			
STS-2				
06/02/81	18			
11/01/81	21			
11/23/81	21			
STS-3				
03/19/82	19			
0[illegible]/31/82	22			
06/24/82	24			
07/07/82	23			

TABLE 2-13.- LIST OF SPECIES NAMES AND CODE NUMBERS OF ORGANISMS COLLECTED AT STATION NUMBER 2

Species name	Species code	Species name	Species code
Cnidaria Unid.	I-A	*Neanthes succinea*	VIII-44
Actiniaria Unid.	I-1	*Neanthes* sp.	VIII-45
Platyhelminthes Unid.	II-1	*Glycinde solitaria*	VIII-49
Nemertina Unid.	III-1	*Pectinaria gouldii*	VIII-55
Phoenis sp.	VI-1	Crustacea Unid.	X-2
Crepidula maculosa	VII-7a	Cylindroleberidae Unid.	X-3
Odostomia sp.	VII-16	Podocopida Unid.	X-7
Turbonilla protracta	VII-18	*Cyclaspis* sp.	X-8
Aceteocina canaliculata	VII-19	*Oxyurostylis smithi*	X-9
Amygdalum papyrium	VII-25	Tanaidacea Unid.	X-10
Mulinia lateralis	VII-29	*Apseudis* sp.	X-11
Parastarte triquetra	VII-40	*Leptochelia* sp.	X-14
Anomalocardia auberiana	VII-41	*Edotea montosa*	X-17
Lynosia hyalina floridana	VII-42	*Ampelisca* sp.	X-19
Haploscoloplos foliosus	VIII-2	*Gitanopsis tortugae*	X-20
Aricidea fragilis	VIII-4	*Grandiderella bonnieroides*	X-24(23)
Aricidea fauveli	VIII-4a	*Corophium* sp.	X-25
Streblospio benedicti	VIII-15	*Corophium lacustre*	X-25a
Spiochaetopterus oculatus costarum	VIII-16	*Gammarus mucronatus*	X-26
Capitella capitata	VIII-19	*Melita* sp.	X-26a
Eteone heteropoda	VIII-28	Mysidacea Unid.	X-27
Gyptis vittata	VIII-31	Apodida Unid.	X1-2

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TABLE 2-14.- SPECIES PRESENCE AT SAMPLE STATION NUMBER 2
FOR THE DURATION OF THE BETHNIC SAMPLING PROGRAM

Species code						STS-1		STS-2			STS-3		STS-4	
	12/06/79	03/28/80	07/09/80	09/24/80	12/11/80	04/09/81	04/20/81	06/02/81	11/01/81	11/23/81	03/19/82	03/31/82	06/24/82	07/07/82
VIII-2	x	x	x	x	x	x	x	x	x	x	x	x	x	x
VIII-28	x	x	x	x	x	x	x	x	x	x	x	x	x	x
VIII-31	x	x	x	x	x		x	x	x	x	x	x	x	x
VIII-55	x									x				
X-2	x	x	x	x	x	x	x	x						
X-3	x	x	x		x	x	x	x	x	x	x	x	x	x
X-7	x	x	x	x	x	x	x	x	x	x	x	x	x	x
X-8	x	x	x	x	x	x	x	x	x	x	x	x	x	x
X-9	x												x	
X-11	x	x	x	x	x	x	x	x	x	x	x	x	x	x
X-14	x	x	x	x	x	x	x	x		x	x	x	x	x
X-17	x													
X-19	x	x	x	x	x	x	x	x	x	x	x	x	x	x
X-24(23)	x	x	x	x	x	x	x	x	x	x	x	x	x	x
X-25	x													x
X-26	x	x	x		x	x	x	x				x	x	x
III-1		x				x	x		x	x		x	x	
VII-19		x	x	x	x	x	x	x	x	x		x	x	x
VII-40	x	x	x	x	x	x	x	x	x	x	x	x	x	x
VIII-4		x												
VIII-16		x									x			
VIII-44		x												x
X-10		x		x		x		x		x	x	x	x	x
X-20		x					x		x	x				
X-27		x	x	x		x	x	x	x	x	x	x	x	x
X1-2		x												
1-a			x	x		x								
VII-25			x											
VII-29			x		x	x	x		x				x	x
VII-42			x			x	x	x			x	x	x	
VIII-4a			x		x									
VIII-19			x	x	x	x	x		x	x	x	x	x	x
X-26a			x											
VII-18			x			x								
VIII-15				x					x	x	x	x	x	x
VI-1					x		x		x					
II-1							x							x
VII-7a								x						
VII-41								x				x	x	
I-1									x			x	x	x
VIII-49									x	x				
X-25a									x	x	x	x		
VII-16													x	x
VIII-45													x	

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TABLE 2-15.- MATRIX OF SIMILARITY COEFFICIENTS BETWEEN
SAMPLING PERIODS AT STATION NUMBER 2

[Coefficients based on species presence.]

Date, month/day/year						STS-1		STS-2			STS-3		STS-4	
	Date 12/06/79	03/28/80	07/09/80	09/24/80	12/11/80	04/09/81	04/20/81	06/02/81	11/01/81	11/23/81	03/19/82	03/31/82	06/24/82	07/07/82
12/06/79	100	46	44	43	55	42	63	52	32	37	48	41	39	44
03/28/80		100	50	50	54	64	63	64	48	54	50	57	53	61
07/09/80			100	67	71	76	67	62	47	47	52	55	68	52
09/24/80				100	59	65	44	64	57	65	67	63	58	60
12/11/80					100	63	74	61	50	50	50	54	56	58
04/09/81						100	72	67	50	56	56	65	67	57
04/20/81							100	64	61	59	54	63	64	61
06/02/81								100	39	48	54	63	59	50
11/01/81									100	75	56	77	63	57
11/23/81										100	70	72	61	57
03/19/82											100	74	62	58
03/31/82												100	84	67
06/24/82													100	74
07/07/82														100

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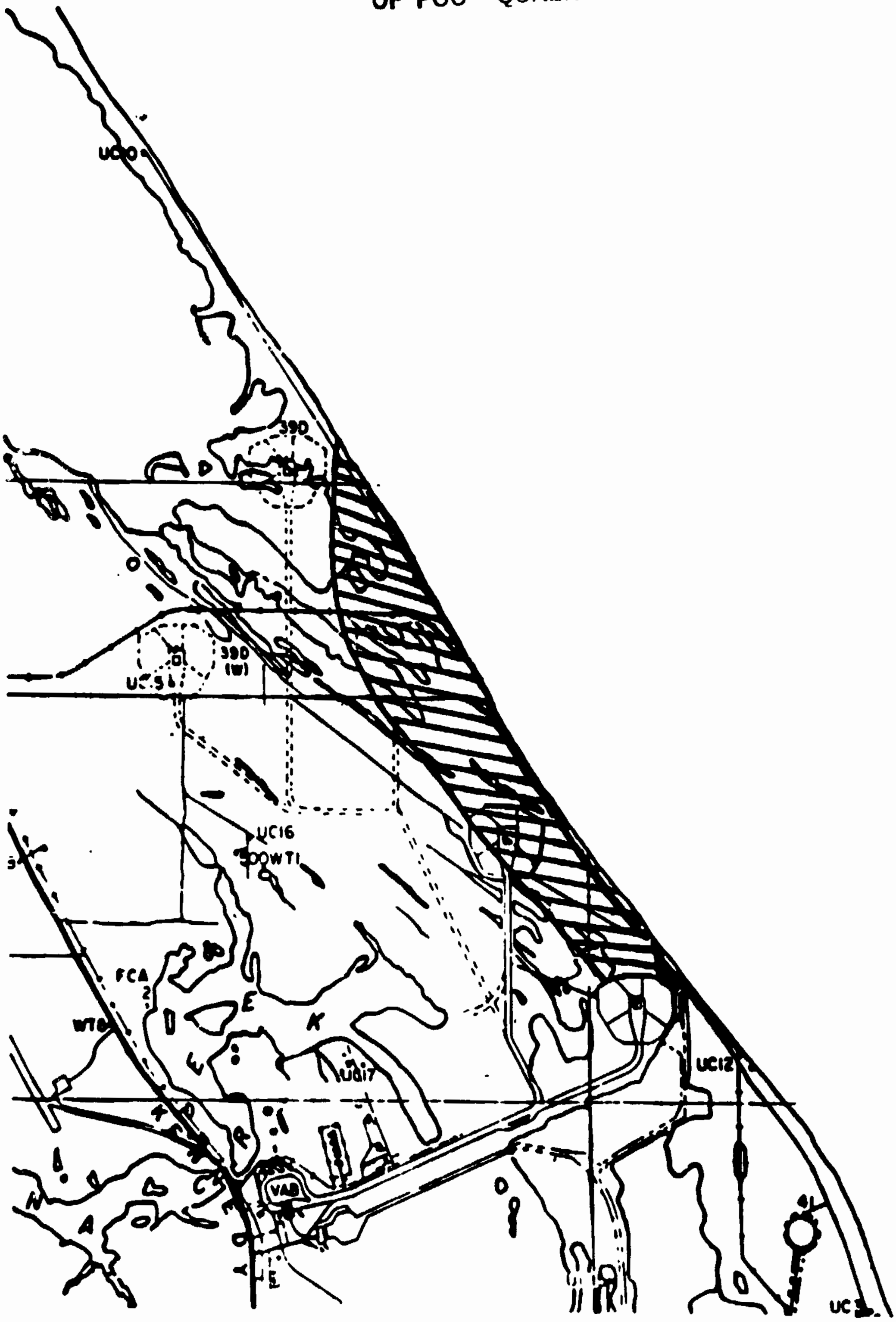

Figure 2-1.- Total area affected by STS-1 acidic deposition.

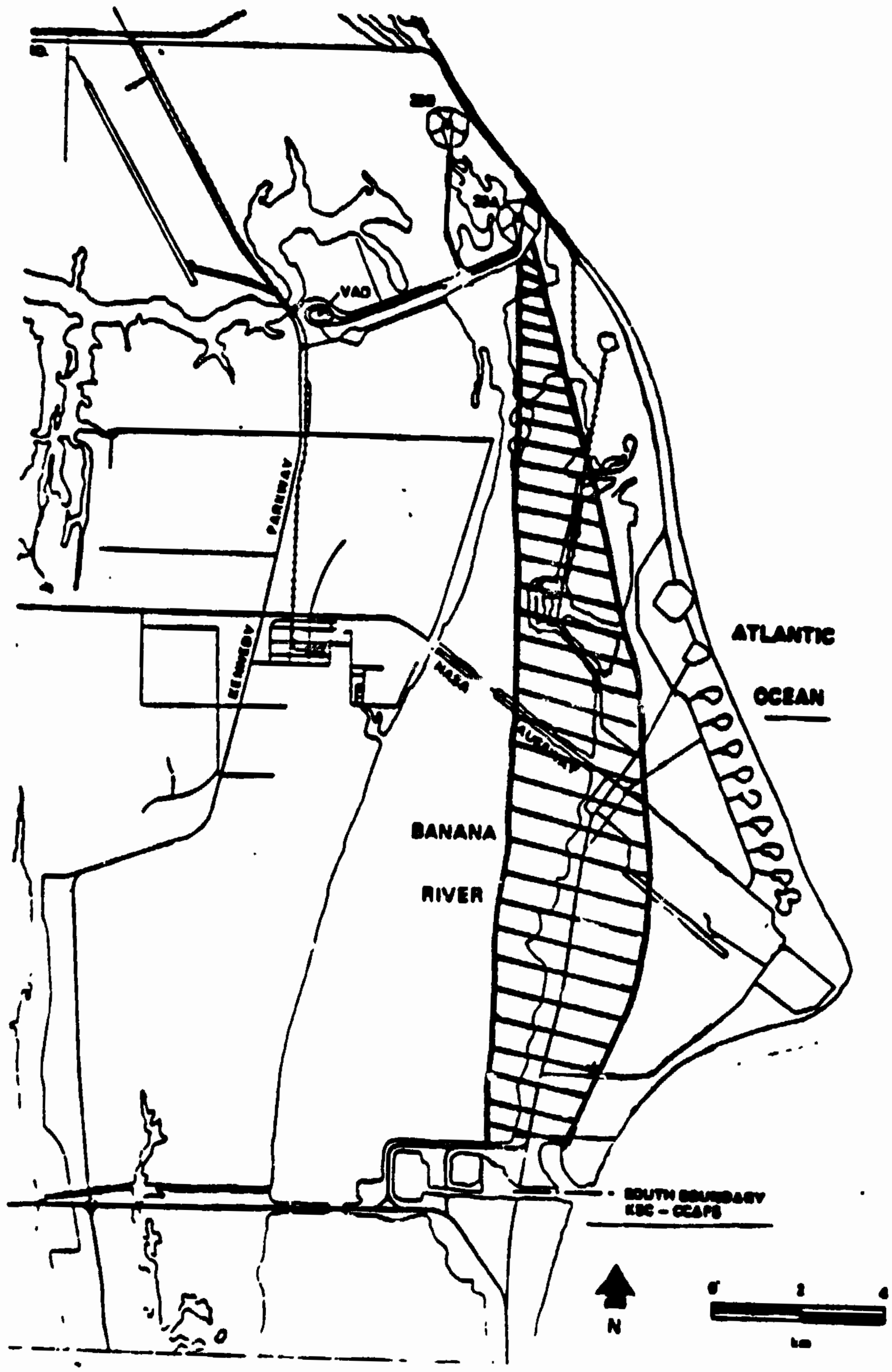

Figure 2-2.- Total area affected by STS-2 acidic deposition.

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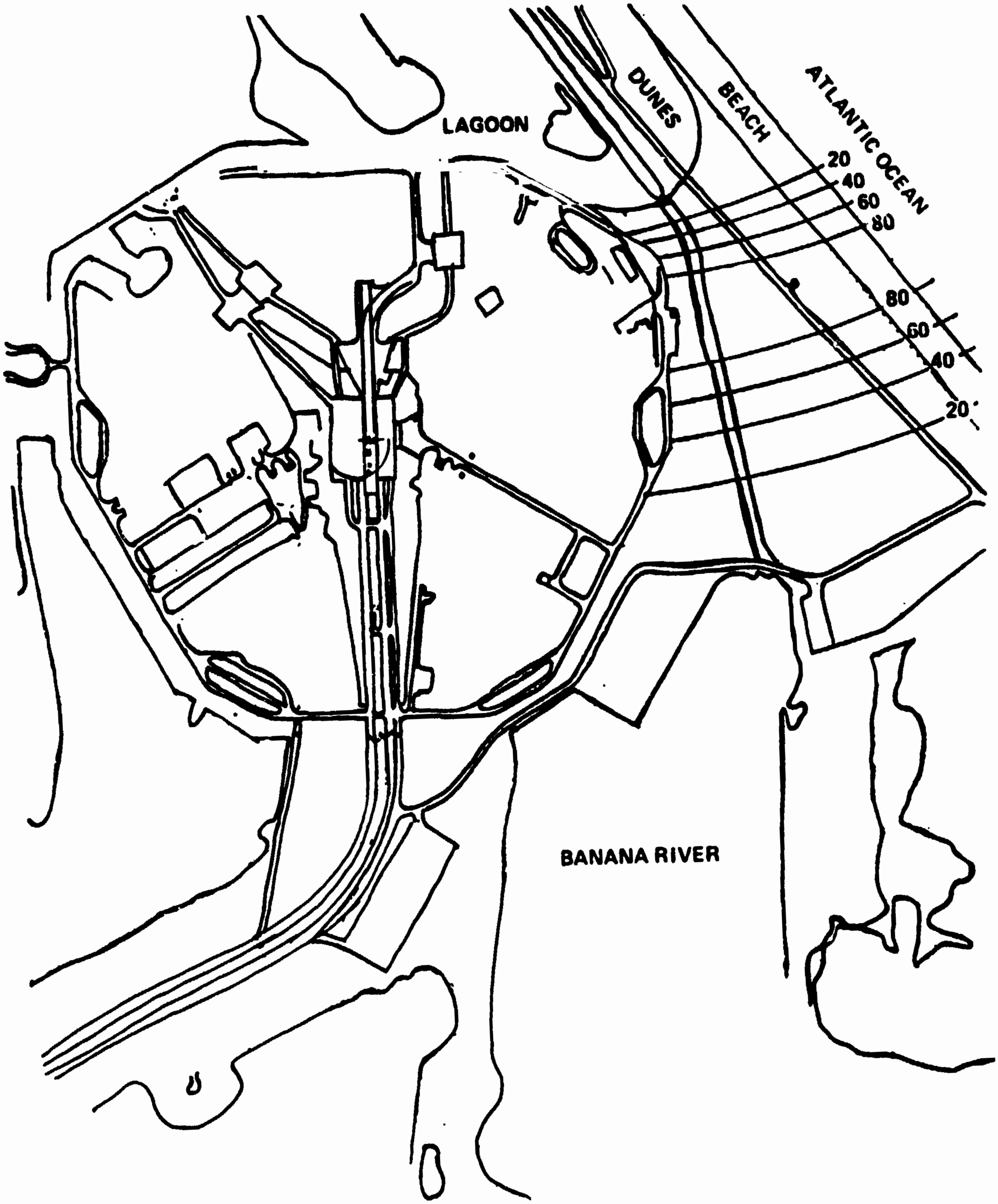

Figure 2-3.- Percent deposition on native flora for STS-3.

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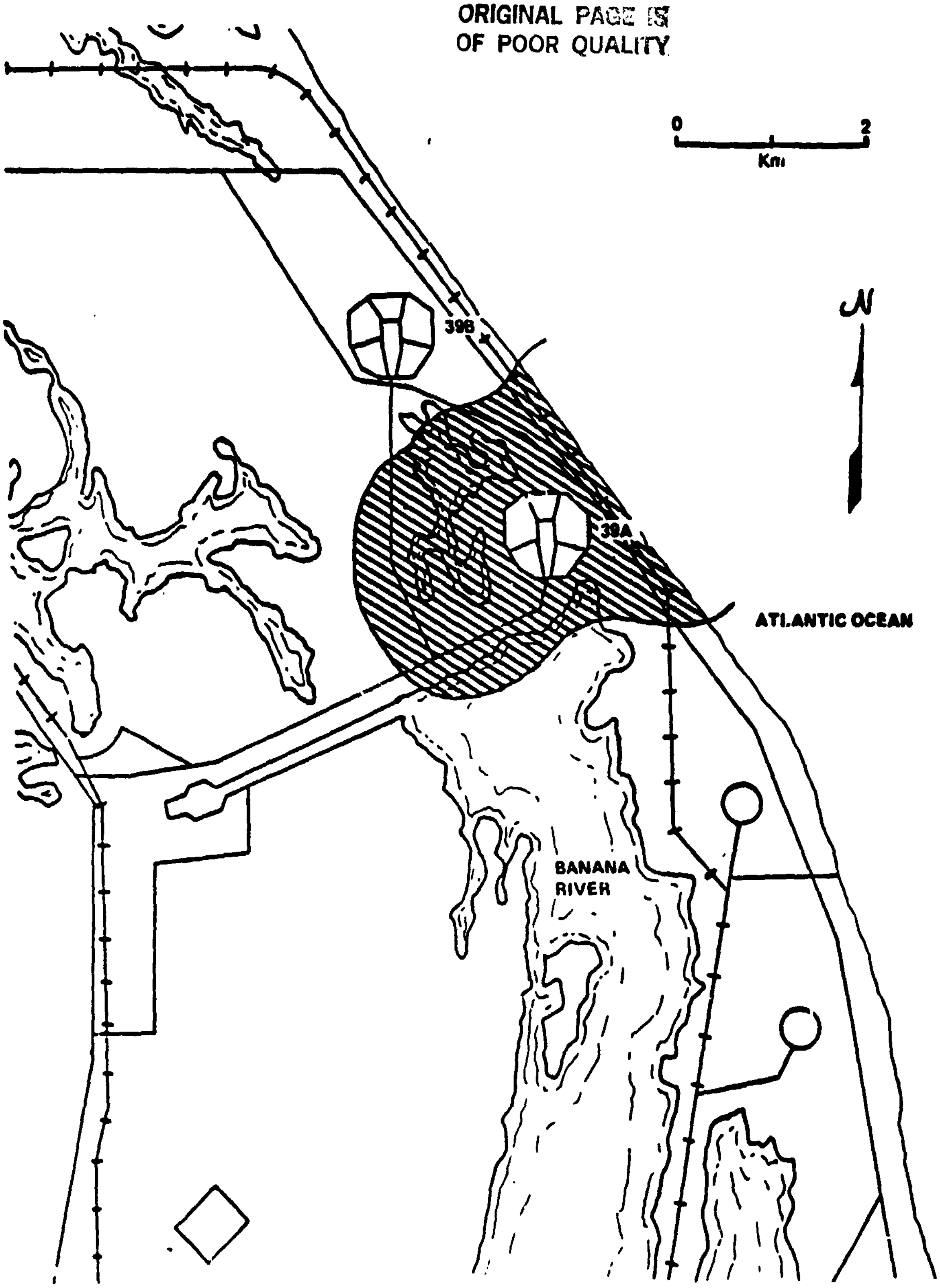

Figure 2-4.- Total area affected by STS-3 deposition.

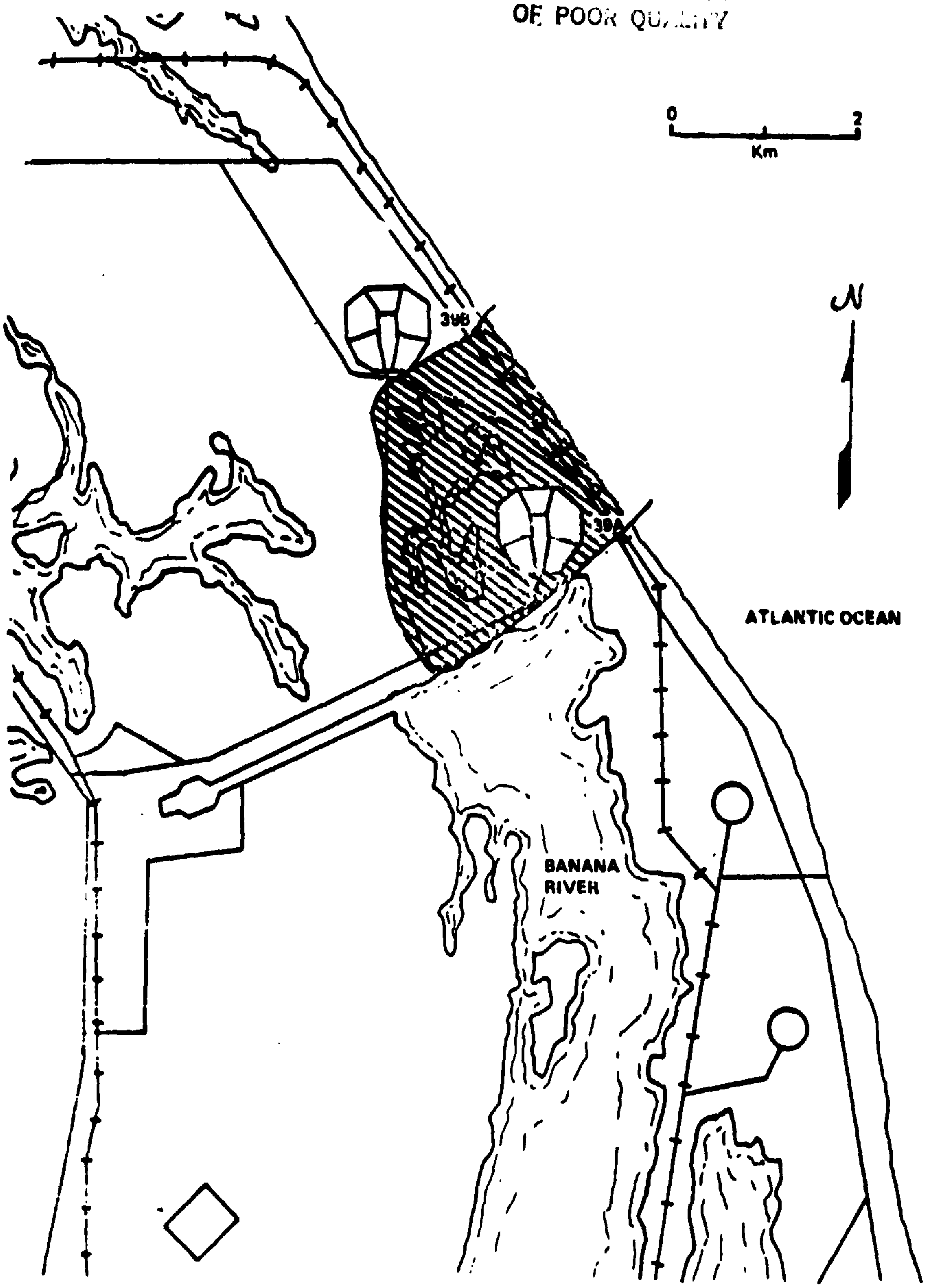

Figure 2-5.- Total area affected by STS-4 deposition.

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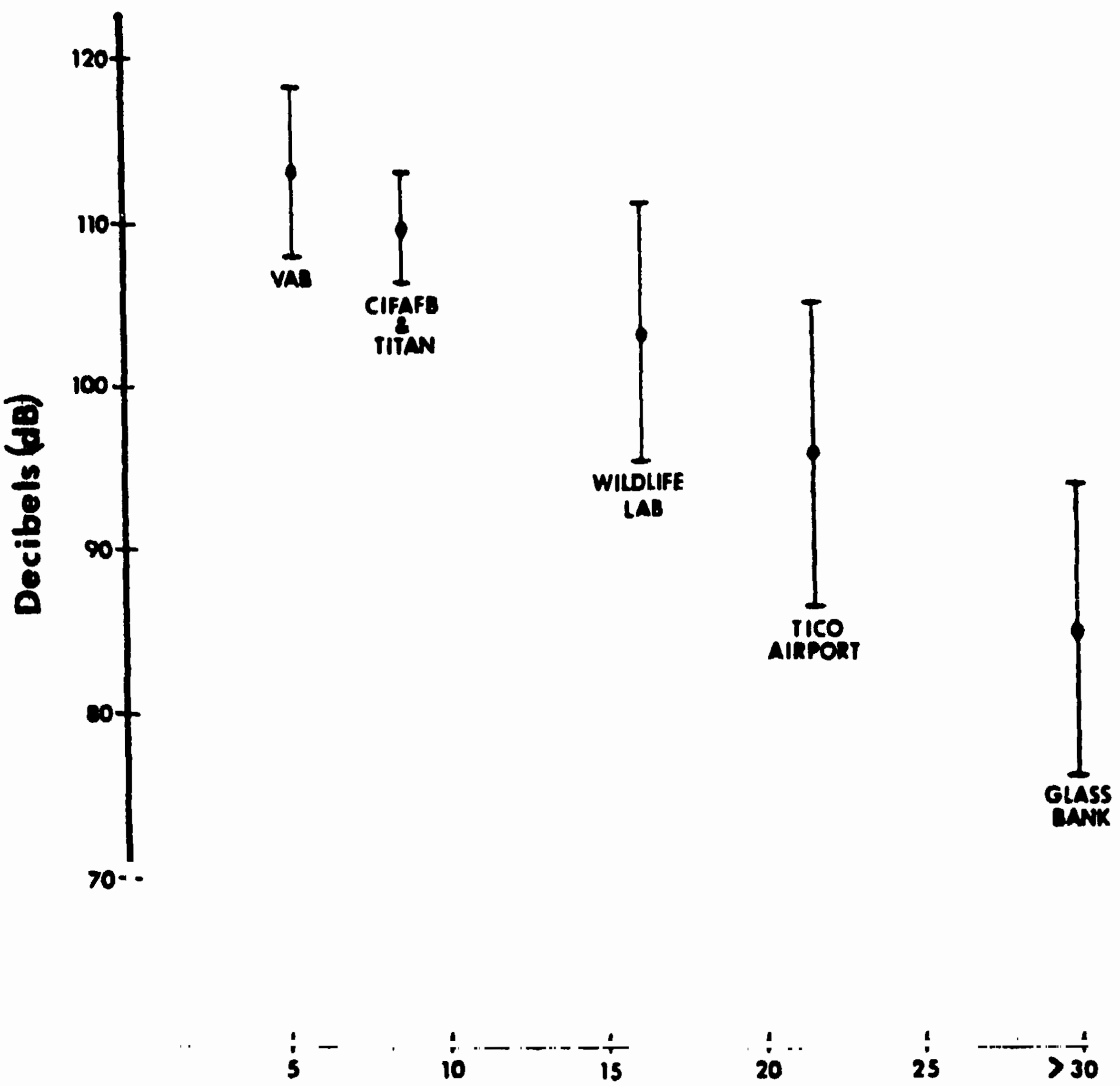

Figure 2-6.- Distance from LC-39A (km) mean peak unweighted noise levels versus the distance for STS-1 through STS-4.

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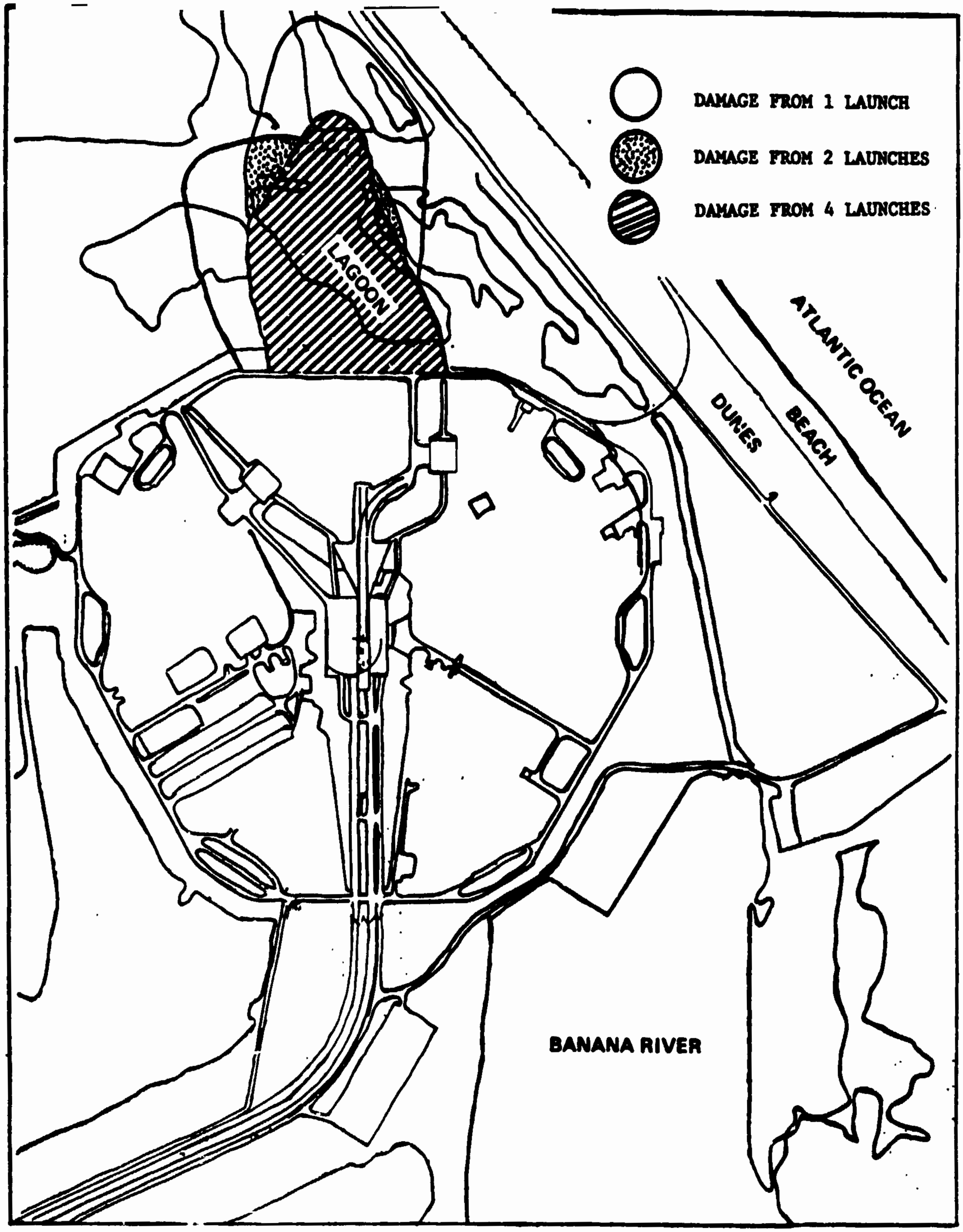

Figure 2-7.- Extent of launch plume on vegetation.

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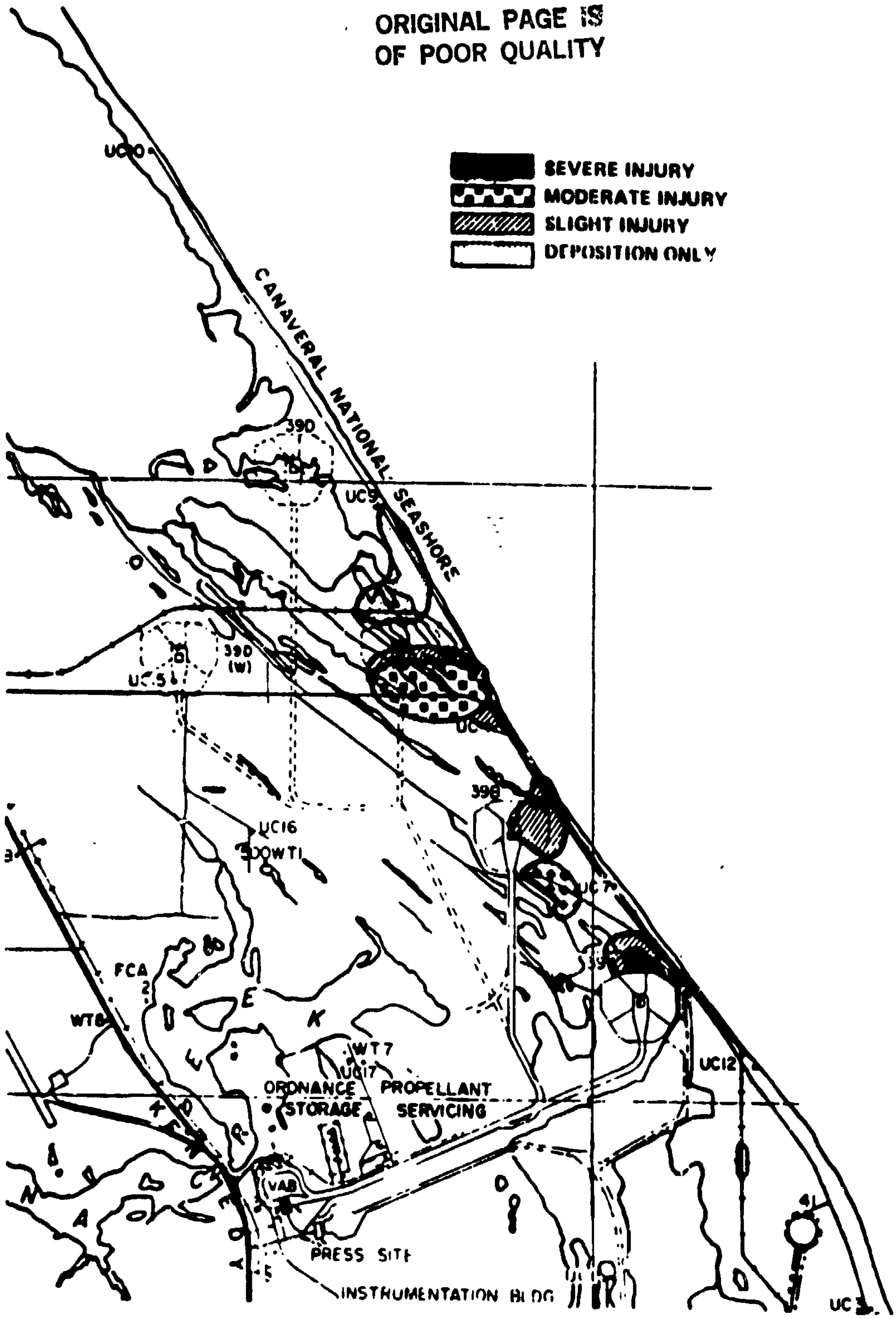

Figure 2-8.- Acidic deposition on native vegetation for STS-1 based on vegetation surveys.

A SUMMARY OF GEOMET HCl DATA FROM STS-1 THROUGH STS-5

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) and the U.S. Air Force (USAF) held a joint review of the Space Shuttle environmental effects at the John F. Kennedy Space Center (KSC) on December 14, 1982. The Earth-meteorological (GEOMET) hydrogen chloride (HCl) data collected during and after the Space Transportation System (STS) launches (STS-1 through STS-5) were documented. The summary of that GEOMET HCl data was presented at the meeting and is documented in this report. Figures 1 through 3 reflect GEOMET-monitor-equipped sites.

STS-1

A total of 12 GEOMET chemiluminescent HCl monitors were deployed for STS-1, NASA deployed ten and USAF personnel deployed two. Eight of the GEOMET monitors were positioned at intensive monitoring locations (within the impact limit line). Four GEOMET monitors were positioned at remote locations in the extensive areas. None of the GEOMET monitors located in the intensive areas measured any HCl. One of the extensive GEOMET monitors measured trace levels (100 ppb peak) of HCl north of Titusville, Florida (background?). Although the cloud passed directly over the northern most GEOMET in the extensive area, no HCl was detected; the distance from LC-39A to this monitor was greater than 20 miles.

STS-2

A total of ten GEOMET's were deployed to monitor HCl in the ground cloud from STS-2. Three GEOMET's were positioned north of the launch pad, and the remainder were positioned in extensive areas. No HCl was detected by any of the GEOMET's. Although an attempt was made to 'chase' the ground cloud with the mobile GEOMET unit, local traffic conditions completely frustrated the effort.

STS-3

Thirteen GEOMET chemiluminescent HCl monitors were deployed for STS-3, seven units on LC-39A, three units on LC-39B, and three units along the Coast Road north and east of LC-39A. No HCl data were recorded on LC-39B, and only one (position 4A) of the three units positioned along the Coast Road recorded any significant levels of HCl. These data are atypical and somewhat dubious in nature. If it represents a measurement of HCl, it is remarkably consistent in amplitude at approximately 0.14 ppm, stepping up to a level of 0.26 ppm prior to complete loss of power (the unit was operating on a 12-volt battery through a dc-ac inverter).

Of the seven GEOMET monitors positioned within the launch pad area, five recorded some HCl data. The two units that failed to record any data either lost power prior to launch (dropped 115-volt circuit) or were not properly deployed (strip chart recorder not fully plugged into the power outlet). The maximum concentration measured was 7.7 ppm on the northeast camera pad (position F). This GEOMET was equipped with a special filter designed to provide a 'total' HCl measurement capability. A second GEOMET, positioned immediately adjacent to this unit and equipped with the standard sampling tube, measured a maximum concentration of 1.7 ppm. Both units recorded a total dose of about 1,160 ppm/sec and 1,000 ppm/sec, respectively. The second highest concentration, recorded at position G (east camera pad), was 6.5 ppm with a total dose of some 1,450 ppm/sec. A GEOMET positioned on the northwest camera pad (position B) appears to have recorded a peak concentration of 4 ppm and a total dose of 4,600 ppm/sec. The signal trace from this unit is indicative of electronic instability. Background voltages vary rapidly over more than half of the scale covering two ranges from 0.05 ppm to 0.8 ppm.

If this unit did record HCl data, the duration of the measurement was approximately 51 min. The recording may be a measure of increased electronic instability rather than an actual measurement of HCl. A GEOMET placed behind a concrete retaining wall in the drainage ditch near the perimeter fence, in line with the solid rocket booster (SRB) flame trench, measured a peak concentration of 1.9 ppm (not 13 ppm as previously reported) and a dose of approximately 3,000 ppm/sec.

STS-4

Seven GEOMET chemiluminescent HCl monitors were deployed for STS-4; four were within the launch pad area (two each at positions B and F) and three along the Coast Road (positions 4, 4A, and 5). The strip chart paper for one of the GEOMET's at position B was destroyed by the paper drive mechanism. A second unit located immediately adjacent to it, however, recorded no HCl data. Neither of the two GEOMET's located at position F (northeast camera pad) recorded any HCl data immediately after launch, but a peak concentration of 25 ppm was recorded by one of these units approximately 2 1/2 hours after the launch. The total dose recorded was some 10,000 ppm/sec. Of the three units positioned along the Coast Road, only one (the northern most unit) recorded any HCl data. The peak concentration measured was 0.9 ppm with a total dose of some 130 ppm/sec. Although heavy acidic deposition occurred at position 4A, the GEOMET located there measured no HCl. A postlaunch evaluation of this unit revealed a plugged reagent line.

STS-5

Eight GEOMET chemiluminiscent HCl monitors were deployed for the launch of STS-5; six units were within the pad area and two units downwind - one located on the southern shore of Banana Creek and one at UCS-6. No HCl was measured at the Banana Creek location. The GEOMET positioned at UCS-6, however, recorded a peak concentration of 9 ppm and a dose of 90 ppm/sec. (The cloud passed directly over this location.) Three of the six GEOMET's positioned within the launch pad area measured HCl with the highest concentration, 29 ppm, recorded at the northwest camera pad (position B). The total dose [illegible] was approximately 480 ppm/sec. A second unit located immediately adjacent to this monitor recorded a peak concentration of 7 ppm with a total dose of approximately 3,200 ppm/sec. The third measurement was recorded at position C where a peak concentration of 12 ppm and a dose of 400 ppm/sec was registered. Two units placed on the northeast camera pad (position F) and one unit located at position E failed to measure any HCl.

Although most of the HCl data shown in table 1 represent actual measurements, only that given for STS-5 can be reported with any confidence. Operational and instrument calibration problems encountered during STS-1 through STS-4 produced strip chart recordings that are both erratic and difficult to interpret. Calibration techniques (liquid HCl injection or Cl_2 permeation) did not provide a correction factor that could be confidently applied to the raw data. If the Cl_2 permeation rates provided by the manufacturer are accurate, the calibration performed on the GEOMET's prior to STS-5 produced a correction factor which can be confidently applied to the raw data.

To this observer, the data shown in table 1 indicate that HCl is present in both the liquid and gas phases immediately after launch. A high percentage of the HCl (greater than 75 percent) exists in the liquid or aerosol phases and slowly comes out of solution by evaporation for long periods (several days) after lift-off.

TABLE 1.- SUMMARY OF GEOMET HCl DATA STS-1 THROUGH STS-5

STS launch	Units deployed	"Hits"	Location of GOMET monitors	Sample inlet	Maximum concentration (ppm)	Dose (ppm/sec)	Remarks
1	12	1	Titusville	Standard tube	0.1	-	Background?
2	10	0					
3	13	6	4A	Standard tube	0.26	Indet.	Anomaly?
			F	OEHL filter	7.7	1,160	Total HCl?
			F	Standard tube	1.7	1,000	
			G	Standard tube	6.5	1,450	
			B	Standard tube	4.0	4,600	Unstable unit
			D	Standard tube	1.9	3,000	
4	7	2	F	Standard tube	25.0	10,000	T + 2.5 hrs
			5	Standard tube	0.9	130	Anomaly?
5	8	4	UCS-6	Standard tube	9.0	90	Aerosol?
			B	Standard tube	29.0	480	
			B	OEHL filter	7.	3,200	Total HCl?
			C	Standard tube	12.	400	

Symbol definition:

GEOMET = Earth/meteorological
HCl = Hydrogen chloride
OEHL = Occupational Environmental Health Laboratory
STS = Space Transportation System
UCS = Universal Camera Site

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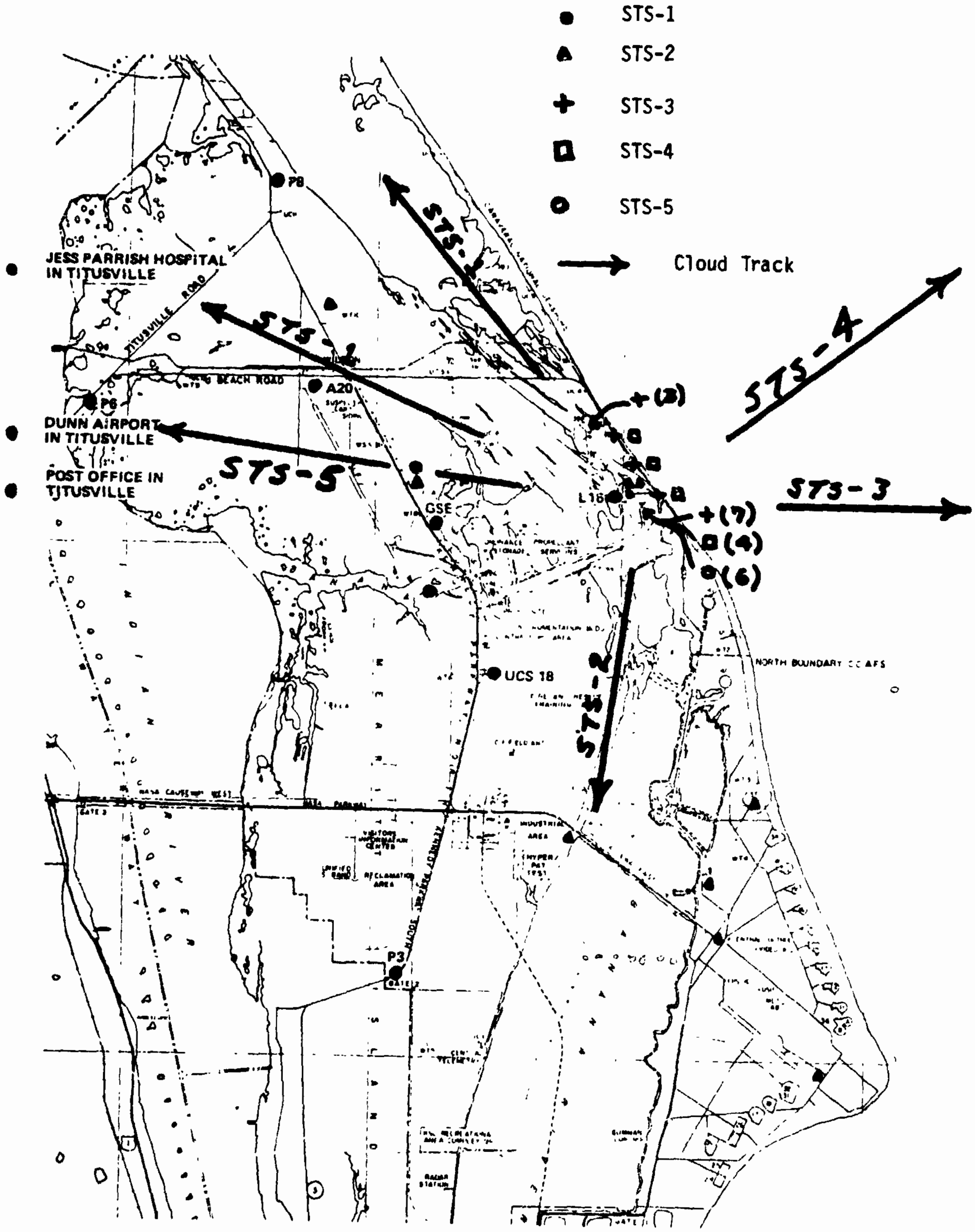

Figure 1.- A map showing locations of KSC sites equipped with GEOMET chemiluminescent HCl monitors during launch of STS-1 through STS-5.

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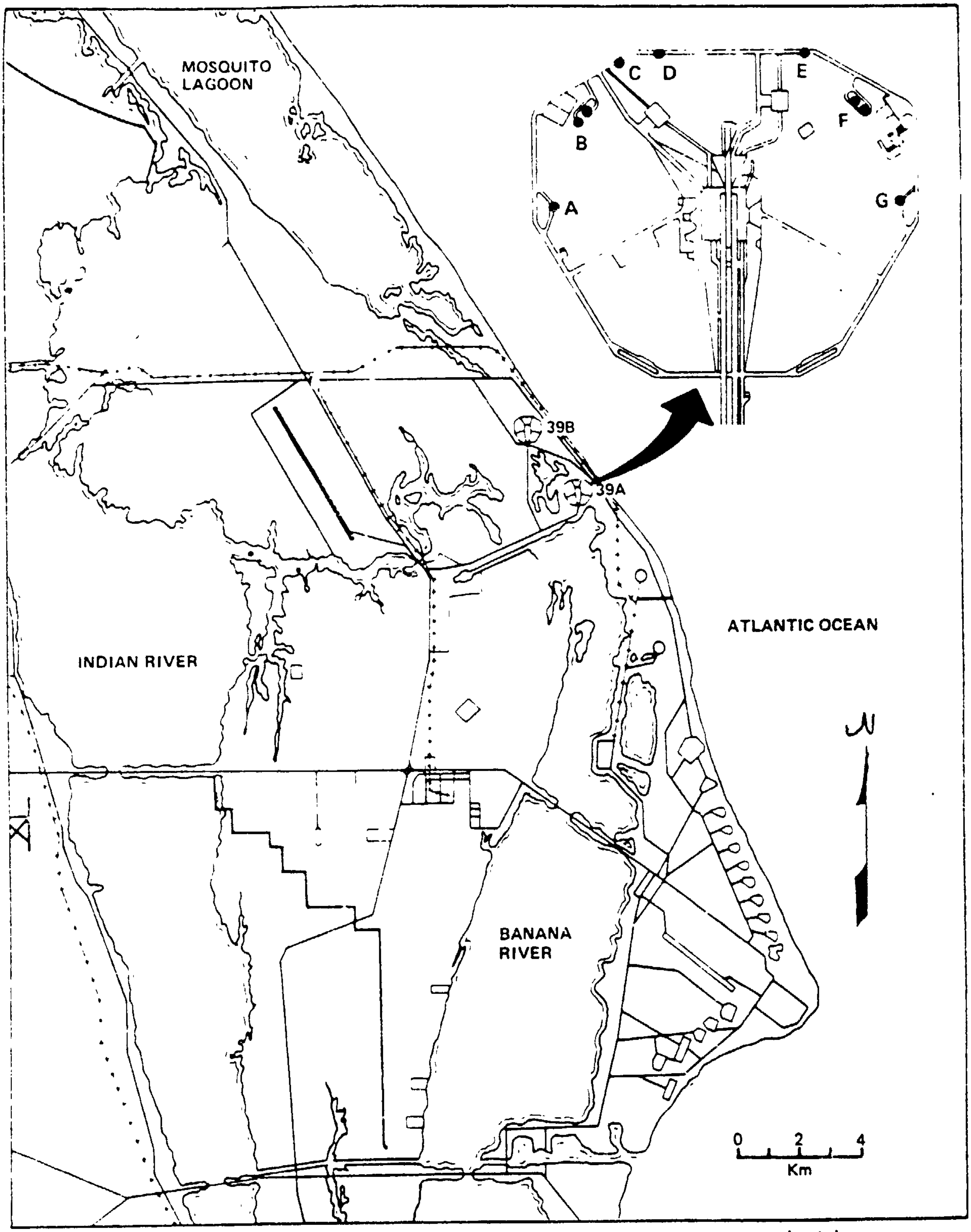

Figure 2.- A map showing locations around the LC-39A site equipped with GEOMET chemiluminescent HCl monitors during launch of STS-1 through STS-5.

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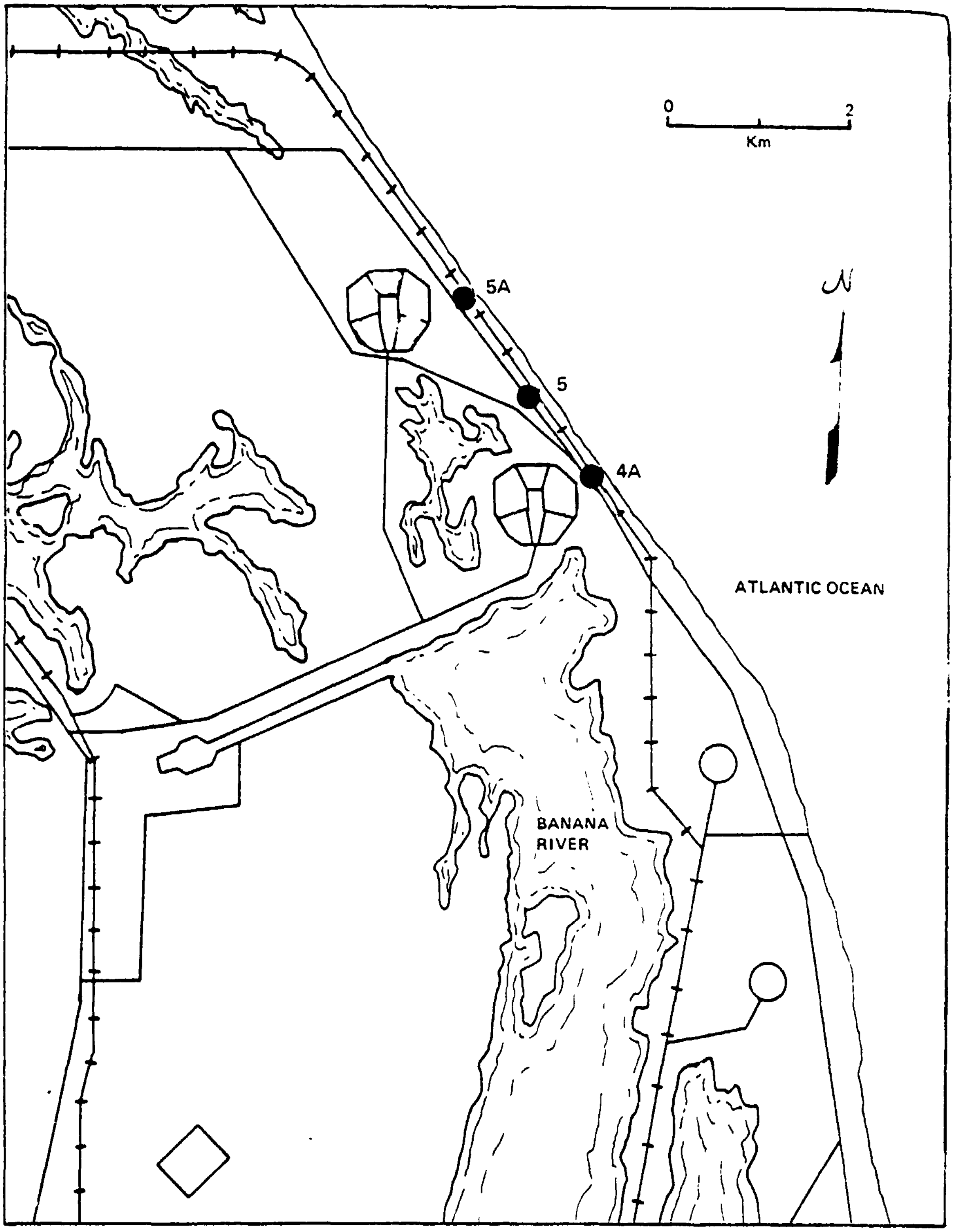

Figure 3.- A map showing far-field sites at KSC equipped with GEOMET chemiluminescent HCl monitors during launch of STS-1 through STS-5.

STS-5 EXHAUST PRODUCT GROUND DEPOSITION

Captain Gerald D. Swoboda
U.S. Air Force
Occupational and Environmental Health Laboratory

The U.S. Air Force (USAF) Occupational and Environmental Health Laboratory (OEHL) participated in an extensive USAF and National Aeronautics and Space Administration (NASA) ground monitoring effort for the launch of STS-5. Sites weie established near field, defined as within or around the LC-39A perimeter fence, and external, defined as points outside the pad area.

Monitoring sites external to the pad area are presented in figure 1. There were four primary sites: Coast Road South (CRS), Coast Road North (CRN), Universal Camera Site-6 (UCS-6), and Banana Creek. Monitoring equipment at each location included: TENAX tube, charcoal tube, impinger, cooper plate, and pH paper (pH = 1.0 to 7.0). TENAX tubes and charcoal tubes measure organic materials, and the impingers were prepared to measure acidity and heavy metals. Copper plates and pH paper are used as passive indicators of acid deposition. In addition to the above equipment, one Earth/meteorological (GEOMET) chemiluminescence HCl monitor was placed at UCS-6 and Banana Creek.

Surface winds at launch time were from the east at 9 knots (09009); upper level winds were east-northeast at 20 knots (06020). The ground cloud moved inland from the east, and the only primary site with visible deposition hits was at UCS-6 where approximately 3,600 drops per meter squared of pH = 1.0 acidity were observed. Two copper plates on Kennedy Parkway North near the entrance to UCS-6 were also hit with acid deposition. Impinger results (table 1) show low concentrations of both HCl and Al at all four primary sites. Analysis of TENAX tubes and charcoal tubes showed no significant amounts or STS-launch-related organic materials.

A number of health-related complaints were voiced by personnel entering Pad LC-39A after the launches of STS-1 through STS-4. For this reason, the pad area was heavily monitored in attempt to try to determine the extent of this problem. Near-field monitoring sites are shown in figure 2. Paired sets of TENAX tubes, charcoal tubes, and impingers were placed at the Northwest-Elevated Camera Pad (S1), Northeast-Elevated Camera Pad (S2), and the Knollenberg Site (S5) opposite the solid rocket booster (SRB) flame trench. The first of the paired sets was turned on at L + 00:05 min. and turned off at L + 00:10 min. The second set was turned on at L + 00:10 min. and shut off by the operator when the environmental team reentered the pad more than 3 hrs later. Two GEOMET's, one HCl gas monitor and one fitted with a filter to enhance detection of aerosol HCl's, were located at S1 and S2. The USAF environmental monitoring team entered the pad area about L + 3:30 hrs and established sites S6, S7, S8, and S9 in the grassy-burn area opposite the SRB flame trench. Each site consisted of a TENAX tube, charcoal tube, and impinger. A GEOMET HCl gas monitor was also set up at the northwest holding pond (S7) and the northeast holding pond (S8) to determine if HCl off-gassing occurs from the deluge and fire suppression water which run into the ponds during launch.

Analysis of TENAX tubes and charcoal tubes showed no significant amounts of Space Shuttle launch-related organic materials. Impinger results are in table 1. The concentrations shown are a time-weighted average (TWA) over the sampling period of each instrument. This means that higher peak concentrations could have occurred sometime within the sampling period. Background readings were subtracted from each sample to eliminate chloride concentrations due to sea salt spray (NaCl). High HCl and Al concentrations were observed at S1 (downwind of SRB exhaust) and S5 (directly hit by SRB exhaust) in the initial 10 min postlaunch. High concentrations of HCl continued for 3 hrs to 4 hrs after launch, whereas Al concentrations dropped. At S2 (upwind of SRB exhaust), HCl concentrations remained relatively constant while Al concentrations dropped after the first 10 min. The one site directly downwind in the vicinity of the northwest holding pond (S7) showed a TWA concentration of 3.3 ppm during the period from 4 hrs to 6 hrs postlaunch.

A joint study was conducted by the USAF-OEHL and Martin-Marietta Corporation. Copper plates and pH paper (pH = 1.0 to 7.0) were set on tripod stands at distances of 400, 600, 800, and 1,000 ft from launch point (fig. 3). Fifteen single copper plates were attached to the perimeter fence opposite the SRB flame trench. The purpose of the study was to identify the spatial distribution of acid fallout to aid in determining the amount of structural washdown water required at Vandenberg Air Force Base (VAFB). These data will also provide valuable material mass balance information which may be used as input data to the dispersion model used in predicting ground cloud fallout.

In general, copper plates were 100 percent covered, and pH was equal to or less than 1.0 at all interior sites (400 ft) and sites downwind of the launch pad. Upwind sites had pH greater than or equal to 3 and a coverage of 100 to 500 deposition spots on the 6-in by 6-in copper plates. Copper plates on the perimeter fence had 100 to 500 tan deposition spots up to the burned grass/green grass line of demarcation and were 100 percent covered by deposition thereafter.

Preliminary results from our monitoring indicate a very productive effort (fig. 4). Health concerns for individuals entering the pad after launch seem justified. A 4-hr average concentration of HCl as high as 38 ppm present, with higher peaks possible at distances out to 1,500 ft from launch point. The threshold limit value (TLV) ceiling concentration, the exposure value not to be exceeded by workers, is 5 ppm. These data combined with the fact that the VAFB Launch Control Center (LCC) is 1,250 ft away from the launch site suggest important health concern questions. Since one data set is not conclusive, future monitoring attempts to define the time history and spatial extent of HCl revolatilization postlaunch are required. Far-field monitoring is also required to better define the acid rain/deposition phenomena that has occurred after every launch.

TABLE 1.- STS-5 IMPINGER ANALYSIS

Location	Site	Sampling time (min)	Total HCl (µg)	HCl Concentration TWA (ppm)[a]	Total Al (µg)	Al Concentration TWA (mg/m3)[a]
W. Pad (launch)	S1	10	315.0	23.8	13.4	1.5
W. Pad (postlaunch)	S1	198	2,997.0	11.4	24.4	0.2
E. Pad (launch)	S2	10	39.0	2.9	9.0	1.0
E. Pad (postlaunch)	S2	[b]91	305.0	2.5	5.4	0.1
Knollenberg (launch)	S5	[b]10	372.0	28.1	16.6	1.8
Knollenberg (postlaunch)	S5	[b]241	12,437.0	38.9	140.0	0.7
Coast Road, South		82	37.0	0.3	12.6	0.2
Coast Road, North		219	27.0	0.1	20.6	0.1
SRB	S6	209	217.0	0.7	26.8	0.1
SRB	S7	154	697.0	3.3	28.0	0.2
SRB	S8	78	16.0	0.2	23.8	0.3
SRB	S9	82	7.0	0.1	20.0	0.3
USC-6		93	28.0	0.2	19.4	0.2
Banana Creek		142	43.5	0.2	23.2	0.2

[a]Postcalibration of the sample flow limiting orifices suggest that actual concentrations could have been even higher than shown in above table.

[b]Sampling times are questionable.

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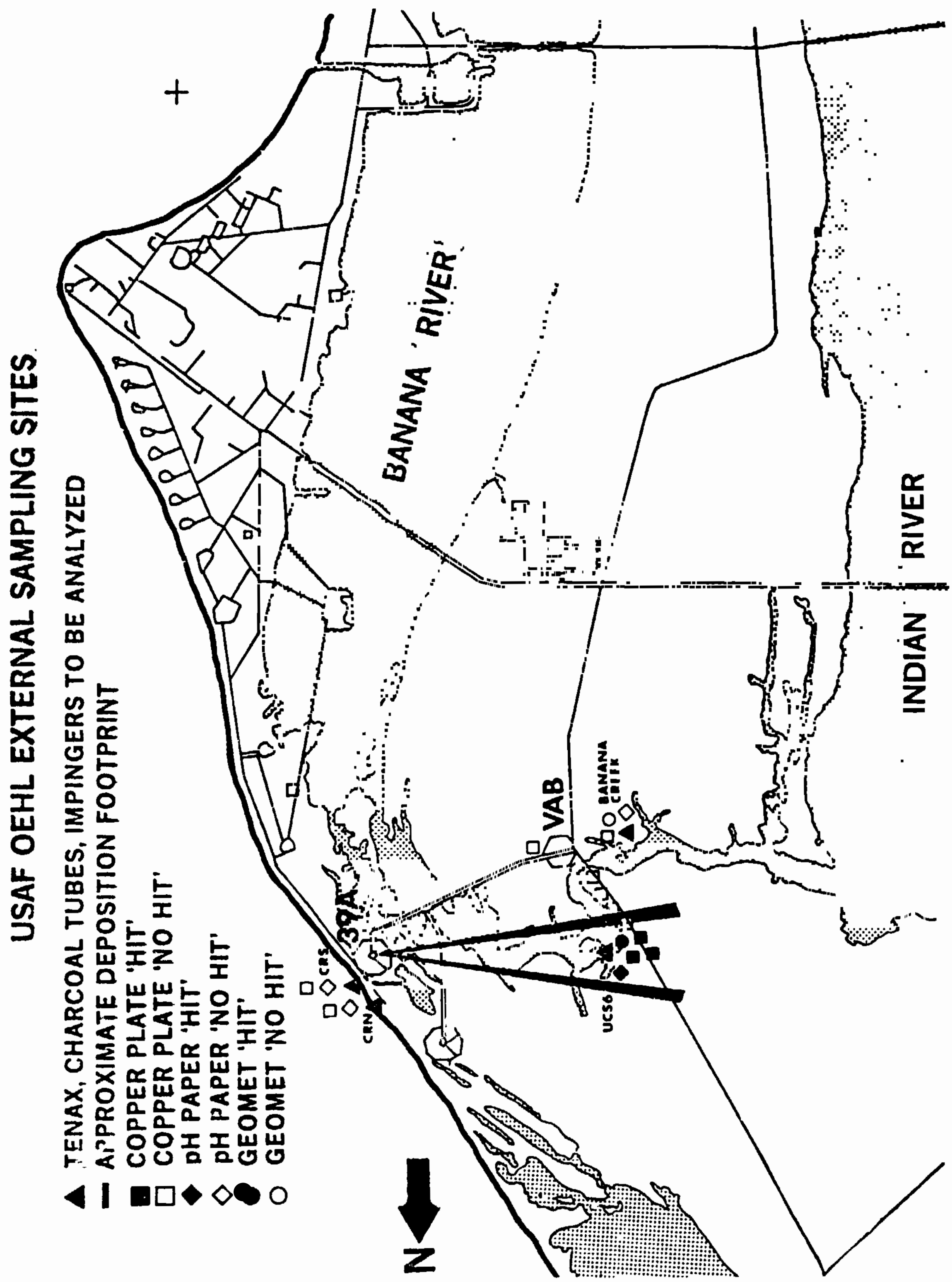

Figure 1.- Monitoring sites external to the pad area.

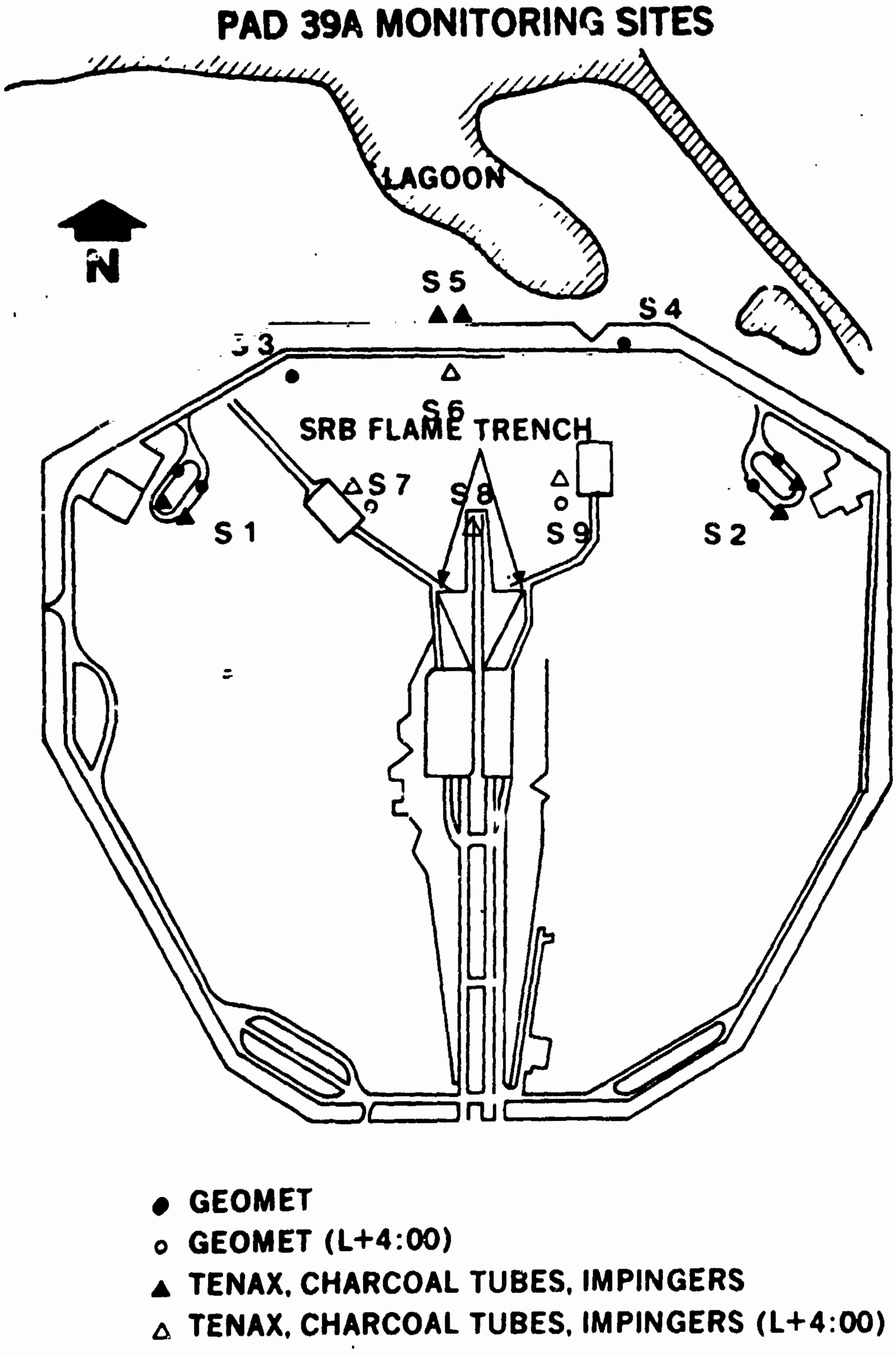

Figure 2.- Near-field monitoring sites.

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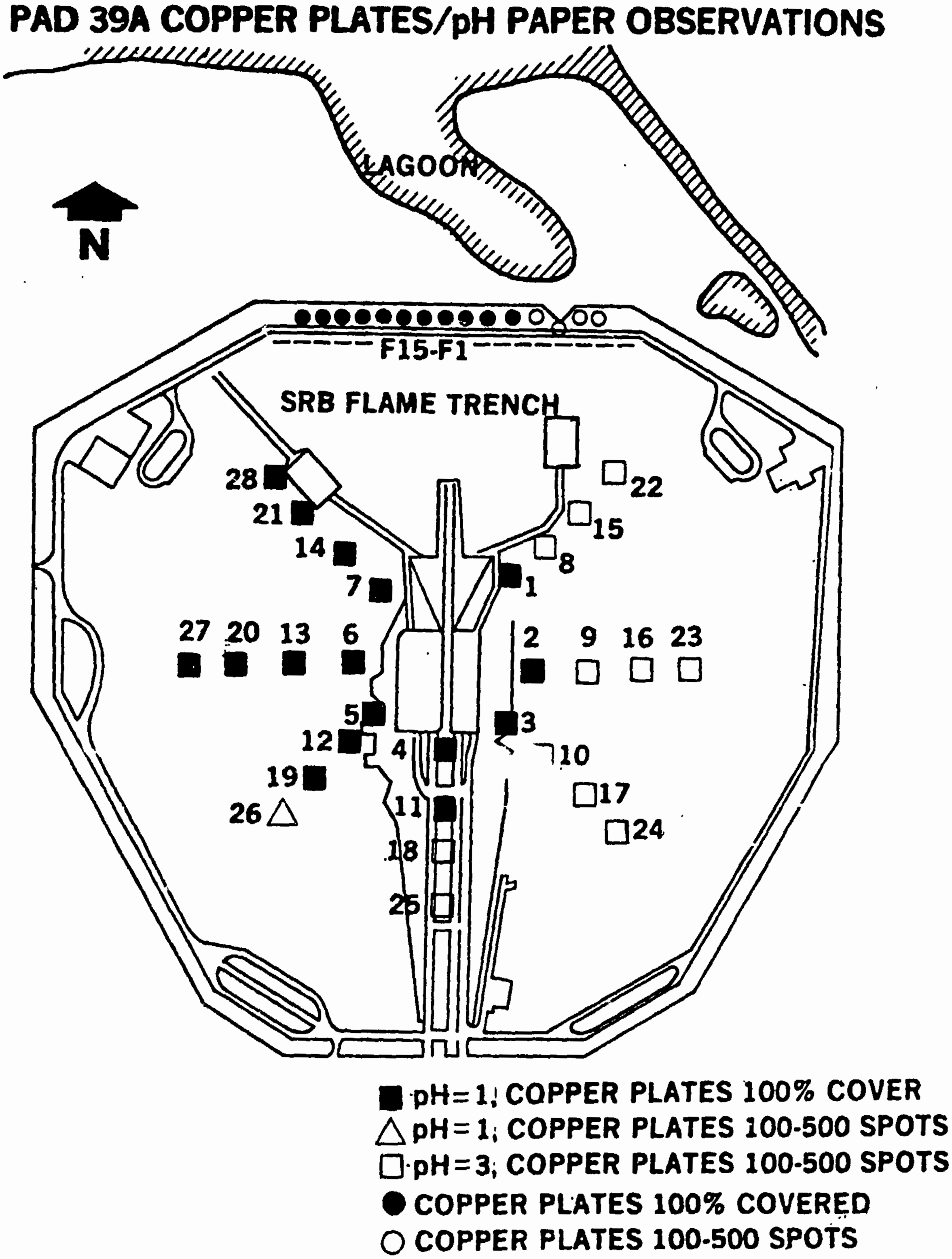

Figure 3.- Locations of tripod stands holding copper plates and pH paper which were placed at distances from 400 ft to 1,000 ft from launch point.

SUMMARY

- HEALTH CONCERNS
  - HCl TLV 5 ppm (CEILING)
- - OBSERVED 38 ppm HCl (TWA OVER 4 HRS)
  - VAFB LCC
- FUTURE MONITORING EFFORTS
  - NEAR FIELD
    - + TIME HISTORY HCl REVOLATILIZATION
    - + SPATIAL EXTENT HCl REVOLATILIZATION
  - FAR FIELD
    - + ACID RAIN/DEPOSITION

Figure 4.- Preliminary results obtained from monitoring.

CHEMICAL ANALYSIS OF ATMOSPHERIC GAS SAMPLES TAKEN AT THE STS-5 LAUNCH SITE

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NASA - Lyndon B. Johnson Space Center
Houston, Texas

After each launch of the Space Shuttle, persons entering the launch pad area noticed a sweetish/musty, choking odor which persisted for several hours. A major component of the odor is HCl, which has been identified by John F. Kennedy Space Center (KSC) industrial hygiene personnel, using field samplers sensitive to HCl. Concentrations of HCl sufficient to produce a choking reaction in persons who inhale the air were found in the pad area. However, other components are present, probably organic in nature, which produce the sweetish/musty aspect of the odor. In an effort to identify these odors, atmospheric samples were collected in the pad area using evacuated stainless steel cylinders which were carried to the sampling location, opened to collect the sample, then closed and returned to Lyndon B. Johnson Space Center (JSC) for analysis. First, background air samples were collected in the pad area 48 hours before launch. Then, the postlaunch samples were taken 2 hours after launch from the same locations as the blank or background samples. Analysis of the gas samples for trace organics was done using gas chromatography and gas chromatography/mass spectrometry. Results are shown in table 1 where concentrations of various organics in ppm are shown for the background control and postlaunch samples, taken at two levels above the surface.

A total of 28 different compounds were identified in the four samples. A number of compounds were detected in the postlaunch samples that were not present in the prelaunch background samples. Of these, five could possibly have been detected by the sense of smell, and thus contributed to the odor noticed in the pad area. These compounds are listed in the following tabulation.

Compound	Eye-level concentration, ppm
Isobutanal	0.012
Hexanone	0.005
Imidazole	0.015
Ethylbenzene	0.008
1,4-Dimethylbenzene	0.001

Of these compounds, imidazole may perhaps be the major contributor to the perceived odor. These organic compounds are probably a result of incomplete combustion of the solid propellant in the solid-rocket boosters.

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TABLE 1.- COMPOUND CONCENTRATIONS MEASURED IN ppm

Sample: Date: Time: Distance above ground: Location:	Background 11/9/82 1403 hrs 1 in LC-39A	Background 11/9/82 1407 hrs 5 ft 5 in LC-39A	Postlaunch 11/11/82 0855 hrs 1 in LC-39A	Postlaunch 12/22/82 0857 hrs 5 ft 5 in LC-39A
COMPOUND				
Methane	1.518	1.423	1.565	1.897
Butene	0.024	0.015	0.029	0.040
Molecular wt = 94	0.014	-	-	-
Ethanal	0.041	0.010	0.054	0.128
Propanal	0.005	0.004	0.022	0.069
2-Propanone	-	0.004	0.039	0.055
Iso-Butanal	-	-	0.017	0.007
Butanal	0.018	0.003	0.011	0.039
2-Butanone	0.002	-	0.006	-0.009
Dichloromethane	-	0.014	-	-
Benzene	0.001	0.002	-	0.002
Hexanone	-	-	0.004	0.005
Imidazole	-	-	0.005	0.015
2-Butanal	0.008	0.002	0.034	0.012
Toluene	<0.001	-	0.001	0.002
Ethylbenzene	-	-	-	0.008
n-Butanol	0.014	0.002	0.003	0.005
1,4-Dimethylbenzene	-	-	-	<0.001
C_7-Ketone	0.001	0.001	0.006	0.008
C_{10}-Alkane	-	-	0.002	0.002
C_{10}-Alkane	-	-	0.001	0.002
C_{11}-Alkane	-	-	0.001	0.002
Siloxane	0.001	0.005	-	0.008
Benzaldehyde	-	-	0.003	0.001
C_{12}-Alkane	-	-	<0.001	0.001
Siloxane	0.009	0.001	-	0.006
Siloxane	0.009	0.006	-	0.004
Siloxane	-	0.004	-	-
TOTAL FOR ALL COMPOUNDS	1.666	1.596	1.804	2.328

NEAR-FIELD EFFLUENT FALLOUT STUDY FOR STS-5

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INTRODUCTION

Two studies relating to near-field effluent fallout were conducted during STS-5. The first was a measurement of the actual fallout within 1,000 ft of the Mobile Launch Platform (MLP). The second was a test of washdown parameters to determine how to most effectively remove the effluent depositions. Both were initiated to support the design of the washdown system for the launch facilities at Vandenberg Air Force Base (VAFB).

NEAR-FIELD DEPOSITION MEASUREMENTS

Following the STS-4 launch, the grasses within Launch Complex-39A showed well-defined zones of what appeared to be acid damage extending 7 ft to 900 ft to the south and 4 ft to 500 ft to the east and west (see fig. 1). The grasses within the zones were brown, whereas those outside were green and apparently healthy. The vegetation to the north, well past the perimeter fence, was also heavily damaged, and it was evident that this was a result of the solid rocket booster (SRB) exhaust being ducted by the flame trench over that area. The winds for STS-4 were relatively light, so the damage was approximately symmetrical about a north-south line through the MLP.

In order to confirm that the cause of grass damage was the SRB effluent fallout and to better understand its characteristics, 26 sites were established around the launch complex from which to measure STS-5 fallout. A sheet of pH paper and a 6 in by 6 in copper plate were positioned at each site by a team from the Office of Environmental Health Laboratories (OEHL). OEHL reported earlier in the conference on the measurement pattern and on their postlaunch observations. The copper plates were given to Martin-Marietta Denver Aerospace (MMDA) for further analysis.

MMDA determined that the depositions observed on the plates could be classified into the following five categories (fig. 2):

1. Spray Zone - each copper plate in the Spray Zone was hit with 300 to 600 acidic droplets having a pH of 3. There was no visible evidence of solid particulates being carried with the droplets.

2. Rainbird Splash Zone - over 70 percent of the surface of each copper plate in the Rainbird Splash Zone was covered with a thin, green mud registering a pH 1. The Microchemical Analysis Section (TC-FLD-21), National Aeronautics and Space Administration (NASA)/John F. Kennedy Space Center (KSC), analyzed the mud and found that it was composed of aluminum oxide, copper chloride hydroxide, copper chloride, and copper oxide. Hydrochloric acid and HCl gas reacted with the copper plates to form the copper compounds.

3. Space Shuttle Main Engines (SSME) Wetted Zone - the two plates in the SSME Wetted Zone had been inundated with acidic water (pH 1). There were also traces of the green mud observed in the Rainbird Splash Zone.

4. SRB Flame Trench Zone - the OEHL team had placed 15 copper plates along the fence on the north side of the launch complex. The depositions on the plates within the SRB Flame Trench Zone were similar to those in the Rainbird Splash Zone.

5. Access Tower Shadow Zone - the most interesting and least expected observations were in the Access Tower Shadow Zone. Here the copper plates had a thin, reddish covering analyzed as copper oxide and copper chloride. Because the plates on the radials on either side of the Shadow Zone were each covered with the green mud, the absence of the mud from the Shadow Zone plates was significant. The Fixed Service Structure and the Rotating Service Tower apparently shield this area from the source of the aluminum oxide mud.

The existence of the Shadow Zone suggests another mechanism for producing near-field fallout, 'rainbird splash'. There are six rainbirds on the top of the MLP (fig. 3). These quench the heat generated during launch on the top of the MLP by spraying 400,000 gal/min over its surface. After lift-off, the vehicle drifts over the deck, its SRB exhaust plumes impinging on the MLP. Figures 4 through 6 show typical SRB plume impingement points at T + 4.65 sec, T + 5.10 sec, and T + 9.15 sec. The angle of impingement is nearly vertical, therefore, any rainbird water not vaporized or atomized would be splattered equally in all directions, hence, the symmetrical fallout pattern seen for STS-4 (no wind). For STS-5, however, there was a 9- to 10-knot easterly wind which blew the fallout pattern towards the west.

Rainbird splash appears to be the prodominate cause of fallout in the near-field area, excluding the area subjected to the SRB flame trench exhaust blast. If so, the near-field fallout at VAFB would be much less than at KSC because the VAFB Launch Mount does not incorporate a rainbird system, nor any deluge system which would have comparable effects. Differences between the two sites in meteorological conditions, terrain, and exhaust duct configurations make such a conclusion premature; however, the possibility justifies the 'wait and see' philosophy adapted at VAFB for washdown facility implementation.

To protect the many facilities and equipment in the VAFB launch complex (see fig. 7), a remote-controlled washdown system will be designed for all steel structures within 700 ft of the Launch Mount. Because of the uncertainty in predicting where the fallout will occur, the design will be implemented in two phases: Phase I will be constructed before the first VAFB launch and will include the Launch Mount, the Access Tower, and the structures within the north SRB exhaust duct pattern; Phase II will include all the other structures within the 700-ft radius, but will be implemented only if actual data show the need for additional systems. The STS-4 and STS-5 data support the 700-ft radius criteria.

The VAFB washdown systems are being designed to provide 0.3 gal/min ft^2 coverage for 10 min after each launch. The adequacy of these requirements was investigated during STS-5.

The objectives of the STS-5 Spray Tests were to evaluate the performance of fixed spray washdown systems as a function of the following:

1. Spray coverages varying from 0.1 gas/min ft^2 to 1.0 gal/min ft^2

2. Spray durations of 10 min or 30 min

3. Timeliness of washdown with some samples washed during launch or others 6 hrs after launch

4. Washdown properties of epoxy-polyurethane and chlorinated rubber coating systems

Two fixtures, one located near the culvert connecting the SRB flame trench and the northwest holding pond and the other located in a comparable position near the northeast holding pond, were used to hold the test samples. The northwest samples were washed during the launch at controlled flow rates and durations. The northeast samples were not washed until 7 hrs after the launch. The following test observations were made.

1. Timeliness of washdown - the samples washed during launch were washed relatively clean, whereas those washed postlaunch could only be cleaned slightly using water alone. These would come clean by wiping the surface with a damp cloth or by spraying with a detergent.

2. Degree of coverage - all the coverage rates tested were effective in cleaning the samples, with the higher rates being slightly more so. Most of the samples washed post-launch were not affected even at 1.0 gal/min ft^2 coverage.

3. Duration of during-launch washdown - there was no significant difference in cleanliness between the samples washed for 5 min and those washed for 30 min.

4. Coating systems - there was no significant difference in the washdown properties between the epoxy-polyurethane coating system and the chlorinated rubber coating system.

CONCLUSIONS

The near-field deposition measurements and the spray tests supported the washdown requirements levied on the VAFB washdown facility designs, but more data are desirable.

The rainbird splash theory requires further evaluation as does the effect of wind on near-field fallout. More extensive measurements will be taken on STS-6.

Finally, because the affinity of HCl gas for water may cause a during-launch washdown to generate more hydrochloric acid, an additional spray test will be conducted during STS-6. This test will evaluate whether delaying the washdown 15 min after launch will still give an effective washdown, and whether the pH of the runoff will be reduced.

STS-4 Acid Fallout - Near-Field Pattern

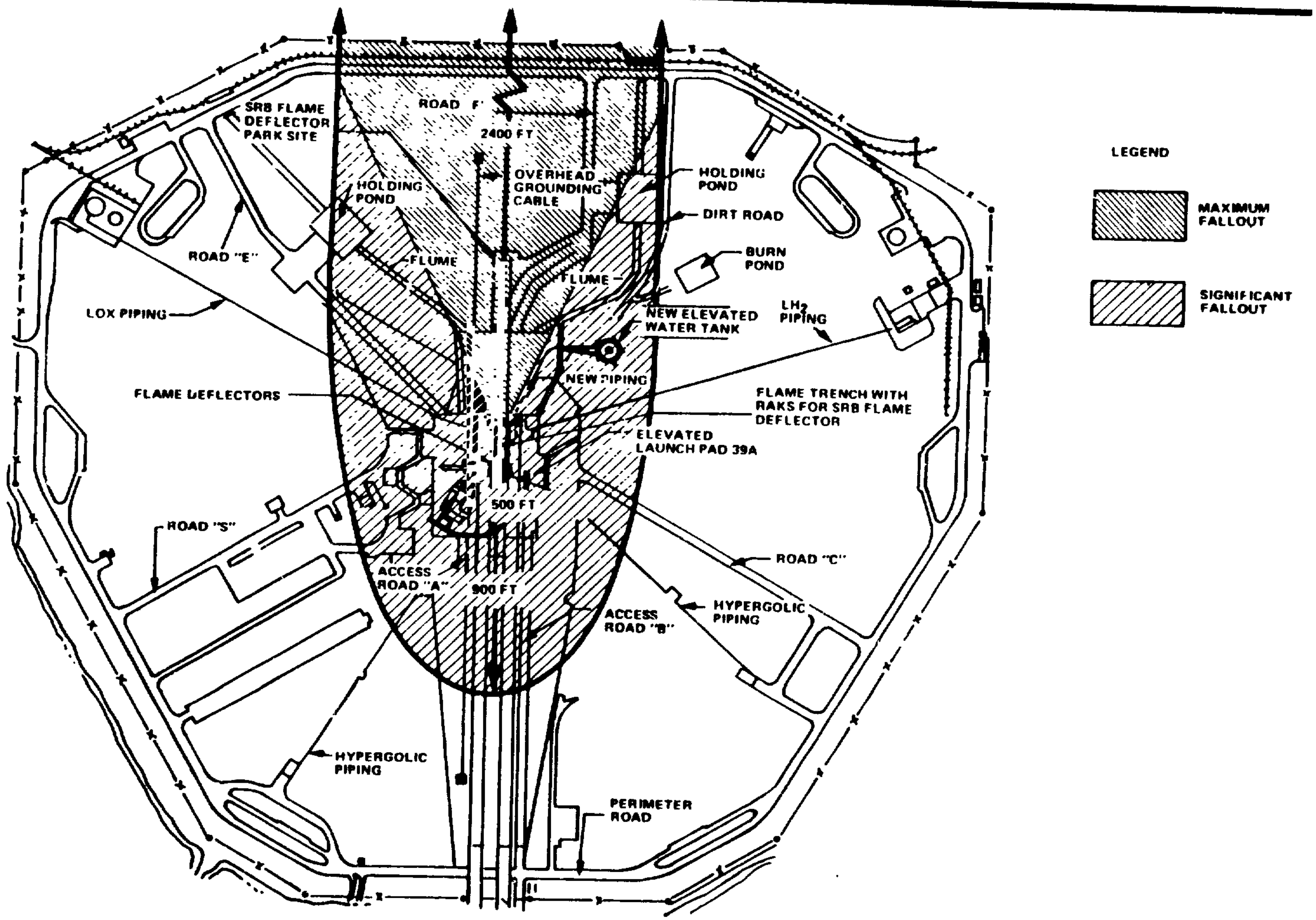

Figure 1.- STS-4 acid fallout - near-field pattern.

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STS-5 Near-Field Fallout

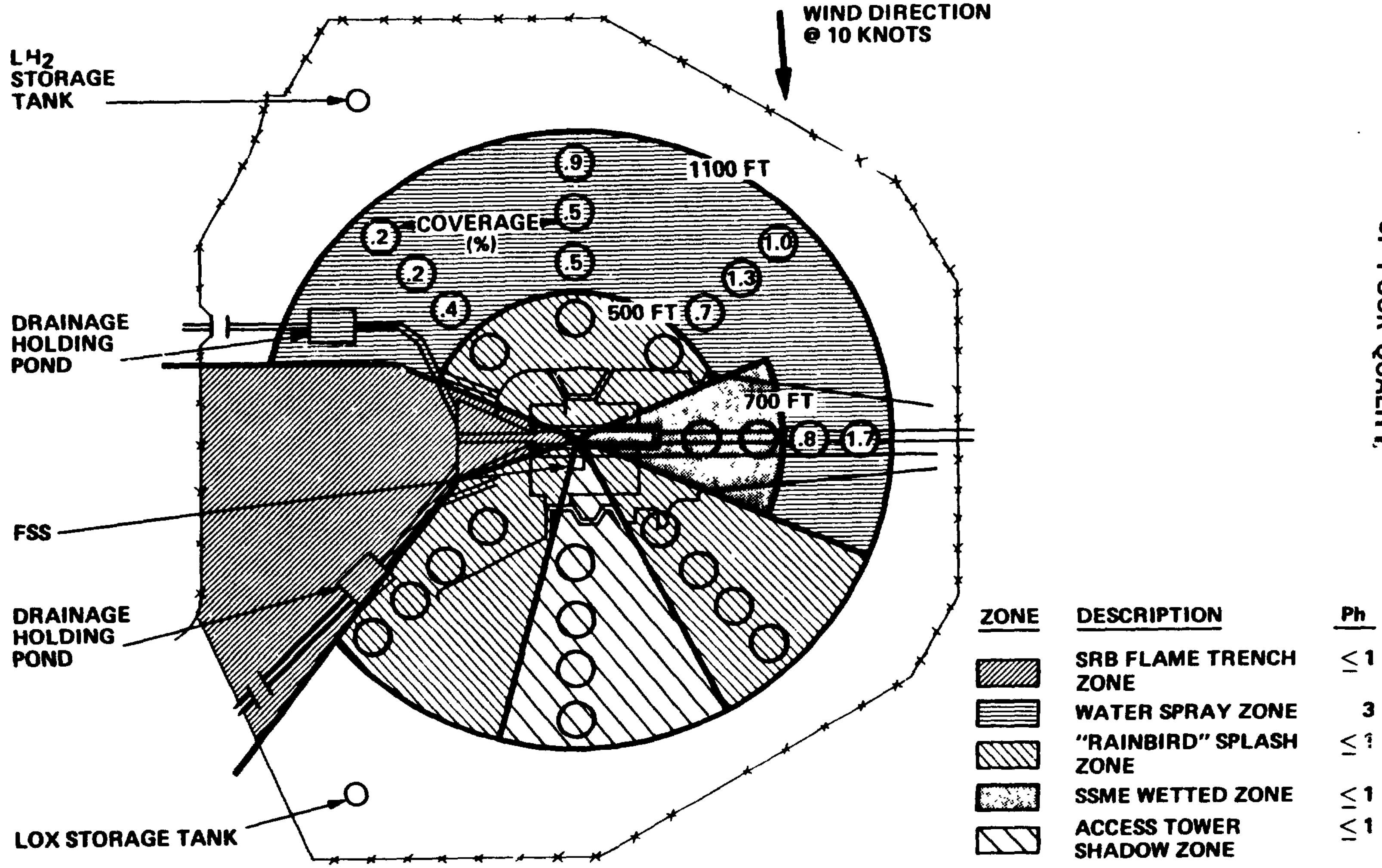


Figure 2.- STS-5 near-field fallout.

MLP-1 Static Pressures and OASPLS

STATIC PRESSURE PSI

KSRYP \ STS	1	2	3
002	–	+6	–
005	–	–	+7.5
008	–	-3.5	-5
011	+25	+12	–
014	+4	-3.5	+4
017	±3	-4	-4

OASPL dB

002	–	187.7	–
005	–	–	188
008	–	181.2	186
011	194	187.7	–
014	187.5	183.5	186
017	186.3	184.1	186.7

FIGURE COURTESY
OF KSC/DE

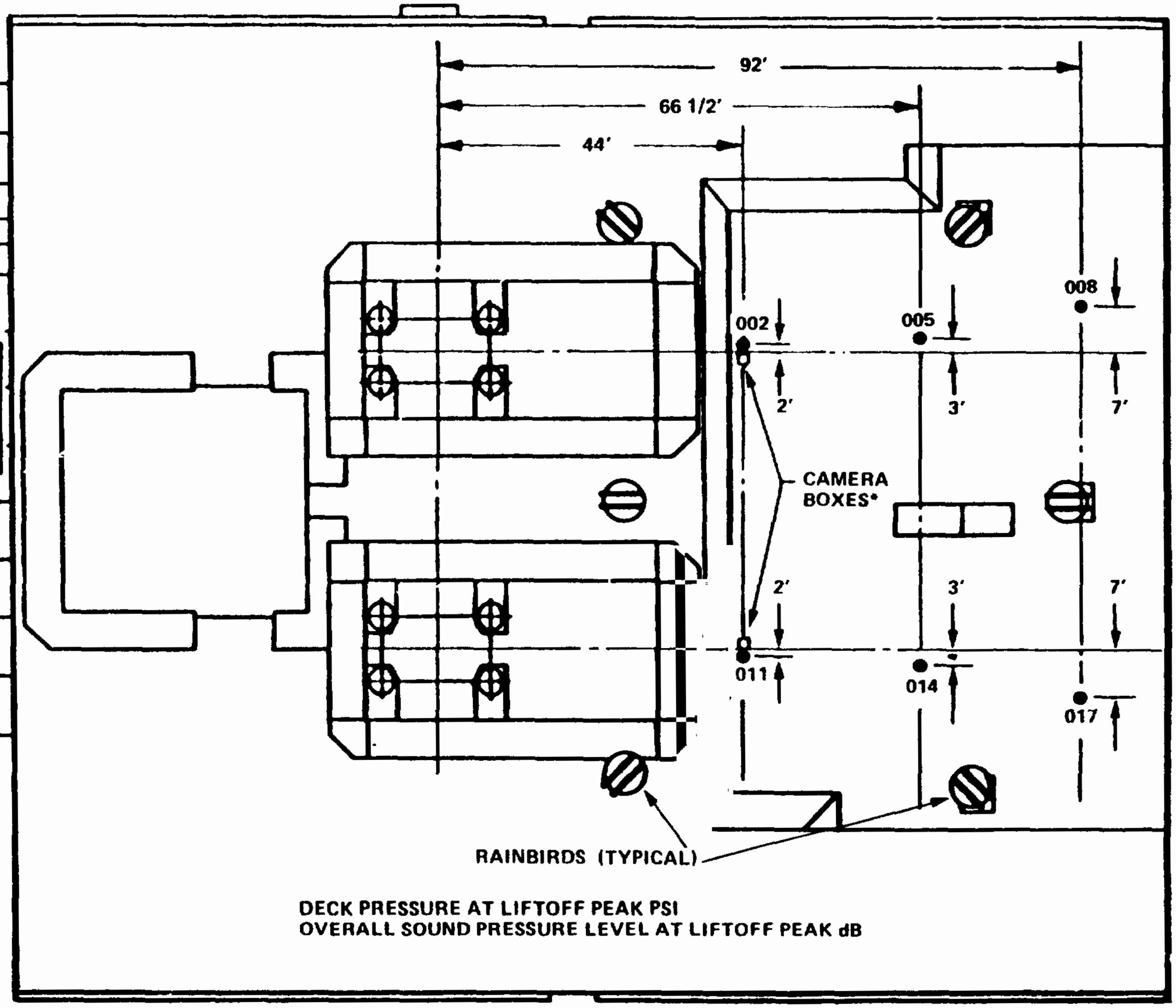


Figure 3.- Rainbird locations.

Shuttle Launch Induced Environment

Predicted MLP Design Criteria

GRAPHIC SCALE

5' 0' 5' 10' 15' 20' 25'

LOAD DATA

TIME: 4.65 SEC
HEIGHT: 125 FT ABOVE DECK "0"

ANNULUS NUMBER	CIRCLE RADIUS (FT)	AVERAGE PRESSURE (PSF)	AVERAGE PRESSURE (PSI)
1	2	13903	96.5
2	4	12463	86.5
3	6	9158	63.6
4	8	5320	36.9
5	10	2599	18.0
6	12	1426	10
7	16	706	4.9
8	20	518	3.6
9	28	93	.6

SRB EXHAUST LOAD AND FOOTPRINT ON MLP DECK
– NORMAL LAUNCH –

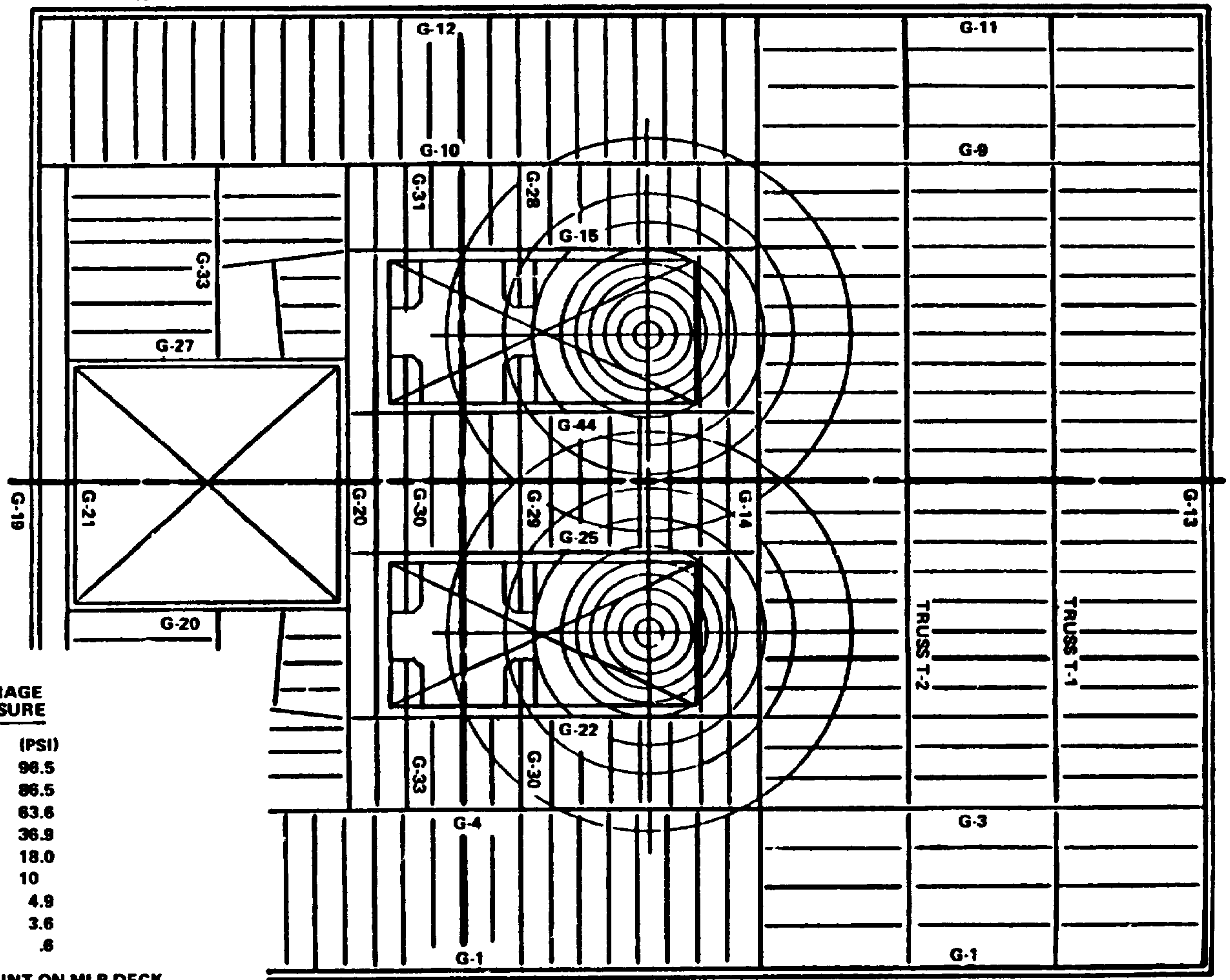


FIGURE COURTESY OF KSC/DE

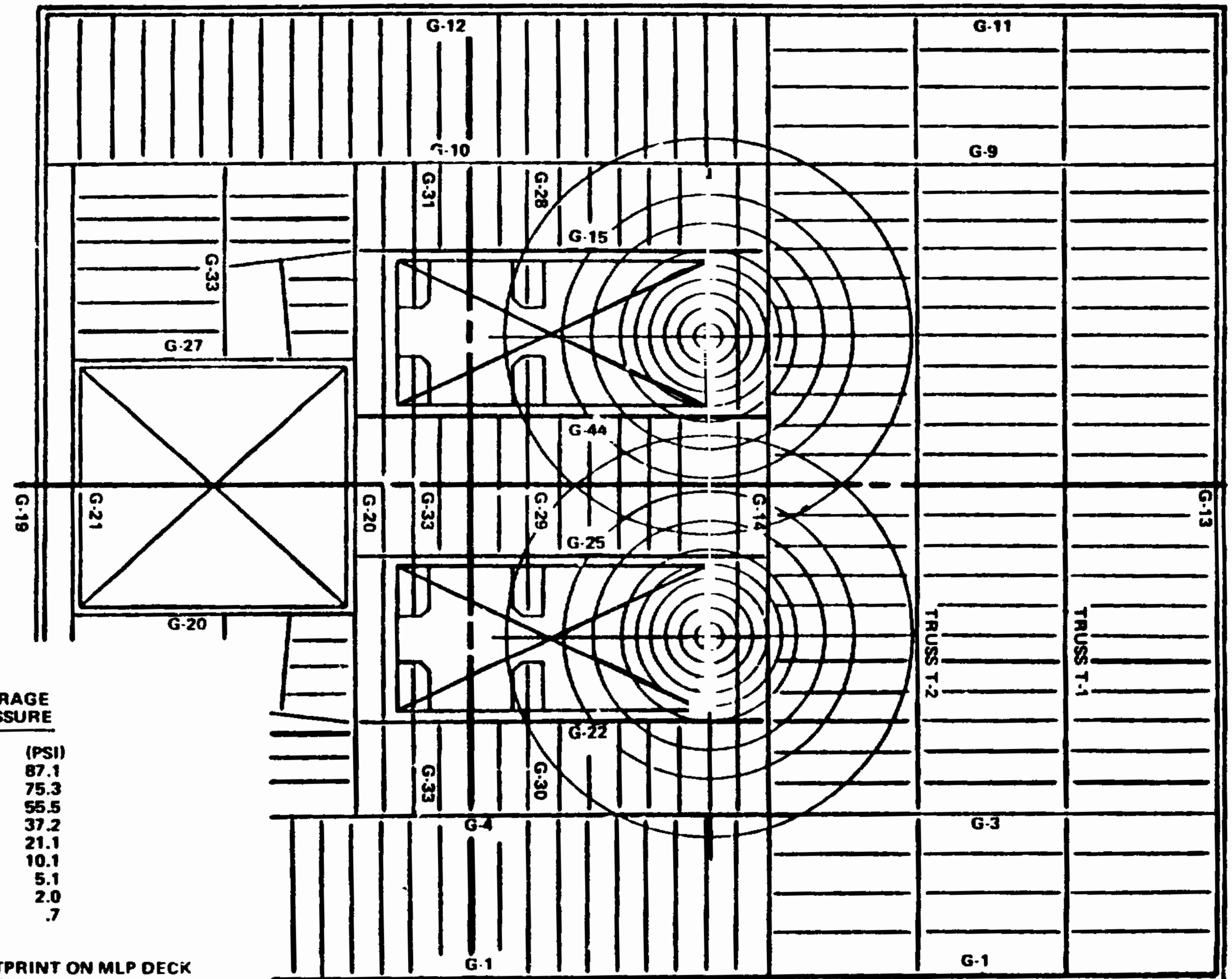
Figure 4.- SRB plume impingement at T = 4.65 sec.

Shuttle Launch Induced Environment

Predicted MLP Design Criteria

GRAPHIC SCALE

5' 0' 5' 10' 15' 20' 25'



LOAD DATA

TIME: 5.10 SEC
HEIGHT: 153 FT ABOVE DECK "0"

ANNULUS NUMBER	CIRCLE RADIUS (FT)	AVERAGE PRESSURE (PSF)	AVERAGE PRESSURE (PSI)
1	2	12546	87.1
2	4	10645	75.3
3	6	7993	55.5
4	8	5357	37.2
5	10	3043	21.1
6	12	1458	10.1
7	16	73C	5.1
8	20	292	2.0
9	28	103	.7

SRB EXHAUST LOAD AND FOOTPRINT ON MLP DECK
– NORMAL LAUNCH –

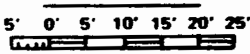
FIGURE COURTESY OF KSC/DE

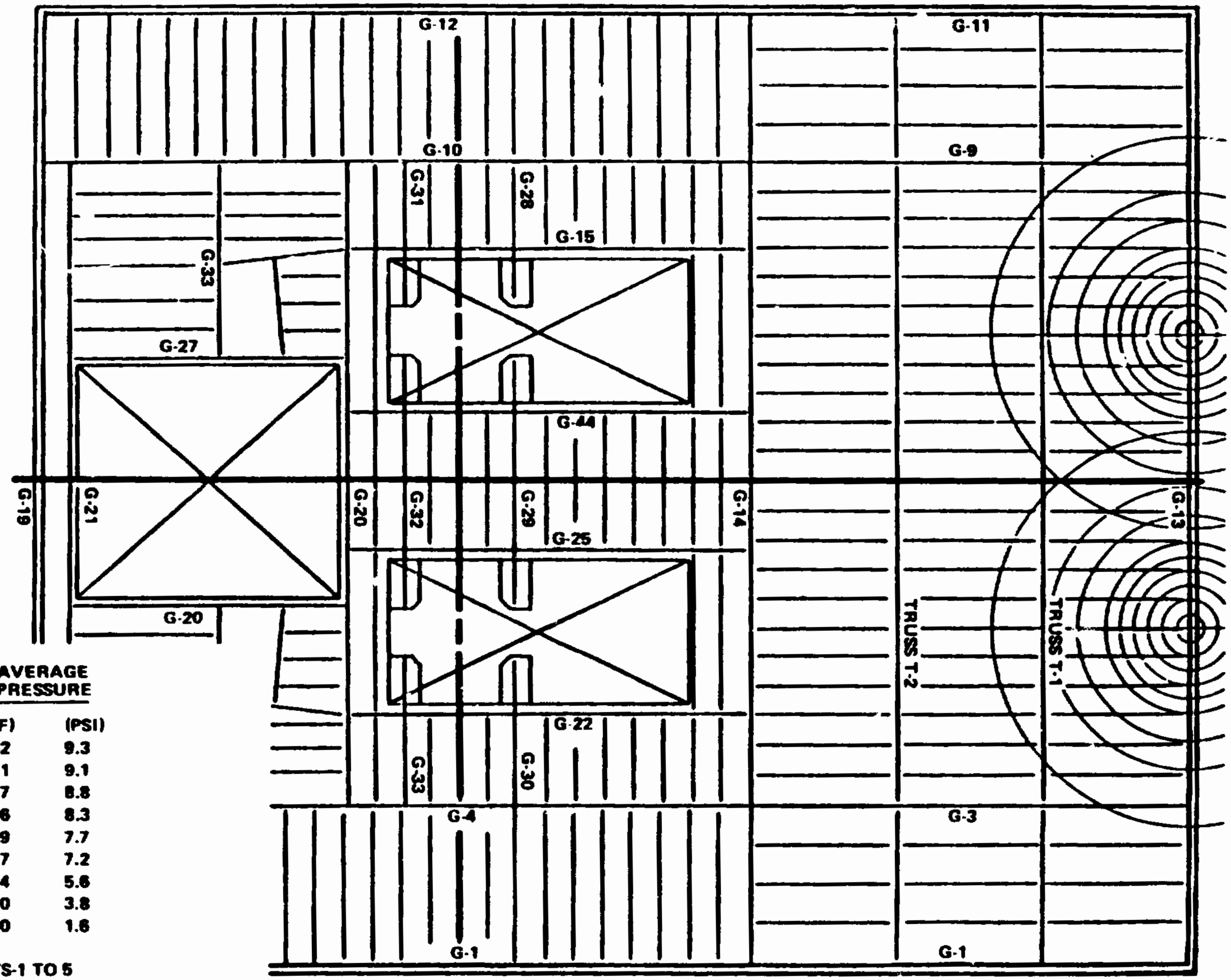
Figure 5.- SRB plume impingem nt at T = 5.1 sec.

Shuttle Launch Induced Environment

Predicted MLP Design Criteria

GRAPHIC SCALE





LOAD DATA

TIME: 9.15 SEC
HEIGHT: 535 FT ABOVE DECK "0"

ANNULUS NUMBER	CIRCLE RADIUS (FT)	AVERAGE PRESSURE (PSF)	(PSI)
1	2	1332	9.3
2	4	1311	9.1
3	6	1267	8.8
4	8	1196	8.3
5	10	1109	7.7
6	12	1037	7.2
7	16	814	5.6
8	20	540	3.8
9	28	230	1.6

ACTUAL LAUNCH DATA, STS-1 TO 5
MAX STATIC PRESSURE = 3 PSI (432 PSF)

SRB EXHAUST LOAD AND FOOTPRINT ON MLP DECK
– NORMAL LAUNCH –

FIGURE COURTESY OF KSC/DE

Figure 6.- SRB plume impingement at T = 9.15 sec.

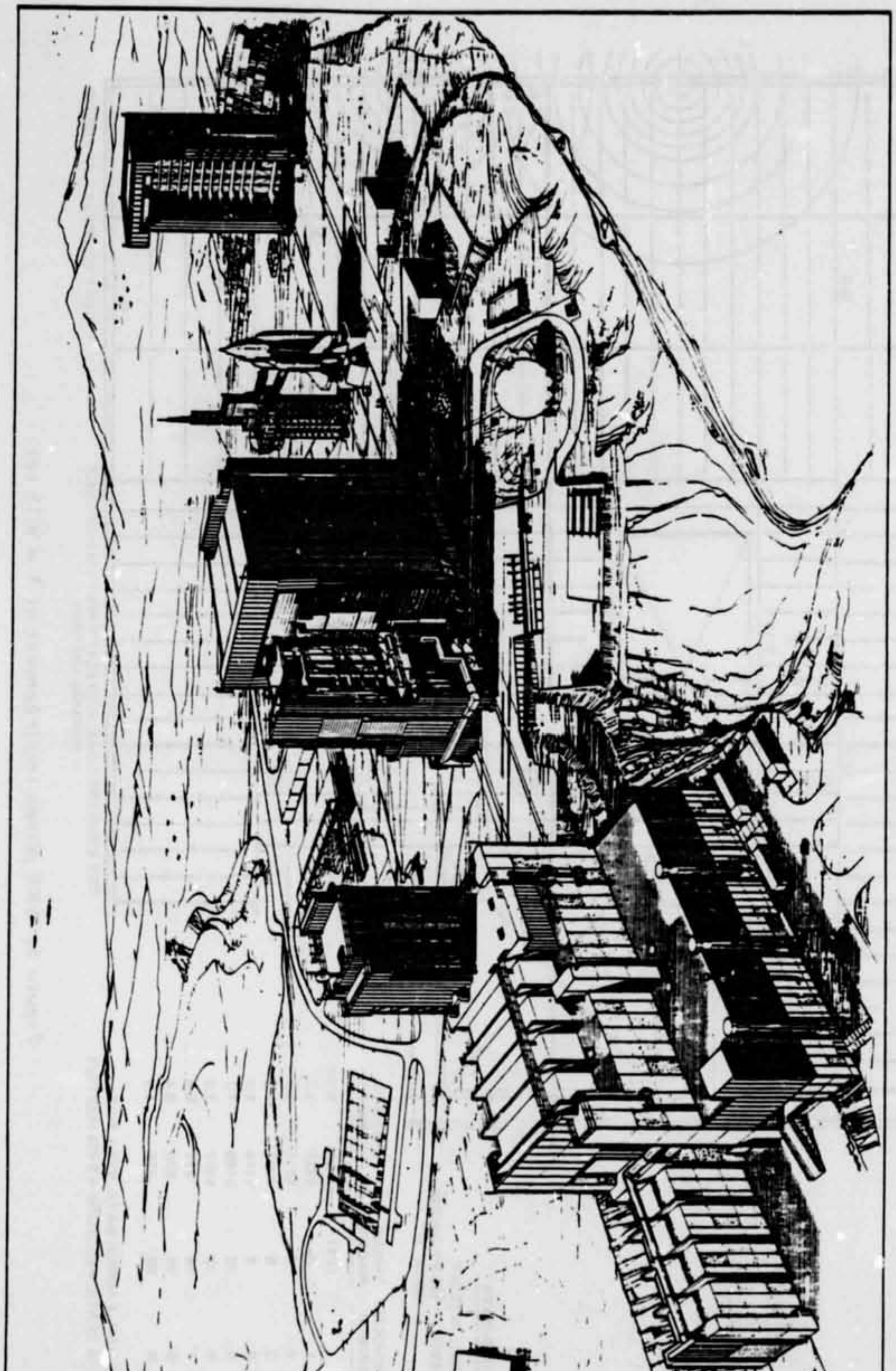


Figure 7.- Space Launch Complex-6 (Vandenberg Air Force Base).

STS-5 FISH KILL, KENNEDY SPACE CENTER, FLORIDA

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Brooks Air Force Base, Texas

ABSTRACT

Because fish kills were observed following previous Space Transport System (STS) launches, the U.S. Air Force Occupational and Environmental Health Laboratory was requested to conduct an onsite investigation of any possible fish kill associated with STS-5 on 11 November 1982. Due to the acuteness of the fish kills and close association with time of launch, STS exhaust products, such as HCl and/or aluminum oxide, were suspected as the cause. Other potential causes which were considered included diseases, parasites, mechanical interference with respiration, insufficient oxygen, trauma, temperature and pH changes, and exposure to other toxic substances. Water temperature and dissolved oxygen concentrations were found to be normal, both prelaunch and postlaunch. Water and sediment heavy metal analyses, both prelaunch and postlaunch, were unremarkable. A moderate parasite load was found in the fish population by histopathology, but not believed to be a contributing cause of death. The only other pathologic changes were limited to the gills. These changes, including swollen erythrocytes, epithelial and endothelial dilatation, and goblet cell prominence, were consistent with edematous change. In addition, postlaunch water pH was significantly lower than prelaunch. These impressions were confirmed by laboratory bioassay procedures. The conclusion was that the fish died from ionic imbalances and fatal anoxia, resulting from severe gill damage caused by a rapid decrease in the water pH. The change in water pH was a transitory phenomenon and not perceived to be a long-term environmental threat.

1. INTRODUCTION

Since fish kills were observed following previous Space Transport System (STS) launches, the U.S. Air Force (USAF) Occupational and Environmental Health Laboratory (OEHL) was requested to conduct an onsite investigation of any possible fish kill associated with STS-5 on 11 November 1982 at the John F. Kennedy Space Center (KSC). Due to the acuteness of the fish kills and close association with time of launch, STS launch exhaust products, such as HCl and/or aluminum oxide, were suspected as the cause. Other man-made and natural causes, however, could not be ruled out.

This report presents the possible causes of fish kills, the investigative procedures employed, and tests conducted before and after the launch of STS-5. It also presents the results obtained, observations made, a diagnosis of the problem, and recommendations concerning immediate and long-term environmental impact.

2. BACKGROUND

2.1 CAUSE OF FISH KILLS

Fish are easily stressed by environmental factors, either man-made or natural. These stresses, singly or in synergism, can be a direct or contributing cause of death. The various causes of fish kills include infectious diseases, parasites, mechanical interference with respiration, insufficient oxygen, trauma, exposure to toxic substances, and changes in water temperature and pH.

2.2 DISEASES AND PARASITES

Most fish, whether in the wild or reared in captivity, harbor parasites. Likewise, all fish are subject to naturally occurring diseases. Death from diseases and parasites in fish occurs continually, but generally goes unnoticed because only a few individuals die in a given area at one particular time. Occasionally, however, epizootic conditions occur in large concentrated populations and result in many deaths in a short period of time. Man can sometimes trigger an epizootic kill by accidental introduction of pathogens into bodies of water where they are not normally found, or by imposing stress factors that lessen or eliminate natural tolerance or immunity to existing pathogens.

2.3 MECHANICAL INTERFERENCE WITH RESPIRATION

Materials, such as silt and petroleum compounds, or even depositions of insoluble metal compounds, such as aluminum oxides, can interfere with normal respiratory functions if introduced in sufficient quantity to coat gill surfaces and, therefore, prevent oxygen uptake.

2.4 INSUFFICIENT OXYGEN

At least four to six parts per million (ppm) of dissolved oxygen (DO) in water is necessary to support a fish population. Increased biochemical oxygen demand resulting from decomposing organic materials will decrease DO. Likewise, increased chemical oxygen demand resulting from spontaneous, oxygen-requiring, chemical reactions will lower DO. If the DO level falls below that required to support fish life, a fish kill occurs.

2.5 TRAUMA

Traumatic causes of fish kills are usually catastrophic events such as hurricanes, tornadoes, and earthquakes. However, in small bodies of water, physical injury and subsequent death of fish may result from such things as dumping of solid wastes, construction, explosions, and missile blasts.

2.6 EXPOSURE TO TOXIC SUBSTANCES

Direct introduction of toxic substances, in sufficient concentration, will cause an immediate or acute kill. However, death can also occur as a result of chronic exposure to lower concentrations of the given toxin over a period of days, weeks, or even months. This dilemma of acute versus chronic toxicity can be further complicated by seasonal mixing and periods of water turnover. In this case, sublethal amounts of a toxin may enter the water and settle out in the bottom sediment, only to be freed at a later time in lethal amounts during mixing periods.

2.7 TEMPERATURE AND pH CHANGES

Some fish species can tolerate wide ranges of water temperature and pH. Other species can survive only within very narrow ranges of these environmental factors. Regardless of tolerance, however, most species are adversely affected by sudden, drastic changes in water temperature or pH.

2.8 FISH KILLS ASSOCIATED WITH THE STS

Fish kills associated with the STS launches have been acute kills observed shortly after the launch. These kills, according to the definition in Standard Methods (ref. 1), can be characterized as moderate kills (100 to 1,000 dead or dying fish of various species within 1 km to 2 km of stream or equivalent area of a lake or estuary). These kills at KSC have been limited to small species (<5 cm length) in a brackish lagoon immediately north of Launch Complex Pad-39A in an area impacted by the solid rocket booster (SRB) exhaust plume (fig. 2). The objectives of the fish kill investigation before and after the launch of STS-5 were to rule out natural environmental stresses as the cause, identify a specific man-made STS-related cause, and assess the impact of that event on the environment.

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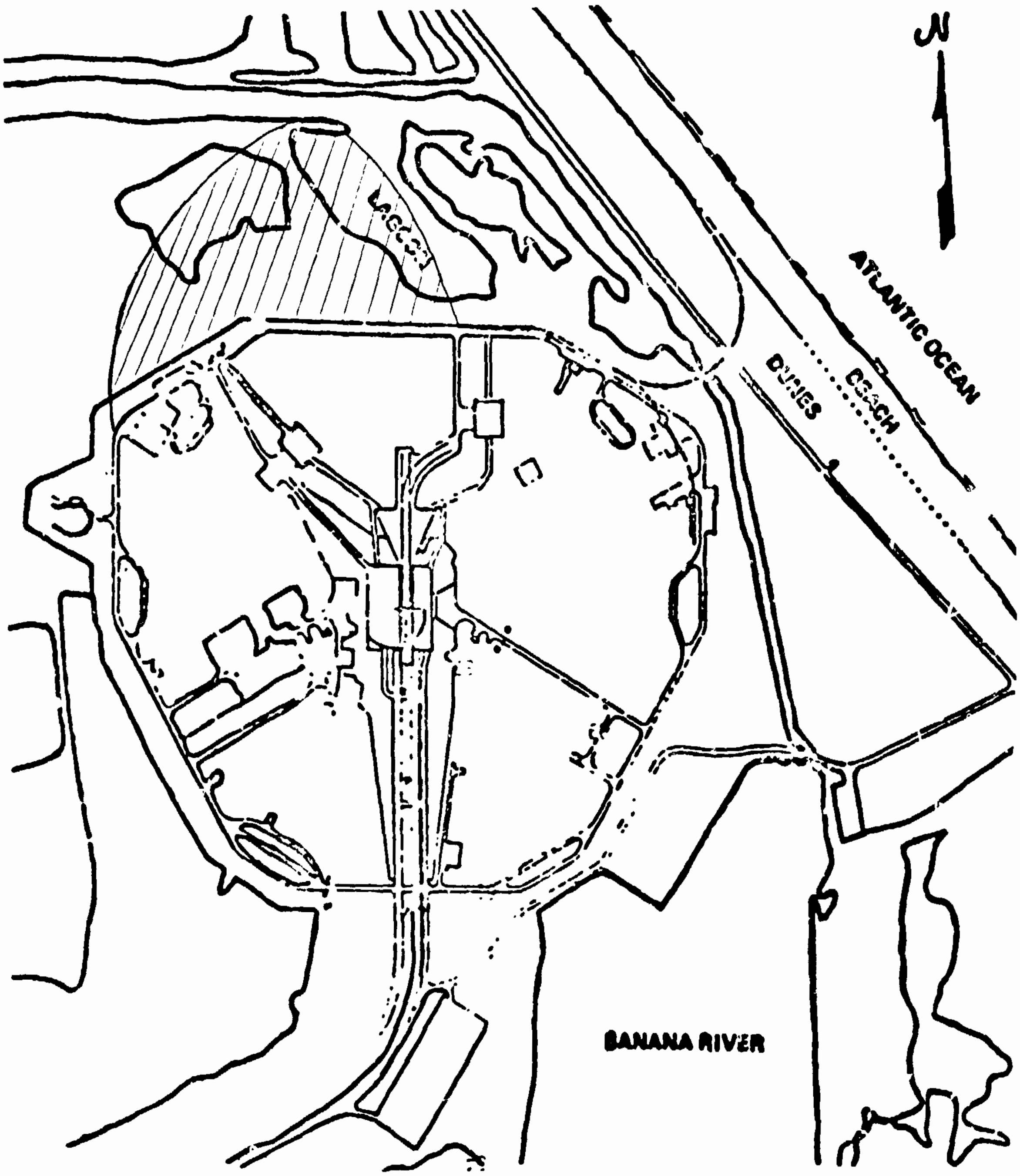

Figure 2-1.- Launch Complex Pad-39A and brackish lagoon to its north in area impacted by the SRB exhaust plume.

3. MATERIALS AND METHODS

3.1 WATER AND SEDIMENT SAMPLING

One-liter water samples were collected, both prelaunch and postlaunch, at three sites in the lagoon (fig. 3-1, Sites A, B, and C) in accordance with the USAF OEHL Water Sampling Guide (ref. 2). Temperature, pH, and DO were measured onsite using a YSI 51-B DO Meter (Yellow Springs Instrument Co., Yellow Springs, Ohio) and a Fisher Accument pH Mini-Meter (Fisher Scientific, Pittsburg, Pa). Culturette swab subsamples were collected from each sample using a Culture Collection and Transport System (Precision Dynamics Corp., Burbank, Calif.) and submitted to the Epidemiology Division, USAF School of Aerospace Medicine (USAFSAM) for bacterial culture and identification. The one-liter water samples were then preserved with nitric acid and submitted to the Analytical Services Division, USAF OEHL, for heavy metal analysis. Lagoon bottom sediment samples were also collected, both prelaunch and postlaunch, at the same sites and submitted for heavy metal analysis. An additional water sample was collected postlaunch at the site of eventual fish kill (fig. 3-1, Site D) and tested as described above. Temperature, pH, and DO were also determined for the covered and uncovered bucket water, as described below.

3.2 SPECIMEN COLLECTION

Representative live specimens of native fish species were collected from the lagoon (fig. 3-1., Site C) on the day prior to launch using a seine net. These specimens were identified as Cyprinodon variegatus (sheepshead minnow), Gambusia affinis (mosquitofish), Peocilia latipinna (sailfin molly), and Lucania parva. Five specimens of each species (euthanized with halothane in water) were necropsied as controls, and gross appearance was observed and recorded on 35-mm color slides. In addition, two blood smears were made from each specimen and observed for dyscrasias. The blood smears were fixed with methanol. The fish were preserved with formalin and submitted to the Veterinary Sciences Division, USAFSAM, for histopathologic examination. Five live specimens of each of the three predominant species (minnow, mosquitofish, molly) were placed in an uncovered 20-liter bucket of brackish water adjacent to the lagoon (fig. 3-1, Site E) on the day prior to launch. Five of each species were also placed in a covered bucket at the same site. At approximately 1 1/2 hrs postlaunch, a fish kill was observed in the lagoon (fig. 3-1, Site D). Two mosquitofish, one minnow, one Anchova mitchilli (bay anchovy), and one Microgobius gulosus were collected at the site. These fish kill specimens, as well as the fish from the buckets, were necropsied postlaunch and subjected to the same examinations as described above. Another 100+ dead fish were discovered the following day at Site F (fig. 3-1), in shallow water, but were not examined due to postmortem decomposition.

3.3 BIOASSAY

In an attempt to confirm, in the laboratory, the suspected cause of the fish kill in the lagoon, a bioassay was conducted with Pimephales promelas (fathead minnow). Five fish were placed in a 500 ml beaker of deionized distilled water adjusted to pH 2.4 with HCl. Another five fish were sacrificed as controls with halothane in water. All fish, following death, were necropsied, preserved in formalin, and submitted for histopathology.

3.4 HISTOPATHOLOGY

All fish specimens were preserved in 10-percent buffered formalin. The lagoon fish killed by the STS-5 launch and the bucket fish were not preserved in formalin until L + 3:45 hrs to 5:15 hrs. The control fish and the fish used in the bioassay were immediately placed in formalin after their deaths. Whole body decalcification and tissue processing were done using standard techniques. The paraffin blocks were cut at 4 µm and stained with hematoxylin and eosin. Special stains and electron microscopy were also done using standard techniques.

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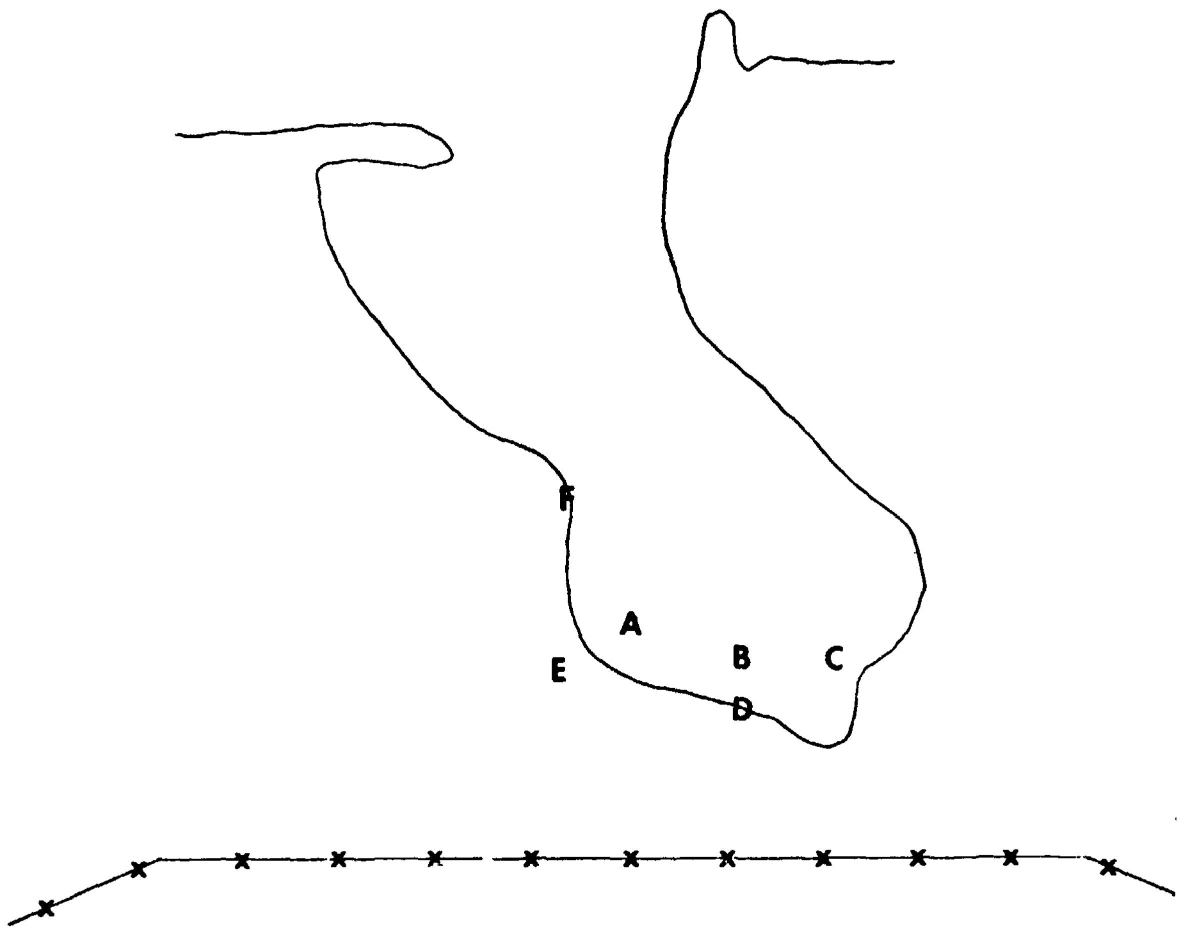

Figure 3-1.- Lagoon north of Launch Complex Pad-39A. Sites A, B, and C are primary STS-5 water and sediment sampling sites; Site D is the fish kill site; Site E is the site of covered and uncovered bucket placement; and Site F is an additional fish kill site.

4. RESULTS AND DISCUSSION

4.1 WATER SAMPLES

Prelaunch water samples were collected on 10 November 1982, at 1010 hrs, under clear skies, at 26°C ambient temperature, and northeast winds at 15 mi/hr to 20 mi/hr. Postlaunch samples were collected on 11 November 1982, at 0853 hours (L + 1:34 hr), under clear skies, at 21°C ambient temperature, east-northeast winds at 6 mi/hr to 10 mi/hr. Water depths at the sampling sites were: Site A, 45 cm; Site B, 45-50 cm; Site C, 30 cm; Site D, 7-10 cm.

4.1.1 TEMPERATURE, pH, AND DO

The results of the onsite measurements of water temperature, pH, and DO are presented in table 4-1. No significant differences were noted:

a. There were no significant temperature differences in the various samples, and those temperatures were compatible with fish survival. These data disprove the theory that the fish kills could be caused by excessive temperatures generated during the launch.

b. There were also no significant DO differences in the various samples, and those DO concentrations (6.5-7.5 ppm) were above the minimum (4.0-6.0 ppm) necessary to support fish life.

c. There were no significant prelaunch and postlaunch pH differences at the three primary lagoon sampling sites (fig. 3-1 in section 3 Sites A, B, and C). At the fish kill area along the lagoon edge, water pH was notably lower (pH 6.2) than the normal range (pH 8.0-8.5) measured in this lagoon. In addition, the water pH in the uncovered bucket (pH 2.4) was greatly reduced from that in the covered bucket (pH 7.2). These data indicate that a significant acid deposition is resulting from the SRB exhaust. The deep water areas are probably resistant to this acid influence due to the inherent dilution effect of a large water volume combined with natural wave action mixing. The shallow water of the grass-protected lagoon edge, however, probably experiences a sudden and drastic reduction in pH, similar to that measured in the uncovered bucket. This sudden and drastic pH change would be sufficient in itself to cause an acute fish kill.

4.1.2 HEAVY METALS

The lagoon water samples were analyzed for Al, Fe, Cd, Pb, and Mn. The concentrations of these metals reported to be toxic to fish (ref. 3) are as follows:

a. Al - 5,000 µg/l (dissolved Al in acidic water)

b. Fe - 900 µg/l at pH 6.5-7.5; >1900 µg/l at < pH 6.5

c. Cd - 4,000-20,000 µg/l (dissolved Cd)

d. Pb - 300 µg/l (dissolved Pb in acidic water)

e. Mn - 0.1-1.5 g/l

The results of the [illegible] analysis for heavy metals in the [illegible]unch and postlaunch lagoon samples from Sites A, B, and C (fig. 3-1) are presented in table 4-2. The two predominant metals present, Al and Fe, range from 160-830 µg/l and 100-360 µg/l, respectively. Statistical analysis of that data is presented in table 4-2. There was no significant difference between prelaunch and postlaunch means. All of the metals analyzed were present in concentrations far below those reported to be toxic in fish.

The Al and Fe concentrations in the water sample collected from the fish kill site (Site D) were 1980 µg/l and 803 µg/l, respectively. Although these levels are also below toxicity levels, they are much higher than deepwater site concentrations. Statistical validity, of course, cannot be determined on a sample size of one. However, in view of expected mixing effects between launch and collection, it would not be unreasonable to infer that this higher trend indicates a near-toxic or toxic concentration of Al and/or Fe may have existed in the grassy-area shallow water immediately postlaunch. On the other hand, it should be noted that reported toxic concentrations of metals usually refer to concentrations of soluble metals. The analysis performed on this sample measured insoluble as well as soluble Al and Fe. The Al increase, for example, is at least partially attributable to the expected deposition of insoluble Al oxides present in the SRB exhaust plume. Furthermore, an independent analysis of water in the closed and open buckets, postlaunch, reveals < 200 and 1300 µg/l Al and 200 and 1600 µg/l Fe, respectively. These 'worst case' data support the latter theory that soluble heavy metal concentrations do not reach high enough levels in the lagoon, postlaunch, to cause acute death in fish.

4.1.3 BACTERIAL CULTURES

Results of the lagoon water bacterial cultures are shown in table 4-3. All of the organisms cultured are known to occur widely in water. None of these organisms are reported pathogens in fish (ref. 4). Therefore, water culture results do not support the presence of an infectious disease as the cause of death.

4.2 SEDIMENT SAMPLES

The results of the lagoon bottom sediment sample analyses for heavy metals are reported in table 4-4. The results of these analyses are unremarkable and do not support the theory of heavy metal intoxication as the cause of death.

4.3 FISH PATHOLOGY

4.3.1 GROSS PATHOLOGY

The external pathology in the fish collected at the launch site was difficult to evaluate with assurance due to the postmortem decomposition. The impression was that there was less redness in the gills of the control fish examined prior to the launch than in the killed lagoon fish examined after launch. The external body pigmentation and internal organs of the killed fish were perceived to be lighter in color than those of the controls. The fish in the bioassay had marked differences in the gill color between the test and controls. The gills of the test fish were light red with occasional foci of dark reddness, and the fine gill structure was discernible due to loss of the protective mucous layer (fig. 4-1). The epidermal pigmentation and internal organ colors were not remarkably different in the test or control bioassay fish.

4.3.2 MICROSCOPIC PATHOLOGY

The morphologic differences between controls and fish killed by the STS-5 launch were difficult to describe with assurance because of postmortem decomposition. The morphologic impression of the gills was that there was marked tissue separation by clear spaces consistent with edematous change. Also, that gill epithelium or endothelium were markedly dilated, and that the goblet cells were prominent. The goblet cells in the pharyngeal epithelium were also considered to be enlarged. The erythrocytes in the lamellar capillaries were considered to be markedly swollen. Moderate swelling of erythrocytes were recognized in capillaries at the base of lamellae and deep within the gill filaments. These changes collectively increased the width of lamellae approximately five to ten times. The morphologic examination of tissues from test and control fish used in the bioassay confirmed these impressions with marked differences between test and control fish (figs. 4-2 through 4-5). These changes were further documented with scanning and transmission electron microscopy.

The scanning electron microscopic examination of control gills showed smooth exterior mucous surfaces which covered and concealed the fine clumps of the mucous coating, and the gill structure was easily visualized (figs. 4-6 and 4-7). The test gill lamellae, unlike the control gill lamellae, had marked swelling of cells which extended above the lamellar surface (figs. 4-8 and 4-9).

The transmission electron photographs of the control gill lamellae showed essentially normal cellular architecture (figs. 4-10 and 4-11). The photograph of the test gills illustrated the marked morphologic alteration in the cells. The major change was the marked distention of cell cytoplasms, organelles, nuclei, erythrocytes, and endothelial and epithelial cells (figs. 4-12 and 4-13). Edematous change was also recognized.

Fish examined from the launch site and bioassay had moderate trematode and protozoal infestations (figs. 4-14 and 4-15). Parasites occurred in almost all fish populations examined. The parasitic lesions recognized in both the lagoon and laboratory bioassay fish were an incidental and expected finding. They did not have any significant effect on the pathogenesis of the fish kill.

No other remarkable histopathology was recognized in the fish.

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TABLE 4-1.- ONSITE MEASUREMENTS OF WATER TEMPERATURE, pH, AND DO

Parameters	Site A		Site B		Site C		Site D	
	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch
pH	8.0	8.0	8.0	8.5	8.1	8.3	--	6.2
DO, ppm	7.5	7.2	7.4	6.6	7.4	6.9	--	7.4
Temperature, °C	20.5	21.0	21.0	20.0	21.0	21.0	--	21.0

TABLE 4-2.- HEAVY METAL CONCENTRATIONS IN LAGOON WATER SAMPLES

Location	Al, μg/l		Fe, μg/l		Cd, μg/l		Pb, μg/l		Mn, μg/l	
	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch
Site A	830	830	202	100	<10	58	<50	<50	<50	<50
Site B	160	760	200	116	10	<10	<50	<50	<50	<50
Site C	180	320	223	360	<10	<10	<50	<50	<50	<50
Mean[a]										
	390	637	208	192						
± Standard error of the mean (S.E.)										
	(269)	(195)	(9)	(103)						

[a] No significance.

TABLE 4-3.- LAGOON WATER BACTERIAL CULTURE IDENTIFICATION

Location	Bacteria present	
	Prelaunch	Postlaunch
Site A	No growth	*Aeromonas (Vibrio) poteolytica* *Acinetobacter calcoaceticus var. Lwoffi* *Pseudomonas sutida*
Site B	*Acinetobacter calcoaceticus var. Lwoffi* *Aeromonas Hydrophilia*	No growth
Site C	*Pseudomonas maltophilia* *Pseudomonas sp.*	*Bacillus sumilus* *Pseudomonas sp.* *Staphlococcus epidermidis*

TABLE 4-4.- HEAVY METAL CONCENTRATIONS IN LAGOON SEDIMENT SAMPLES

Metal	Site A		Site B		Site C	
	Pre-launch	Post-launch	Pre-launch	Post-launch	Pre-launch	Post-launch
Al, µg/l	242.5	80.1	85.6	59.1	115.7	57.3
Fe, µg/l	322.8	96.8	86.0	75.3	130.2	59.2
Cd, µg/l	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pb, µg/l	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Mn, µg/l	1.9	1.1	0.8	0.8	1.0	0.7
Ni, µg/l	1.5	0.2	0.2	<0.1	0.2	<0.1
Si, µg/l	25.0	32.5	60.0	37.5	42.5	35.0

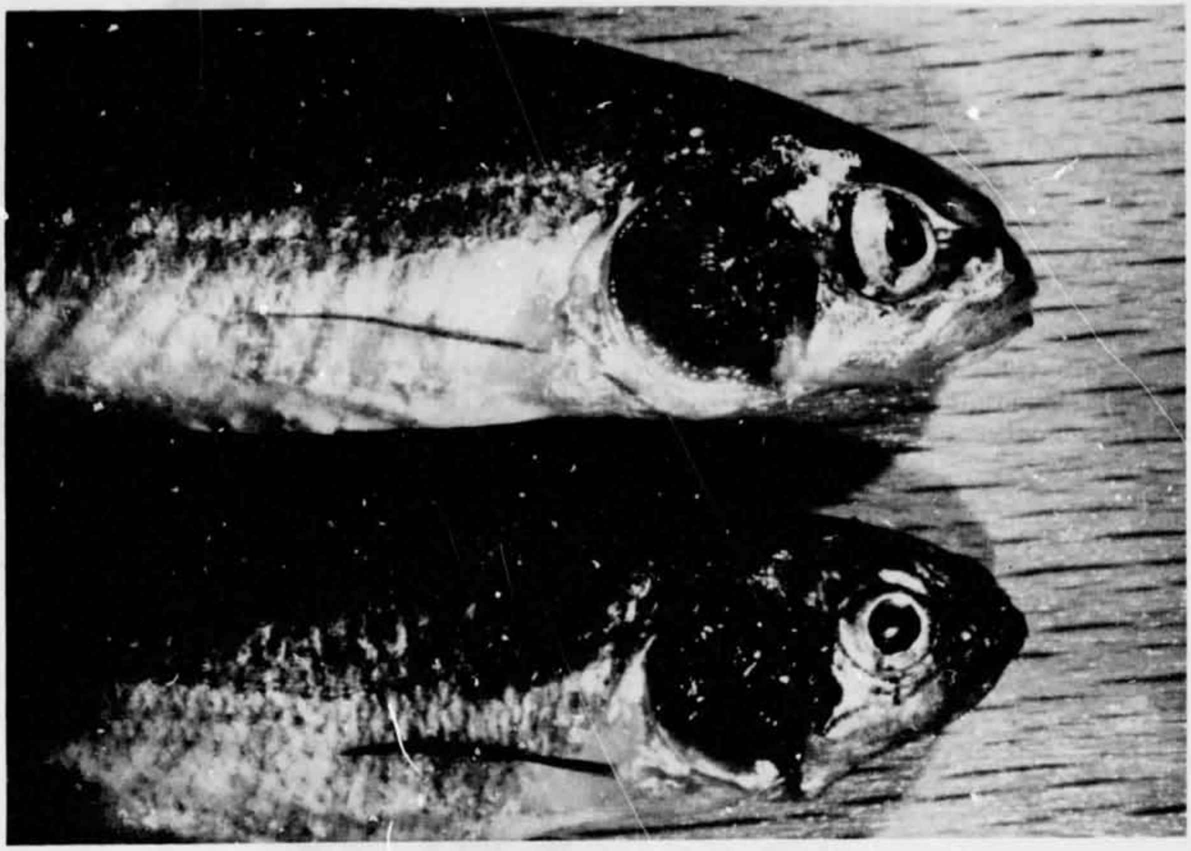

Figure 4-1.- The gills of the bioassay test fish (pH 2.4, top) are paler than the gills of the control fish (pH 8.4, bottom). The gill structure of the test fish is very evident due to loss of the mucous coating of the gill.

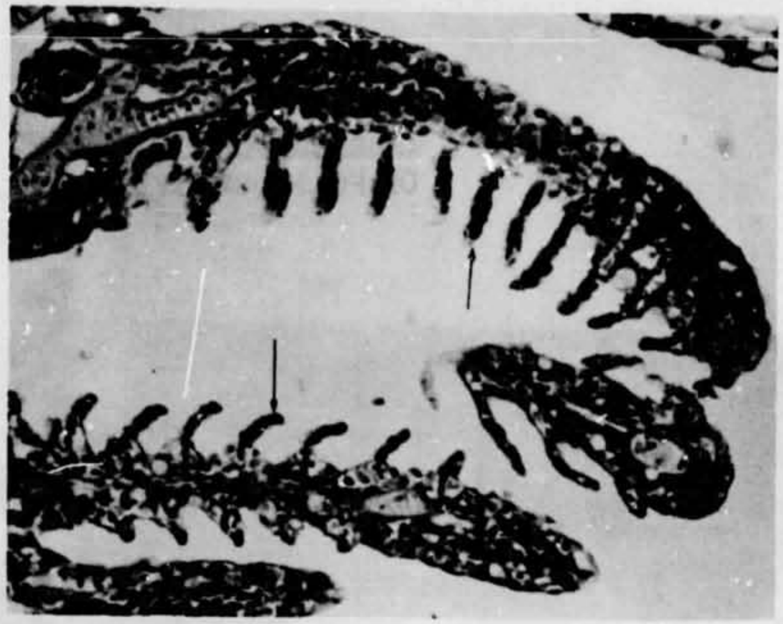

Figure 4-2.- The gill lamellae (arrows) of a bioassay control fish (pH 8.4) are delicate with inconspicuous goblet cells, intact erythrocytes, and normal epithelial and endothelial cells. H&E. 310X.

Figure 4-3.- Gill lamellae (arrows) from a bioassay test fish (pH 2.4) with prominent goblet cells (g), swollen erythrocytes, and ballooned epithelial and endothelial cells. Note the increased width of the gill lamellae. H&E. 520X.

Figure 4-4.- Pharyngeal epithelium (E) from a bioassay control fish (pH 8.4). Note the relatively small size and lack of prominence of the goblet cells (g). H&E. 490X.

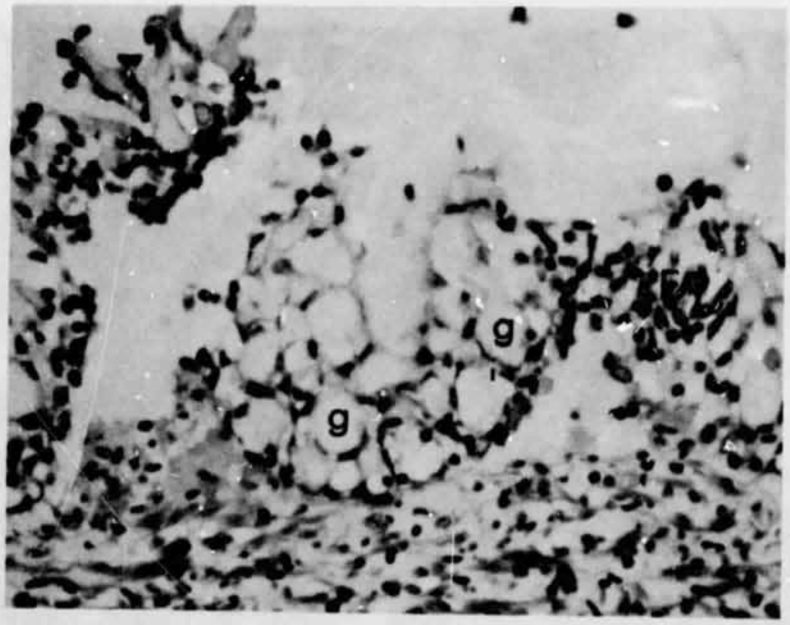

Figure 4-5.- Pharyngeal epithelium (E) from a bioassay test fish (pH 2.4). Note the prominent, large goblet cells (g). H&E. 490X.

Figure 4-6.- This scanning electron photograph of the gill of a bioassay control fish (pH 8.4) demonstrates the intact mucous protective layer (M) which masks the fine morphology of the gill lamellae (g). 160X.

Figure 4-7.- This scanning electron photograph demonstrates the normal gill lamellae (L) without the protective mucous layer. Note the lack of swollen epithelial cells (pH 8.4). 1400X.

Figure 4-8.- This scanning electron photograph of the gill of a bioassay test fish (pH 2.4) demonstrates the loss of the mucous protective layer and reveals the fine structure of the gill lamellae (L). 120X.

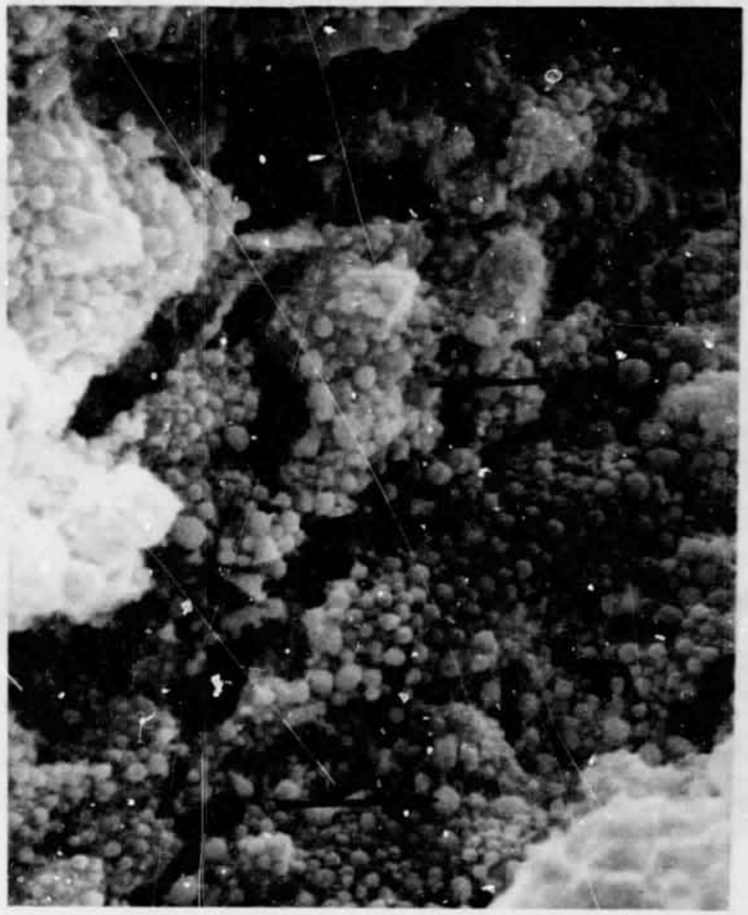

Figure 4-9.- This scanning electron photograph demonstrates the swollen cells (arrows) of the unprotected gill lamellae of a bioassay test fish (pH 2.4). 1600X.

Figure 4-10.- Transmission electron photograph of gill lamellae with normal cells and cell configurations. Note erythrocyte (E), endothelial cell (arrows), epithelial cell (c), and capillary lumen (C). 3600X.

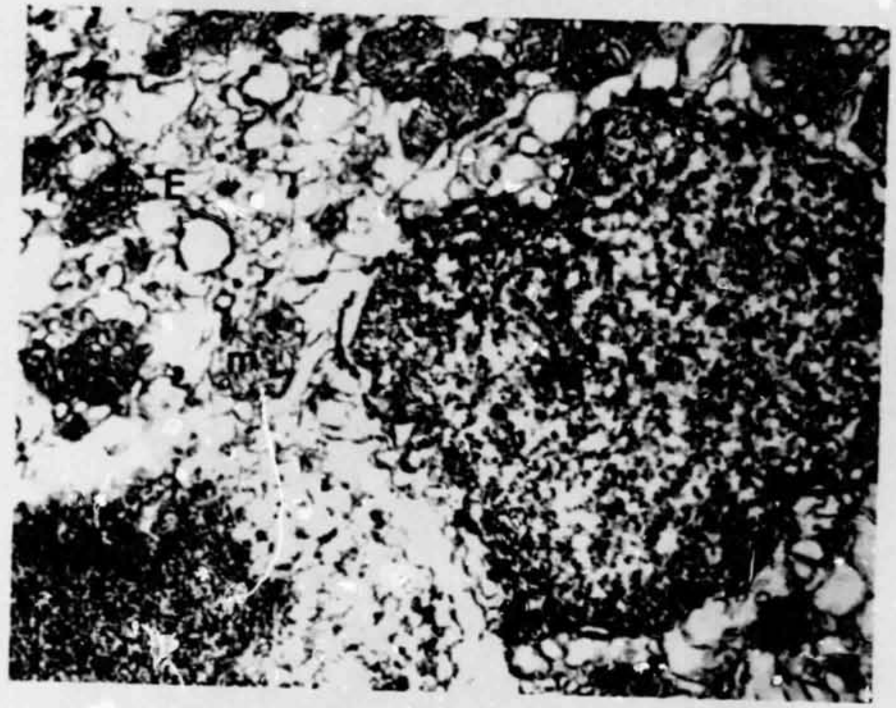

Figure 4-11.- Transmission electron photograph of typical normal cell morphology. Note nucleus (N), mitochondria (m), and endoplasmic reticulum (E). 2400X.

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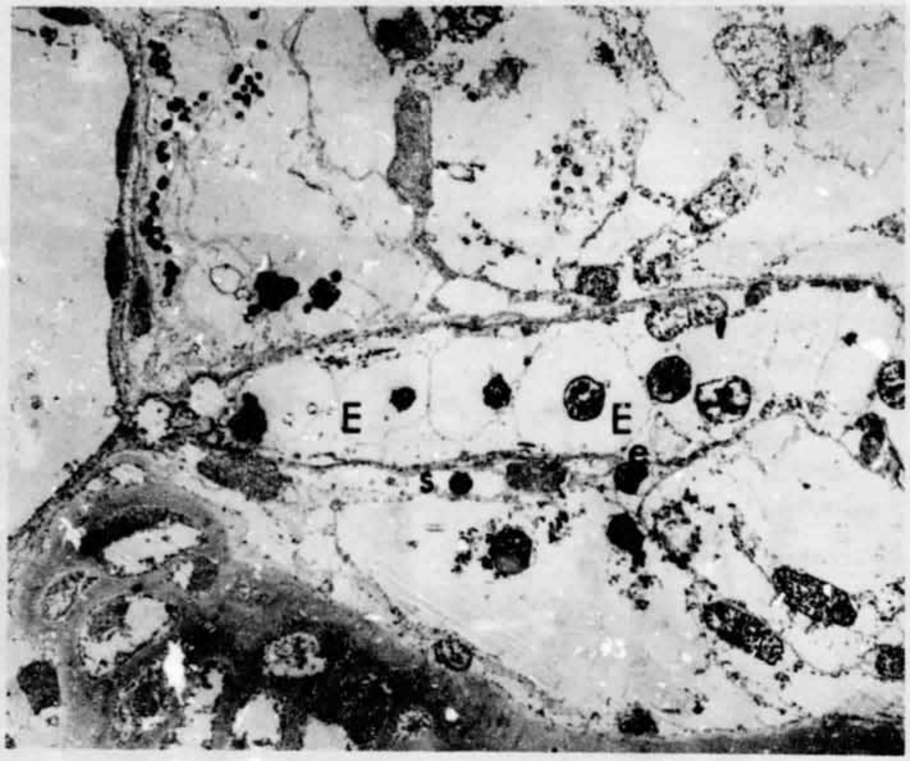

Figure 4-12.- Transmission electron photograph of gill lamellae with swollen erythrocytes (E), endothelial cells, (s), and intercellular spaces. 1800X.

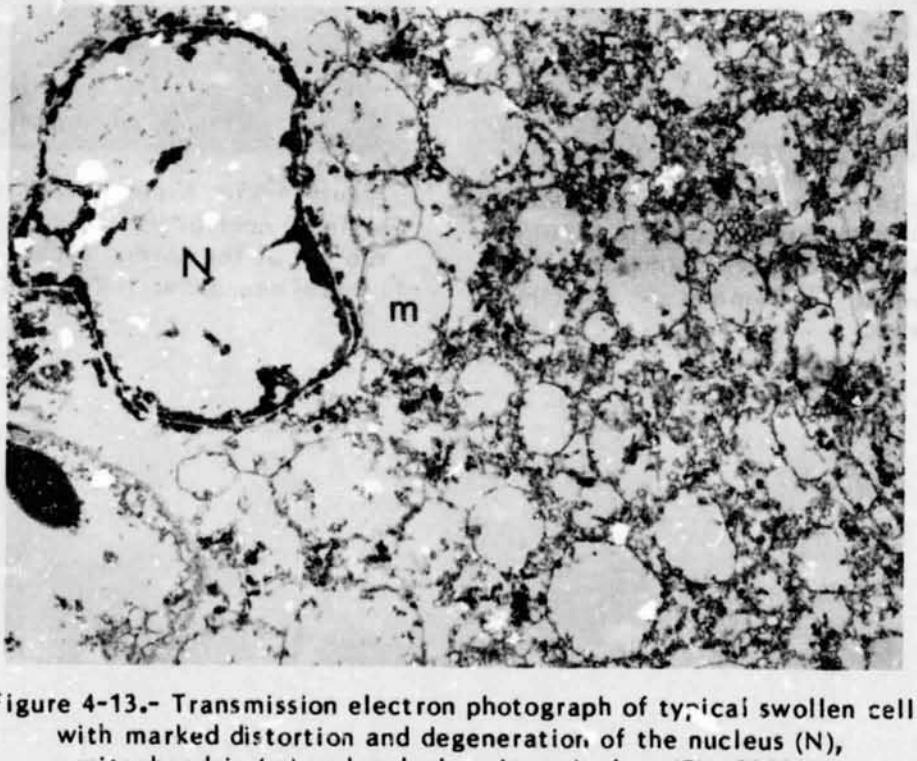

Figure 4-13.- Transmission electron photograph of typical swollen cell with marked distortion and degeneration of the nucleus (N), mitochondria (m),and endoplasmic reticulum (E). 9000X.

Figure 4-14.- A typical cross section of an encysted trematode parasite (T) in the lamina propria of a gill lamellae. Note the minimal inflammatory response. H&E. 290X.

Figure 4-15.- A protozoal cyst (P) in the brain of control fish which is causing disruption of the normal architecture of the central neuropile. H&E. 130X.

5. CONCLUSIONS

5.1 HEAVY METAL TOXICOSIS

Analysis of lagoon water and sludge samples, both prelaunch and postlaunch, were unremarkable. There was no histologic evidence of heavy metal toxicosis.

5.2 HEAT OR TRAUMA

Lagoon and bucket water temperatures were identical prelaunch and postlaunch. The expected sign of inflated swim bladders in traumatic causes of death was not observed. All dead fish sank to the bottom. There was no histologic evidence of death due to heat or trauma.

5.3 INFECTIOUS DISEASES

There were no gross lesions found upon necropsy, other than color changes. Lagoon water cultures were unremarkable. There was no histologic evidence of infectious diseases.

5.4 PARASITES

Protozoal and trematode parasites were present in many specimens, but this was an incidental and expected histologic finding. The parasite load was not heavy and did not contribute to acute death.

5.5 DISSOLVED OXYGEN (DO)

Lagoon DO levels, prelaunch and postlaunch, were not significantly different and were well above minimum levels required to support fish life.

5.6 ACIDITY

The acute deaths of the fish, in our opinion, are related directly to the low pH of the environmental water.

There has been essentially no documentation on the morphologic tissue changes in fish exposed to an acid water environment (ref. 5). However, there is considerable documentation that acid water does adversely affect fish, causing population declines due to death and decreased growth and reproduction (refs. 1, 6, 7, and 8). Fish are able to exist, but with decreased vitality, in pH's as low as 4.1 (ref. 1). Based on the uncovered bucket data, the fish killed by the STS-5 launch may have been exposed to a gradation of pH's as low as 2.4. The test fish used in the bioassay were also exposed to a pH of 2.4, whereas the controls were maintained at pH 8.4.

The morphologic changes recognized in the gills are consistent with acute death due to ionic imbalance and anoxia. Fresh water fish take up ions actively through gill epithelium. Sodium is exchanged for hydrogen ions and chloride for bicarbonate. Increased hydrogen ion activity in the surrounding medium will impede the active uptake of sodium. Severe ionic imbalance is known to affect fundamental physiologic processes such as nerve conduction and enzymatic reactions (ref. 6). Additionally, the increased width of the cells, intercellular tissue, and swelling of erythocytes would seriously impede ion transfer and gas exchange. The observed morphologic changes are admittedly nonspecific, but laboratory data indicate no abnormalities of the environmental water at the launch site other than the low pH. The bioassay had the same water for test and control and yielded the same morphologic changes, again supporting the impression that the changes are due to the acid water.

The 'bottom line' diagnosis, therefore, is: ionic imbalances and fatal anoxia resulting from severe gill damage caused by a rapid decrease in the water pH.

6. RECOMMENDATIONS

It can be predicted with reasonable certainty that fish kills of this type will occur in the lagoon north of Launch Complex Pad-39A with every STS launch. The change in water pH in shallow areas is a transitory phenomenon. There is no evidence to suggest a long-term environmental impact. Due to the limited nature of these fish kills and the absence of long-term impact, it is recommended that these affected fish be considered dedicated in the interest of the mission. Corrective action does not appear to be justified. Continued environmental monitoring, however, would be prudent.

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EFFECT OF ACIDIC DEPOSITION ON ECONOMIC PLANTS IN THE VANDENBERG AREA

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BACKGROUND

Our investigations have concerned the effects on vegetation of Space Shuttle exhaust products. Hydrogen chloride (HCl) gas and aluminum oxide (Al_2O_3) particulates were thought to be the principal components of a lingering ground cloud, and these pollutants were studied under U.S. Air Force (USAF) Contract F33615-76C-5005. Results were presented in several technical reports (refs. 1, 2, 3, 4, 5, 6, 7, and 8).

The ground cloud formed after STS-1 launch and subsequent Space Shuttle missions contained some HCl gas and significant amounts of acid precipitation (refs. 9 and 10). Distinct plant injury has been observed when deposition from the Space Shuttle cloud landed on vegetation (refs. 9, 11, 12, 13, 14, and 15). In view of these observations, our redirected task (sponsored by Contract F33615-80C-0512) has been to advise the USAF on potential effects of this acidic exhaust product deposition on economic plants growing in the vicinity of Vandenberg Air Force Base (VAFB), California. In particular, we are concerned with possible drift and deposition into the Lompoc Valley and along the California coast, figure 1. The town of Lompoc is located 8 miles east of the launch pad, separated from VAFB by a series of rugged hills. The Lompoc Valley, extending eastward, is an important and rich agricultural region supporting a large flower seed industry (fig. 2). The California coast south of VAFB has a diverse agriculture which may be impacted by Space Shuttle cloud deposition under certain wind conditions. Important commodities grown in these areas include avocados, lemons, and cut flowers. Grain is farmed southeast of VAFB. A developing grape industry exists east of Vandenberg toward Buellton and the Santa Ynez Valley.

AIMS

Three specific aims for our research are identified below.

1. Identify and characterize $HCl-Al_2O_3$ acid precipitation plant injury
2. Define nature and mode of action of $HCl-Al_2O_3$ acid precipitation
3. Verify the past occurrence of this pollution

Identification and characterization of injury are being accomplished by simulating the deposition of pollutants under controlled laboratory and greenhouse conditions and by studying plant samples collected after Space Shuttle flights. Plant species sensitivity, conditions under which sensitivity may change, and possible phytotoxic effects of aluminum oxide are being investigated.

Mode of action of acid deposition injury is not well known. Interaction between the leaf surfaces, individual acid droplets, and environmental influeences and subsequent phytotoxicity are being observed.

Various analytic techniques are being used to determine whether the passage of the Space Shuttle cloud could be later verified even in the absence of visible plant injury. A possible approach will be to detect minute deposits of aluminum dust by microscopy.

MATERIALS AND METHODS

For initial tests, plants were reared in the greenhouse and sprayed with acid. Pinto bean seedlings grow rapidly enough for treatments to begin 2 weeks after sowing. Beans have traditionally been used by other pollution-effects researchers, so reactions can be compared with earlier work. Zinnia and marigold plants and citrus and avocado leaves were also used in the spray trials. Acid solutions consisted of distilled water dilutions which ranged from 0 to 1 percent (v/v) HCl and had pH measurements of 4.9 to 0.6. Acid solutions were applied with a plastic spray bottle until liquid dripped from leaves. The plants were observed at 0, 2, 19, 24, 48, and 167 hours after spraying. Amount of visible necrosis, the chief symptom, was estimated. After 7 days, leaves were measured with a leaf area meter and all above-ground parts were dried. Leaf area of plants exposed to highest acid concentration (1 percent) was significantly smaller than for other treatments, but no significant differences in weights existed among the 12 spray treatments. Treatments could be best differentiated using injury ratings. The most dilute concentration required to induce a visible injury response was 0.01 percent HCl under current test conditions. Developing injury symptoms were observed after bean leaves were sprayed with 1 percent solution. Brown necrotic spots were visible 10 minutes after treatment when the leaf was still wet. The brown spots turned white and leaves began to wilt 27 minutes after treatment. After several hours, the spots began to coalesce, and leaf wilt was severe.

In another test, response of bean leaves was compared by spraying upper, lower, or both surfaces with acid. The under-surface of the leaf proved more sensitive than the top, possibly because more stomata were present (table 1).

Speed of plant response was investigated by rinsing leaves with water either immediately following or 5 minutes after spraying with 0.5 percent acid. Considerably more injury occurred if leaves were not rinsed. Injury was significantly reduced even if rinsing was delayed 5 minutes (table 2).

The spray bottles were replaced with a Mini Ulva (Micron Corp., Houston, Texas) spinning disc applicator, a motor-driven device which produced a mist of particles in the 10 to 1000 μm diameter range. Installing the device in a plexiglas chamber facilitated standardized spray applications. With this equipment, three acid concentrations (0.5-, 0.025-, and 0.012-percent solutions with pH's of 1.1, 1.9, and 2.5, respectively) were applied at 20, 50, or 100 ml doses to bean and zinnia plants. On either species, only highest acid concentration (pH 1.1 or 0.5 percent v/v) caused significant injury on either species (tables 3 and 4). Amount of solution was not important for bean injury, but significantly greater injury occurred on zinnia plants sprayed with 100 ml of solution.

The relationship between age and plant sensitivity was studied by spraying bean, zinnia, and marigold plants with a range of five spray concentrations when plants were 1 to 7 weeks old. Threshold concentration for injury to these plants at most ages was 0.1 percent HCl. The results, however, were inconclusive on whether any differences in sensitivity existed between various plant ages. Younger plants appeared more severely affected since more of the few leaves present were injured. Older plants which had a smaller percentage of leaves injured appeared more resilient. Zinnia and marigold flowers were susceptible to injury from acid sprays in the form of necrotic spots.

Buds, flowers, and fruit were removed from mature lemon trees and treated in the greenhouse with HCl sprays. All developed some injury symptoms after exposure to pH 1.1 and 0.8 solutions of HCl (0.5 and 1 percent, respectively). Very few necrotic spots developed on the buds. Flower petals developed depressed necrotic tissue, and speckled injury was observed on the lemon fruit. Fruit spots became more pronounced after 24 hours.

Large amounts of Al_2O_3 dust were applied to zinnia leaves in an initial study with this material. No injury was observed in the 8 weeks since application, and no differences between treated and control plant heights were recorded. Final harvests, when plants are fully mature, will indicate whether the dust reduced any growth parameters. Expanded Al_2O_3 studies will include mixing the dust with HCl solutions.

Immediately after STS-5 launch on November 11, 1982, injured vegetation was sampled near the launch pad. Damaged leaves were sealed in Ziploc plastic bags and transported back to California by USAF Space Division personnel. The leaves have been observed. On opening, one package released a strong odor of dying vegetation. Leaves in this set were from a predominant shrub Sea-oxeye (Borrichia frutescens), and all were water-soaked and necrotic in appearance. Plants sampled for this set grew in an area 100 m from the launch pad wherein plants were rapidly killed by high HCl gas concentrations (refs. 9 and 12). White and colorless crystals 100 to 400 μm diameter were found on leaf surfaces after drying. The second set of leaves, in contrast to the first, were relatively fresh and still green. Chlorotic and necrotic spots were present on the surfaces, apparently the result of acid deposition since leaves were collected 800 μm from the launch pad. Many of the spots consisted of depressions containing in their centers lumpy white powder, reminiscent of aluminum dust.

FUTURE STUDIES

Several of the studies described in the above overview are still under way. Other investigations are being planned. The Space Shuttle exhaust precipitation studies are listed below.

1. Response of additional species to acidic precipitation
2. Detection of aluminum oxide deposition
3. Phytotoxic effects of aluminum oxide and HCl mixtures
4. Influence of environment on plant injury
5. Rinsing to reduce acidic precipitation injury
6. Fate of acidic droplets on plant surfaces

Additional plant species will be tested for general response to HCl sprays and mists. Of particular interest will be flower species found in Lompoc and the sensitivity of flowers and seeds of these species.

We hope to observe the leaves collected at the launch site using scanning microscopy and microprobe facilities and to compare collected leaves with leaves treated in the laboratory with HCl and Al_2O_3 mixtures. Studies will be carried out on HCl and Al_2O_3 by following the fate of droplets of such mixtures as they dry on leaves. Leaf injury, droplet pH, and remaining residues will be studied.

A growth chamber will be used to study the influence of temperature, humidity, light, and wind on the sensitivity of plants to HCl mists and the development of symptoms. High humidity and temperature might be expected to increase injury symptoms and might change injury thresholds. The fate of acid droplets on leaf tissue will be observed for plant-droplet interactions and to observe the micro-environmental influences.

Further tests will be carried out to determine the feasibility of rinsing plants exposed to acid precipitation as a technique to reduce subsequent injury.

CONCLUSIONS

We have been studying the effect of acid deposition on plants. Current research is incomplete but indicates injury would be likely on many economically important plant species in the vicinity of VAFB if the ground cloud passes over the area. Injury appears to be limited to cosmetic damage which may not be important where seeds are the final product but would be of concern when fresh fruit, leaves, or flowers are marketed. Some evidence indicates that prompt remedial measures may reduce acid injury, although this may not be economically feasible.

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TABLE 1.- RESPONSE OF BEANS 7 DAYS AFTER TOP OR BOTTOM LEAF SPRAYS OF HCl

Response measured	Leaf surface treated		
	Both	Bottom	Top
Visible injury (score)	63.7 ± 10.3[a] A[b]	49.7 ± 5.2 B	27.6 ± 10.8 C
Grid injury (arc sin)	74.1 ± 12.2 A	56.6 ± 10.9 B	38.1 ± 9.4 C
Leaf dry weight (g)	27.2 ± 3.8 A	20.6 ± 3.9 A	21.2 ± 4.7 A
Plant dry weight (g)	73.6 ± 24.4 A	58.0 ± 20.0 A	74.0 ± 12.9 A
Leaf area (cm^2)	1[illegible].5 ± 6.1 A	20.4 ± 7.2 A	27.0 ± 6.0 A

[a]Response is given in terms listed, mean and standard deviation of five plants.

[b]Means underscored or followed by the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test.

TABLE 2.- RESPONSE OF PINTO BEANS 17 DAYS AFTER BEING SPRAYED WITH HCl AND RINSED WITH WATER

Response measured	No rinse	Immediate rinse	Rinse after 5 minutes
Visible injury (score)	38.4 ± 8.4[a] A[b]	16.4 ± 8.01 B	18.0 ± 6.00 B
Grid injury (arc sin)	33.2 ± 3.02 A	12.0 ± 5.09 B	15.1 ± 3.04 B
Leaf dry weight (g)	0.21 ± 0.02 A	0.2 ± 0.03 A	0.22 ± 0.02 A
Plant dry weight (g)	0.73 ± 0.13 A	0.74 ± 0.15 A	0.82 ± 0.07 A
Leaf area (cm^2)	26.3 ± 4.09 A	30.0 ± 1.07 A	30.07 ± 2.8 A

[a]Response is given in terms listed, mean and standard deviation of five plants.

[b]Means underscored or followed by the same letter are not significantly different at $p < 0.05$ Duncan's New Multiple Range Test.

TABLE 3.- SUMMARIES OF ANALYSES ON DATA FOR PINTO BEANS SPRAYED WITH HCl

Variable	pH of HCl solution			Amount supplied (ml)		
	2.5	1.9	1.1	20	50	100
Visible injury rating (1-11 scale)	2.5[a]B[b]	4.4 A	4.6 A	3.6 X	3.7 X	4.3 X
Leaves injured/plant (%)	51.8 B	45.7 B	63.9 A	52.4 X	56.0 X	53.1 X
Fresh weight (g)	41.2 A	38.7 A	39.7 A	39.5 X	39.6 X	40.4 X
Dry weight (g)	7.7 A	7.2 A	7.4 A	7.3 X	7.3 X	7.7 X

[a]Values are average injury, (1-11 or %) or weight (fresh or dry in g) per plant, mean of 15 plants.

[b]Means followed by same letter(s) or underscored are not significantly different at $p < 0.05$ Duncan's New Multiple Range Test.

TABLE 4.- SUMMARIES OF ANALYSES ON DATA FOR ZINNIA PLANTS SPRAYED WITH HCl

Variable	pH of HCl solution			Amount applied (ml)		
	2.5	1.9	1.1	20	50	100
Visible injury rating (1-12 scale)	2.2[a]B[b]	2.4 B	6.1 A	2.9 Z	3.6 Y	4.2 X
Leaves injured/plant (%)	29.4 B	29.2 B	54.6 A	29.6 Y	38.5 X	48.2 X
Fresh weight (g)	20.7 A	21.6 A	15.8 B	20.9 X	19.1 XY	18.2 Y
Dry weight (g)	2.5 A	2.6 A	2.0 B	2.5 X	2.3 X	2.2 Y

[a]Values are average injury (1-11 or %) or weight (fresh or dry in g) per plant, mean of 15 plants.

[b]Means followed by same letter(s) or underscored are not significantly different at $p < 0.05$ Duncan's New Multiple Range Test.

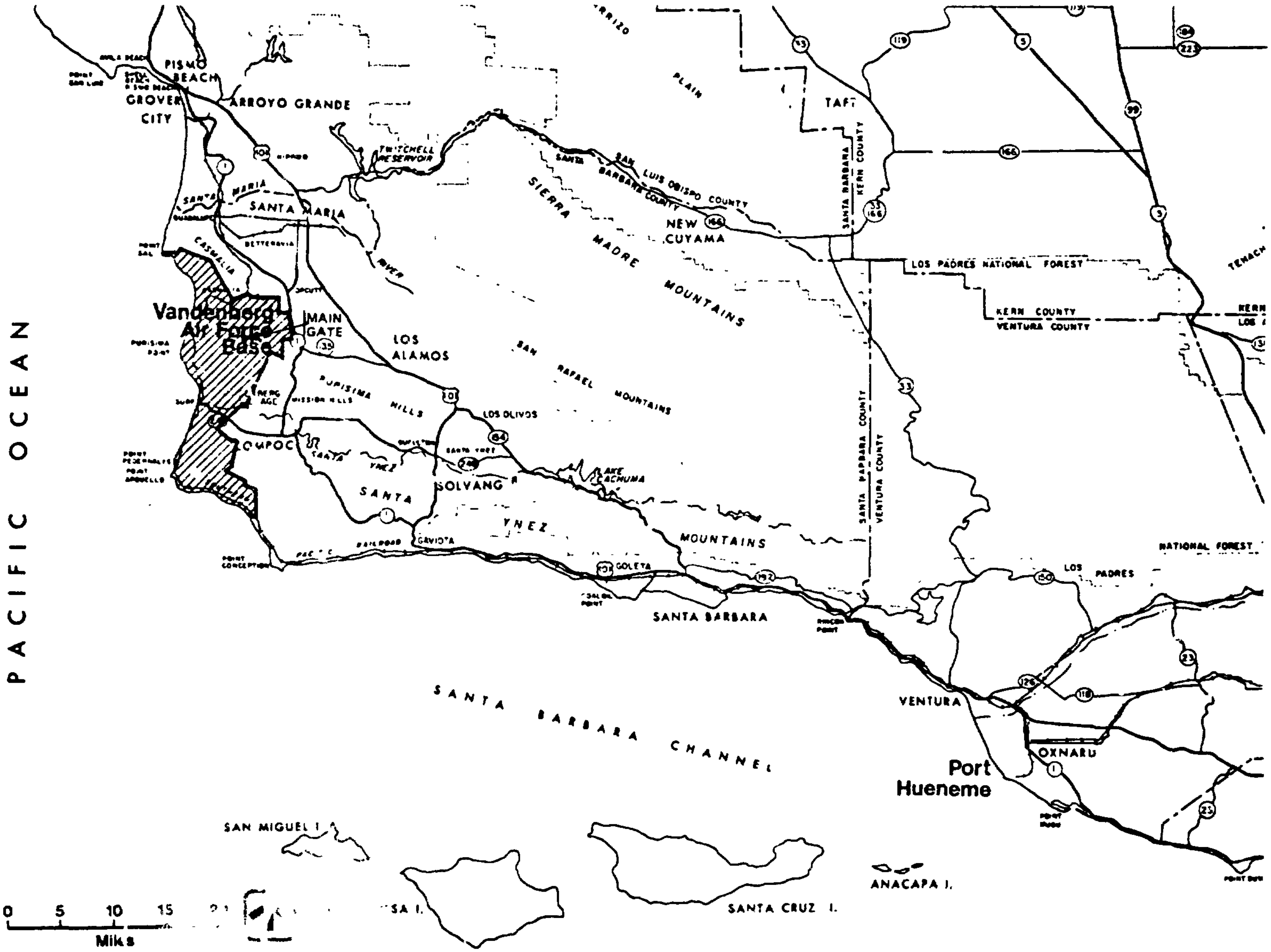

Figure 1.- Vicinity map showing Vandenberg Air Force Base and surrounding communities.

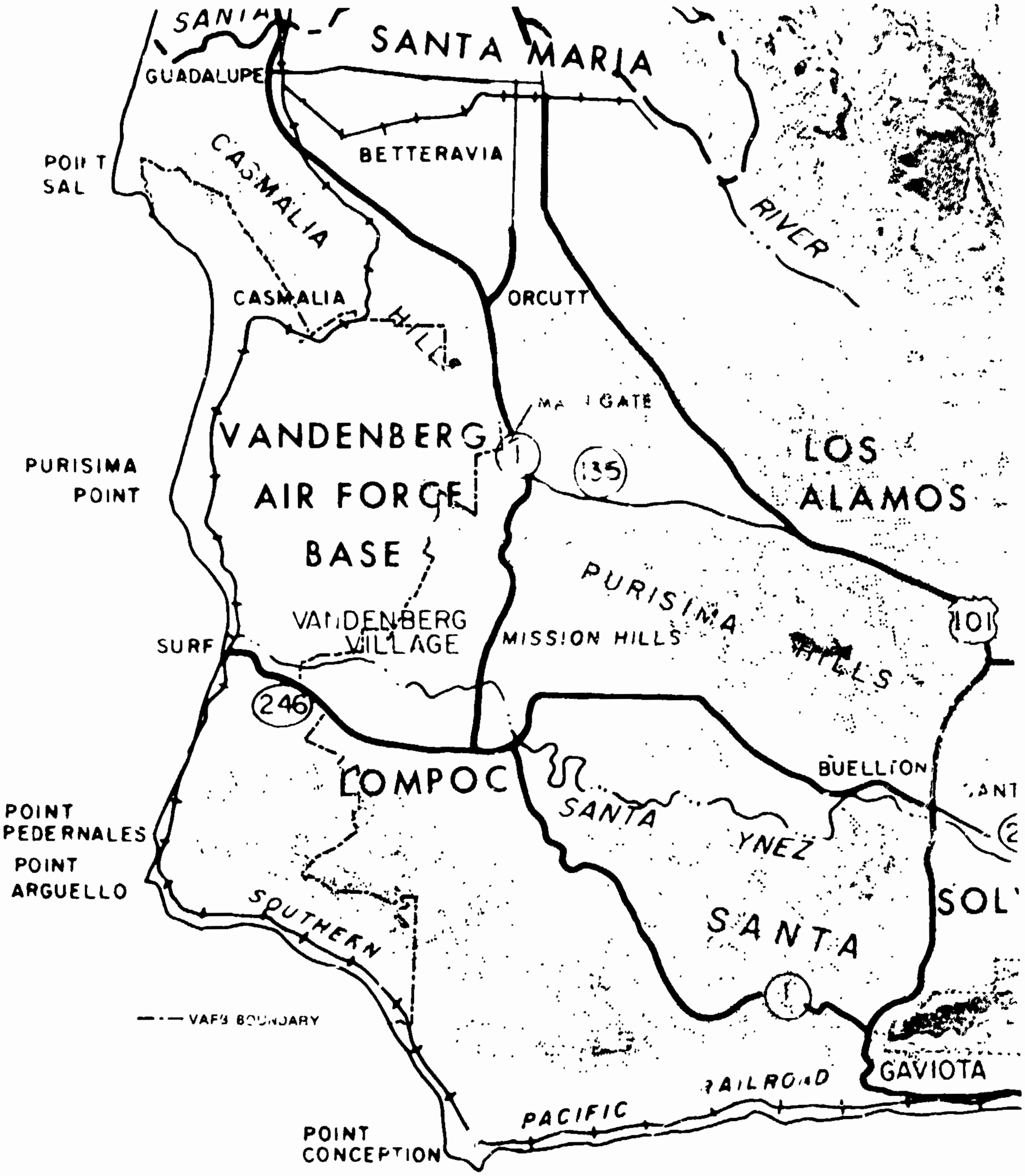

Figure 2.- Topography of the immediate Vandenberg area.

PHYSICAL MEASUREMENTS OF THE EXHAUST CLOUD

- HYDROGEN CHLORIDE MEASUREMENTS IN THE SPACE SHUTTLE EXHAUST CLOUD - STS-1
  Sebacher et al.
- HYDROGEN CHLORIDE MEASUREMENTS IN THE SPACE SHUTTLE EXHAUST CLOUD - STS-5
  Sebacher et al.
- CHARACTERIZATION OF SUSPENDED PARTICLES IN THE SPACE SHUTTLE EXHAUST CLOUD - STS-1
  Woods and Chuan
- SHUTTLE ENVIRONMENTAL EFFECTS: AEROSOL PARTICULATES - STS-2 AND STS-5
  Maddrea and Woods
- ALUMINUM OXYCHLORIDE FORMATION ON SPACE SHUTTLE EXHAUST ALUMINA
  Cofer et al.
- MICROPHYSICAL PROPERTIES OF THE SHUTTLE EXHAUST CLOUD
  Keller and Anderson
- ACID DEPOSITION PRODUCTION MECHANISM
  Anderson and Keller
- PREDICTION STRATEGIES FOR EXHAUST CLOUD IMPACTS: FALLOUT OF ACIDIC DROPLETS AND INADVERTENT WEATHER MODIFICATION
  Keller and Anderson
- NEAR-FIELD DEPOSITION OF ACIDIC DROPLETS FROM TITAN III AND SPACE SHUTTLE LAUNCHES
  Pellett et al.

HYDROGEN CHLORIDE AND PARTICULATE MEASUREMENTS IN THE SPACE SHUTTLE EXHAUST CLOUD - STS-1[a]

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ABSTRACT

Airborne sampling measurements of gaseous HCl, total HCl, particulates, relative humidity, and temperature in the first Space Shuttle exhaust cloud are presented in this paper. Two segments of the exhaust cloud, each at significantly different relative humidity, were monitored. Measurements were taken in the cloud segments from 8.6 min until 2 hr and 8 min after launch. HCl concentrations ranged from 17.5 ppm to 0.9 ppm and relative humidity from 86 percent to less than 10 percent. Particle concentrations ranged from 330 $\mu g/m^3$ to 75 $\mu g/m^3$. A comparison between the Space Shuttle HCl measurements and previous HCl measurements in Titan III exhaust clouds show moderate differences in the levels of HCl concentrations observed. Particle concentrations measured in the ambient air before and after the launch indicate no measurable remaining residue in the cloud path. Ion chromatograph analysis of sampled particles show the effects of chlorine sorption on the solid cloud particles.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is actively engaged in studies to determine the effects of Space Shuttle launchings on the environment in compliance with the National Environmental Policy Act of 1969. These studies, along with previous measurements obtained during Titan III launches, are designed to obtain data for vehicles with solid-fuel rocket motors to be used in the establishment of potential launch constraints using model prediction techniques to develop knowledge in the areas relating to the environmental impact of launch activities.

Significant quantities of HCl and other exhaust products such as Al_2O_3, H_2O, and CO_2 are released in the Earth's atmosphere during each Space Shuttle launch. The tropospheric environmental problem centers on the possible effects of relatively large localized exhaust products, which include approximately 35 kg (38.5×10^{-3} tons) of HCl and 56 kg (61.6×10^{-3} tons) of Al_2O_3 particles, emitted per launch below 4 km altitude (ref. 1). The ground exhaust cloud, formed during these launches, mixes with the surrounding ambient air and rises to a stabilization altitude, which is dependent upon the heat content of the cloud and the height and strength of the local atmospheric mixing layer.

The purpose of this study was to measure the in-cloud concentration of gaseous HCl, aerosol HCl, and particulates along with relative humidity and temperature as the cloud was diluted with ambient air. The experiment was carried out by making airborne measurements in the exhaust cloud produced during the Space Shuttle launch on April 12, 1981. In-cloud HCl concentration measurements were made using a gas filter correlation detector for the gaseous HCl and a chemiluminescence detector for

[a]Presented at the 1981 Annual Meeting of the JANNAF Safety and Environmental Protection Subcommittee, KSC, Nov. 17-19, 1981.

C-2

the total HCl concentration as the exhaust cloud drifted downwind of the launch pad. The difference between these measurements for a given sample is equated to the amount of HCl in aerosol phase.

HCl loss mechanisms in the cloud are directly related to HCl partitioning between the aerosol and gaseous phases. Some experimental results have indicated that if HCl is predominantly in the liquid phase, a considerable reduction in HCl washout occurs relative to gaseous HCl absorption by rain. The larger the droplets, the less efficiently the HCl aerosol is scavenged by falling rain (ref. 2). On the other hand, the aerosol droplets could grow to such an extent that rainout may occur directly from a very moist exhaust cloud. Formation of these aerosols is due to the nucleation of the supersaturated mixture of the condensable vapor in the atmosphere. The nuclei may have any number of origins, including minute particles of Al_2O_3 generated by the solid-rocket propellant in the Shuttle boosters and foreign debris entrained in the cloud as it forms and diffuses.

In-cloud and ambient air particle concentrations were measured using an integrating nephelometer and an airborne piezoelectric crystal microbalance system. Particle samples were also collected with a high-volume sampler for later analysis using an ion chromatograph.

Analytical techniques used in this experiment were developed over a number of years, and were tested in exhaust clouds produced by Titan III launches (refs. 3 and 4). The solid-propellant rocket motor of the Titan III produces approximately half the exhaust HCl and Al_2O_3 of a Shuttle launch. Since similar proportions of HCl to other exhaust products are released in both Titan III and Space Shuttle exhaust clouds, these early Titan III experiments were also useful in verifying analytical models designed to predict the transport and physical-chemical states of in-cloud HCl (refs. 5, 6, 7, and 8). This activity was conducted as part of a continuing NASA program with joint participation by the Langley Research Center (LaRC), John F. Kennedy Space Center (KSC), and Marshall Space Flight Center (MSFC).

EXPERIMENT

Launching of the Space Shuttle produces a plume of hot exhaust effluents which mixes with the ambient air and rises because of buoyant forces, as shown in figure 1. These photographs, taken at launch and approximately 3 min and 7 min after launch, illustrate development of the exhaust cloud with time. Depending on the atmospheric inversion temperature gradient, the ground cloud will either stabilize as one cloud below the top of the mixing layer or segment into several clouds under weak inversion conditions. When segmentation occurs, each section of the cloud stabilizes at an altitude which is dependent on the time required for that part of the cloud to reach equilibrium with the ambient air temperature.

Segmentation of the Space Shuttle exhaust cloud occurred because of weak inversion conditions existing at launch time. Relative humidity and temperature of the ambient air from rawinsonde measurements at launch time indicated a strong possibility that part of the exhaust cloud would pass through the boundary layer and break up at higher altitudes. The large variations in the relative humidity/altitude profile also indicated that the cloud segments would stabilize at different levels of relative humidity as encountered during the airborne sampling.

After rising and mixing for about 8 min, the exhaust cloud, as expected, separated into at least five segments of various volumes and at various altitudes. Two parts of the separated cloud were selected for sampling in order to obtain the optimum range of relative humidities. The first cloud slowly drifted northward at altitudes from 650 m (2,133 ft) up to 950 m (3,117 ft) under high relative humidity conditions. The second cloud segment drifted westward at altitudes from 1,350 m (4,429 ft) up to 1,880 m (6,168 ft) under low relative humidity conditions.

Sampling passes were flown through the center of the lower altitude cloud every 2 min to 5 min from 8.6 min until 45 min after launch. The higher altitude cloud was similarly sampled from 49 min until 2 hr and 8 min after launch. Due to easterly winds, the high altitude exhaust cloud segment drifted from the KSC to Orlando, Florida, by the end of the sampling mission. Relatively clean and clear marine environmental conditions occurred over this area due to easterly winds which were continuous for several days after launch.

INSTRUMENTATION

A twin-engine light aircraft was equipped to monitor gaseous HCl, total HCl, particulates, relative humidity, and temperature (ref. 9). In addition, routine flight parameters (altitude, heading, and air speed) were recorded. Total HCl measurements are based on a sequence of reactions which take place on the inner surface of a coated inlet tube to generate Br_2 which is then quantified by chemiluminescent oxidation of alkaline luminol. A comprehensive evaluation of the total HCl detector can be found in references 4 and 10.

The gas filter correlator, used to measure gaseous HCl, is a nondispersive infrared absorption instrument which employs a concentrated sample of HCl to provide a selective filter for radiation absorbed in a gas mixture containing traces of HCl. Since this selective filter only absorbs radiation at particular wavelengths, characteristic of gaseous HCl, this instrument responds only to gaseous HCl and not to HCl in the liquid phase. Details on the design and calibration of the gas filter correlator have been documented in references 4 and 11.

Air samples for the HCl instruments are obtained through aircraft nose probes designed to provide free-stream uncontaminated air samples. Isokinetic flow sampling inlets are provided for these probes, and they are alined to be parallel to the free-stream during sampling. Both HCl instruments are mounted in the nose compartment of the aircraft to minimize HCl losses in the inlet lines. In addition, the sampling inlet tube for the total HCl detector was designed to be used as the aircraft sampling probe. The gas filter correlator inlet line was teflon, and the sampling cell was teflon coated. Sample flow rates provide a sample volume exchange rate in the instrument's detection chamber of 6 per sec and 3 per sec for the total and gaseous instruments, respectively. Instrument lag times, as a result of sample flow rates and short inlet lengths, are both less than 1 sec. The lower detection limit for both instruments for the April Shuttle measurements is approximately 0.2 ppm by volume.

Mass concentration, as a function of particle diameter, was measured with a multistage impactor which contains a piezoelectric crystal microbalance in each stage for sensing the mass of the impacting particles. An integrating nephelometer was also used to measure total particle concentrations and scattering coefficients and to indicate when the aircraft entered and exited the cloud. Details on both of these instruments may be found in reference 9.

AIRBORNE MEASUREMENTS

Within 8 min after launch, all parts of the segmented ground exhaust cloud stabilized at various altitudes, depending on their internal characteristics and the local meteorological conditions. Two of the cloud segments were selected for sampling. Gaseous and total HCl profiles, along with particulate, temperature, and relative humidity profiles, were measured in each segment as it diffused with time. For each pass through the cloud, mass concentration, as a function of particle diameter, was also measured with the multistage impactor microbalance system. The lower altitude cloud segment was sampled until 45 min after launch, and results from a typical pass are shown in figure 2(a). The higher altitude cloud segment was sampled from 49 min until 2 hr and 8 min after launch, and representive results are shown in figure 2(b). All data are plotted against time after launch.

During the first few aircraft passes while rapid dilution of the cloud occurred, total HCl concentrations also decreased rapidly. Measurements obtained in the lower cloud segments [fig. 2(a)] show the total HCl to be considerably greater than the gaseous HCl which indicates that a significant amount of HCl was present in the aerosol phase. Relative humidity profiles measured in the lower altitude cloud indicate a high relative humidity within the cloud segment which decreases with time and cloud dilution.

Measurements obtained in the higher altitude cloud segment [fig. 2(b)] show the total HCl and the gaseous HCl concentrations to be approximately equal for each pass, indicating no measurable aerosol HCl present. Relative humidity measured within the higher altitude cloud segment was significantly lower as indicated by the rawinsonde measurements. Temperature was relatively constant during the measurement period.

In-cloud profiles obtained within the nephelometer show that the total particle concentrations reflect the general shape of the HCl concentration profiles. The high-volume sampler was open continuously during the entire sampling sequence so that only one sample, integrated over all the passes, was available for ion chromatograph analysis. This was necessary to obtain a sufficient sample. Details on this analysis and the results of the multistage impactor samples will be given in a later section.

RESULTS

Peak Profile Measurements with Time

A comparison between the data from both exhaust cloud segments is presented in figure 3, where peak HCl concentrations measured by both HCl detectors during each airborne pass are plotted as a function of time after launch. Each data point on these plots represents the maximum value measured for a single pass at a specific time during the pass referenced to launch time. Particle concentration, relative humidity, and temperature peak values are also plotted. Dashed lines have been faired through each data set. The decrease in HCl concentrations with time is a result of cloud dilution with the surrounding atmosphere and any direct rainout of HCl aerosols which may have occurred. Chemical reaction of atmospheric HCl is relatively slow and is insignificant for the times of this experiment (ref. 4).

The measured values of peak total HCl concentration in the low altitude/high relative humidity cloud segment [fig. 3(a)] are seen to be at least five times higher than the gaseous HCl concentrations. Since the total HCl detector measures both aerosol and gaseous HCl, these distributions indicate that most of the HCl in the lower cloud remains in the aerosol phase. The levels of relative humidity and particle concentration are shown in the bottom part of this figure. Both total and gaseous HCl concentrations appear to decrease at the same dilution rate.

In contrast to the lower cloud, the higher altitude/low relative humidity cloud segment [fig. 3(b)] produces measured concentration of total HCl and gaseous HCl that have identical distribution with time. This segment of the exhaust cloud rose rapidly to equilibrate with the ambient air temperature at the low relative humidity observed at the higher altitudes (RH = 10 to 20 percent). The data indicate that all the HCl is in the gaseous phase at these low levels of relative humidity. A dashed line faired through the HCl concentrations of figure 3(b) fits the total HCl values equally as well as the gaseous HCl concentrations. Scattering of the data measured in the higher altitude cloud segment is due to: (1) the difficulty in finding the cloud center as it became increasingly transparent with dilution and (2) variation in response times and calibration techniques between the two HCl detectors. Large differences in the aerosol concentrations measured with the integrating nephelometer in the two cloud segments reflect the differences observed in the relative humidity and HCl measurements. All the data indicate a significant amount of the lower altitude cloud to be in a liquid aerosol phase.

Space Shuttle and Titan III HCl Data Comparison

Decay curves faired through the peak HCl concentrations measured in the Space Shuttle cloud segments are compared to similar data measured during three Titan III launches in figure 4. Total HCl concentrations are presented in figure 4(a) and gaseous HCl in figure 4(b); both are plotted against elapsed time after launch. A number of first-order features are apparent from these data sets.

First, all the measured in-cloud HCl concentration data appear to be characterized by single-term power-law decay expressions, as indicated by modeled results. Secondly, the magnitude of HCl remaining in the ground cloud for each launch varies with the in-cloud relative humidity which in turn is determined by the local meteorological conditions. Lower HCl concentrations are usually associated with high moisture concentrations. Details on modeling of Titan III data for various standard meteorological regimes can be found in reference 8.

The decay curves in figure 4 also indicate that the HCl concentrations found in the Space Shuttle exhaust cloud are only on the moderately high side of those measured in Titan III exhaust clouds. This conclusion may be misleading, since the Shuttle cloud separated into a number of segments early in its formation. If a strong inversion layer were present to trap a larger part of the exhaust into a low cloud, the HCl concentrations could have been significantly greater.

Particle Measurements

Airborne mass concentration measurements that were measured in the ambient air near the launch site before the launch, 6 hr after the launch, and during two passes in the exhaust cloud are presented in figure 5 as a function of particle geometric mean diameter. Mass concentrations measured in the Shuttle exhaust cloud are several orders of magnitude greater than those found in the ambient air before and after launch. The mass distribution is bimodal, and the size distribution character in the cloud changes with time after launch. Pass 2 measurements show a larger concentration of small particles.

Differences in the mass concentrations measured in the ambient air near the exhaust cloud path 24 hr before and 6 hr after launch are almost identical. These measurements indicate that no measurable particle residue remains in the atmosphere after the exhaust cloud has passed. Ion chromatograph analysis of particles collected with the high volume samples are shown in table 1.

TABLE 1.- ION CHROMATOGRAPH ANALYSIS OF HIGH VOLUME SAMPLES

Sampling location	Cl^-/Na^+
Ambient air before launch	0.36
In exhaust cloud	1.36
Ambient air after launch	0.58

Results of this analysis are presented as ratios of Cl^-/Na^+ for filtered samples taken before and after the launch and in the Shuttle exhaust cloud. The ambient air measurements before and after the launch show a lower ratio of Cl^-/Na^+ than in the exhaust cloud, although the after launch ratio is higher than the pre-launch value. Since no statistical analysis of the Cl^-/Na^+ ratio daily variations is available in the launch region, the significance of the difference between the ambient values is uncertain. The filtered sample collected in the exhaust cloud shows a much higher ratio of Cl^-/Na^+ than either ambient value which suggests the effects of chlorine sorption on the solid cloud particles. Details of this reaction can be found in reference 12.

CONCLUSIONS

Airborne measurements of gaseous HCl, particulates, relative humidity, and temperature were obtained in the first Space Shuttle exhaust cloud. The exhaust cloud separated into at least five segments of which two were monitored. HCl concentrations in the Shuttle cloud segments were high compared to previous measurements in Titan III exhaust clouds, and all the measured HCl decay curves have the characteristics of single-term power-law expressions. Particle mass concentration measurements indicate that no measurable particle residue remains in the atmosphere after the Space Shuttle exhaust cloud has passed.

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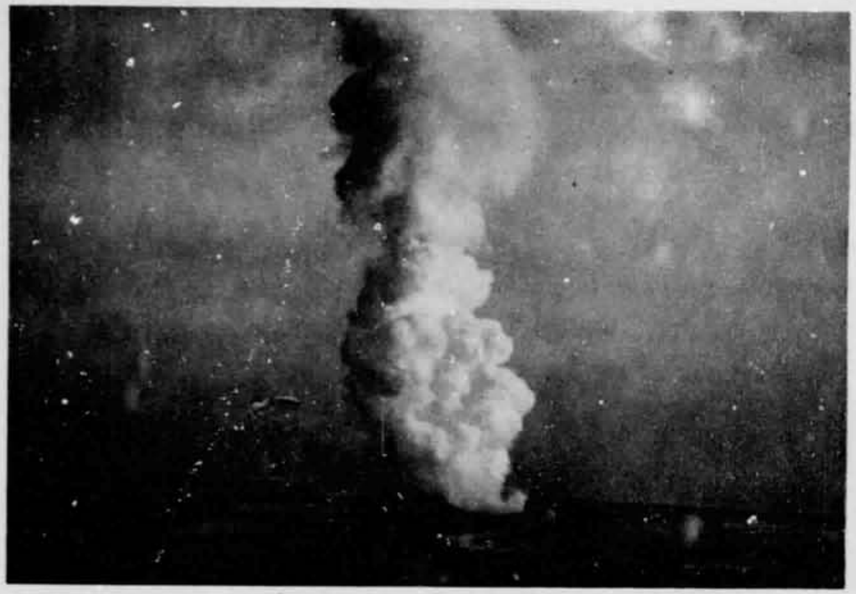
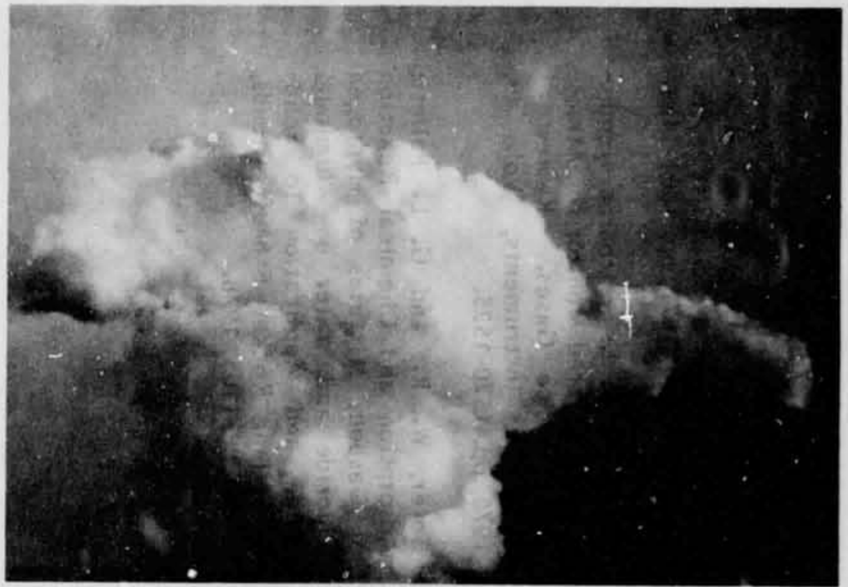
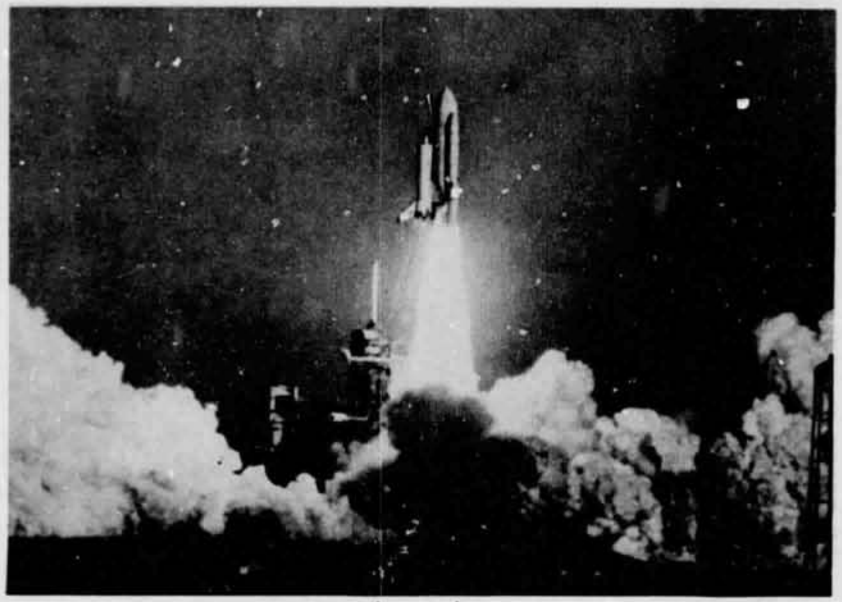


3 minutes after launch



7 minutes after launch



Launch

Figure 1.- Photographs of the Space Shuttle exhaust cloud growth with time.

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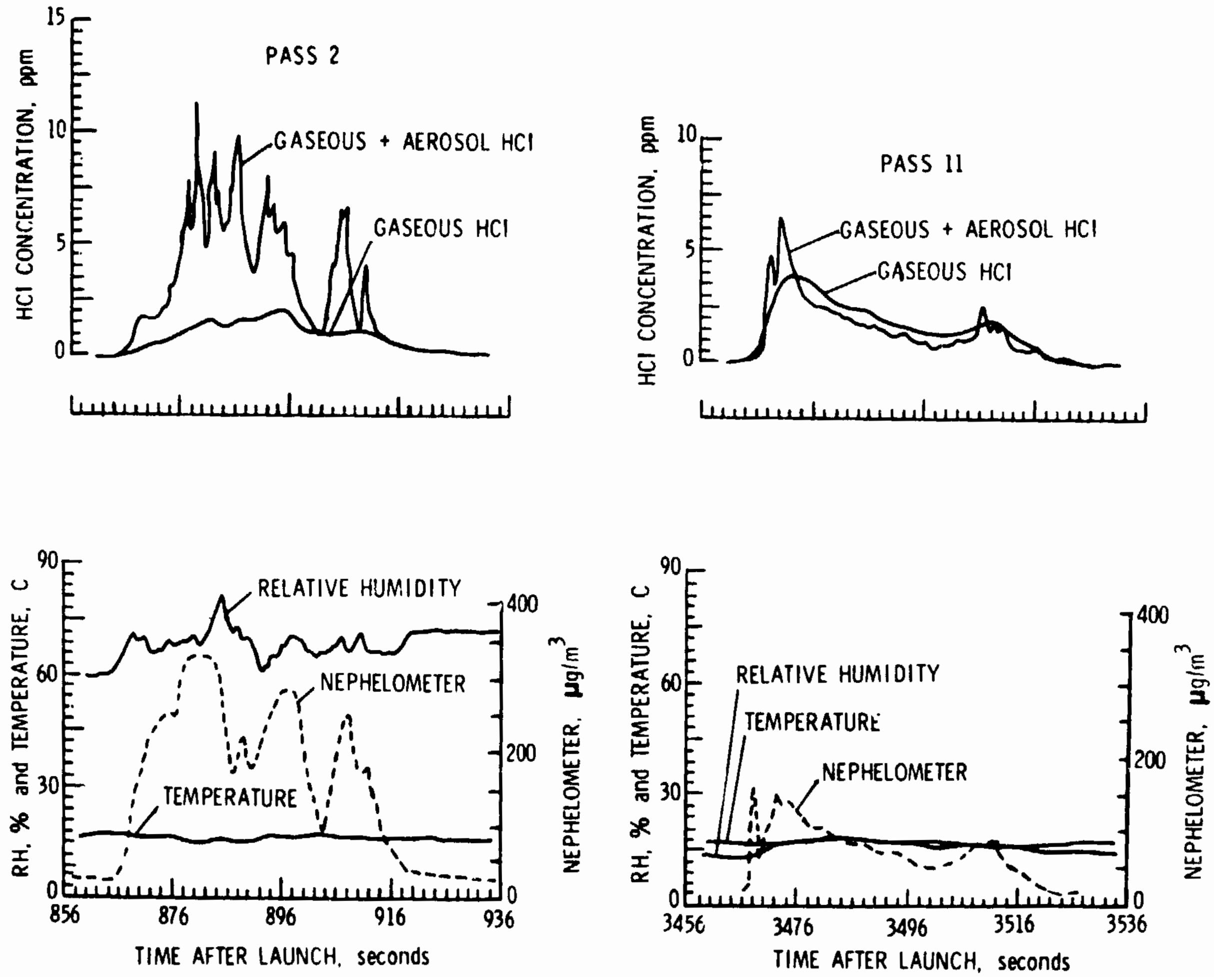
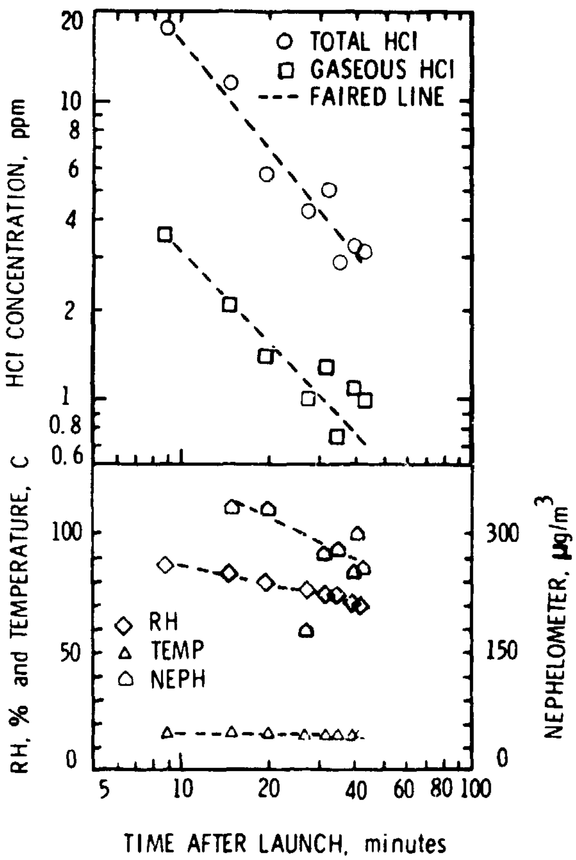


(a) Low altitude segment (b) High altitude segment

Figure 2.- Typical measurements of total HCl, gaseous HCl, particle concentration, relative humidity, and temperature through two segments of the Space Shuttle exhaust cloud.



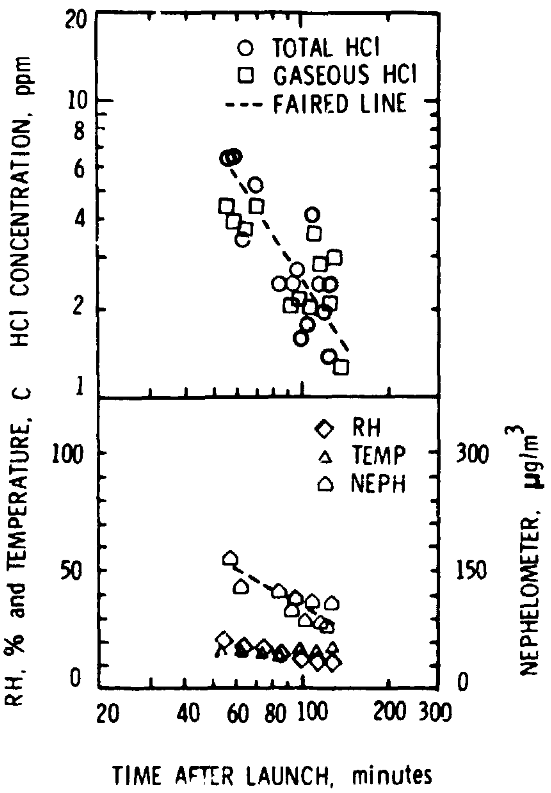


Figure 3.- Peak measured values of total HCl, gaseous HCl, particle concentration, relative humidity, and temperature for each pass through two segments of the Space Shuttle exhaust cloud vs. time after launch.

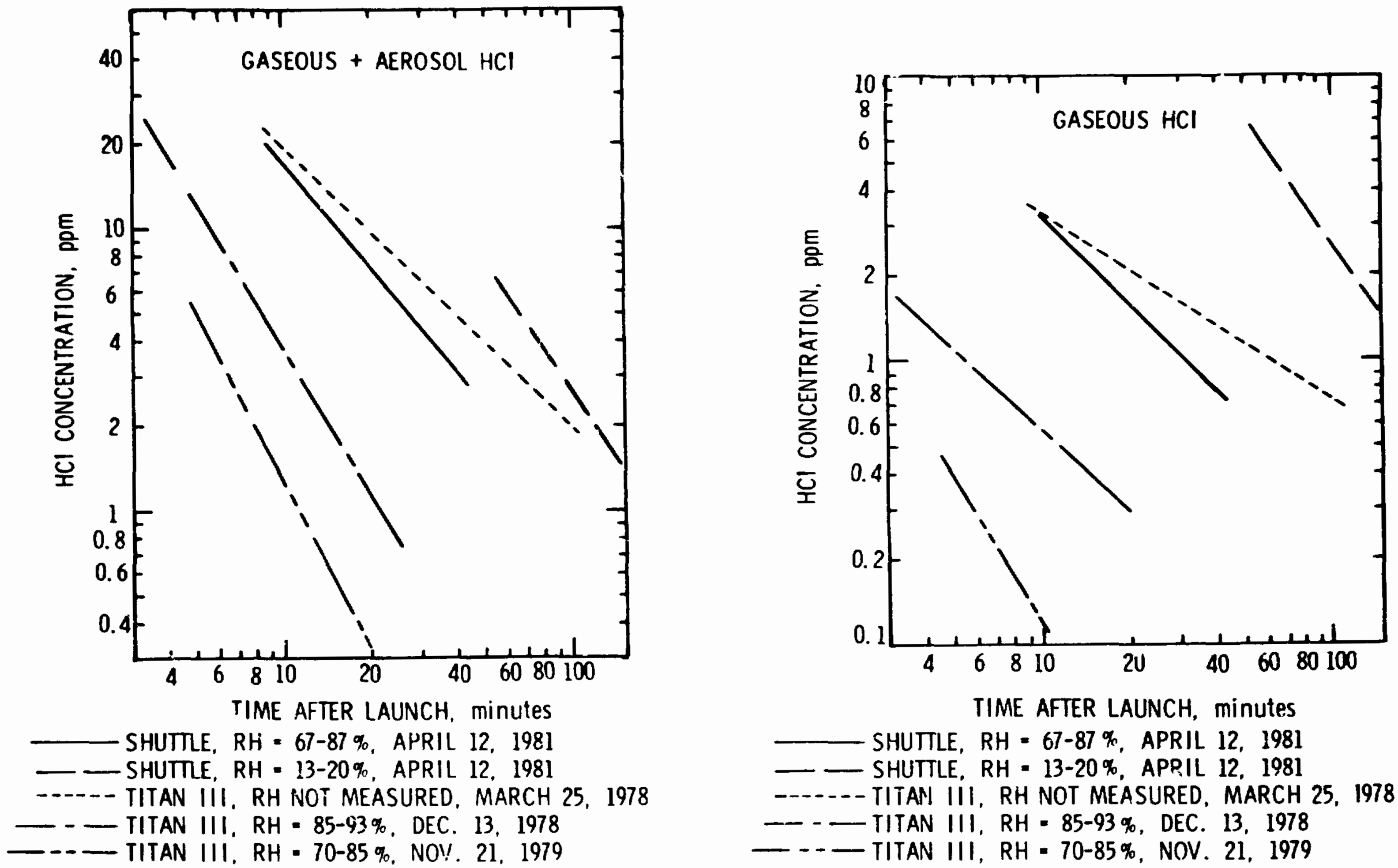


Figure 4.- Comparison of the measured Space Shuttle exhaust cloud HCl concentration history with time to previous measurements in Titan III exhaust clouds.

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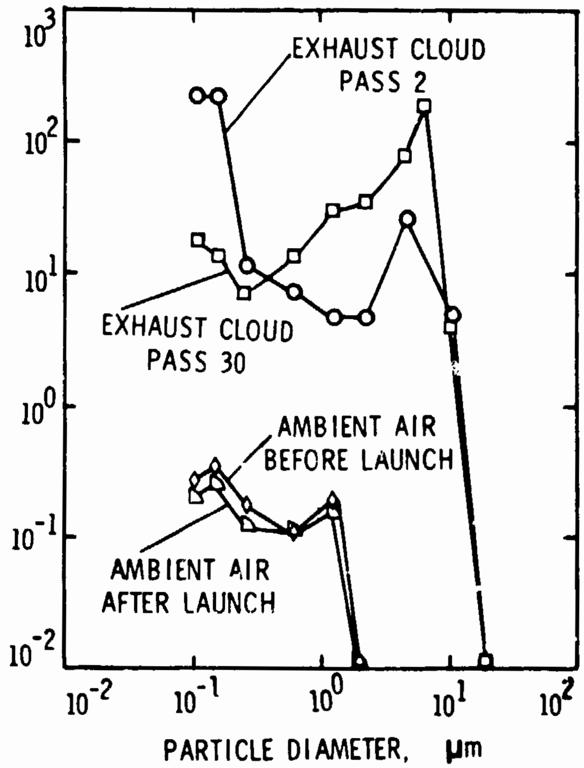

Figure 5.- Particle mass concentrations measured in the Space Shuttle exhaust cloud and in the ambient air where the cloud was located before 6 hr after launch.

HYDROGEN CHLORIDE MEASUREMENTS IN THE SPACE SHUTTLE EXHAUST CLOUDS - STS-5

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) is actively engaged in studies to determine the effects of Space Shuttle launchings on the environment in compliance with the National Environmental Policy Act of 1969. These studies, along with previous measurements obtained during Titan III launches, are designed to obtain data for vehicles with solid-fuel rocket motors to be used in the establishment of potential launch constraints using model prediction techniques to develop knowledge in the areas relating to the environmental impact of launch activities.

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The purpose of this study was to measure the in-cloud concentration of gaseous HCl and aerosol HCl, as the cloud diluted with ambient air. The experiment was carried out by making airborne measurements in the exhaust cloud produced during the Space Shuttle launches. In-cloud HCl concentration measurements were made using a gas filter correlation detector for the gaseous HCl and a chemiluminescence detector for the total HCl concentration as the exhaust cloud drifted downwind of the launch pad. The difference between these measurements for a given sample is equated to the amount of HCl in the aerosol phase.

HCl loss mechanisms in the cloud are directly related to HCl partitioning between the aerosol and gaseous phases. Some experimental results have indicated that if HCl is predominantly in the liquid phase, a considerable reduction in HCl washout occurs relative to gaseous HCl absorption by rain. The larger the droplets, the less efficiently the HCl aerosol is scavenged by falling rain (ref. 2). On the other hand, the aerosol droplets could grow to such an extent that rainout may occur directly from a very moist exhaust cloud. Formation of these aerosols is due to the nucleation of the supersaturated mixture of the condensable vapor in the atmosphere. The nuclei may have any number of origins, including minute particles of Al_2O_3 generated by the solid-rocket propellant in the Shuttle booster and foreign debris entrained in the cloud as it forms and diffuses.

Analytical techniques used in this experiment were developed over a number of years and were tested in exhaust clouds produced by Titan III launches (refs. 3 and 4). The solid-propellant rocket motor of the Titan III produces approximately half the exhaust HCl and Al_2O_3 of a Shuttle launch. Since similar proportions of HCl to other exhaust products are released in both Titan III and Space Shuttle exhaust clouds, these early Titan III experiments were also useful in verifying analytical models designed to predict the transport and physical-chemical states of in-cloud HCl (refs. 5, 6, 7, and 8). This activity was conducted as part of a continuing NASA program, with joint participation by the Langley Research Center, John F. Kennedy Space Center (KSC), and Marshall Space Flight Center (MSFC).

EXPERIMENT

Launching of the Space Shuttle produces a plume of hot exhaust effluents which mix with the ambient air and rise because of buoyant forces, as shown in figure 1. These photographs, taken at launch and approximately 3 min and 7 min after launch, illustrate development of the exhaust cloud with time. Depending on the atmospheric inversion temperature gradient, the ground cloud will either stabilize as one cloud below the top of the mixing layer or segment into several clouds under weak inversion conditions. When segmentation occurs, each section of the cloud stabilizes at an altitude which is dependent on the time required for that part of the cloud to reach equilibrium with the ambient air temperature.

After rising and mixing for about 7 min, the Space Shuttle 5 ground cloud stabilized at about 1.2 km, and useful data were obtained up to 2 hr and 23 min after launch, using the airborne sampling system. Airborne sampling passes were executed first under the cloud, then through the center of the cloud in both the downwind and crosswind direction every 3 min to 5 min. The ground cloud which formed from the exhaust of the Space Shuttle 5 launch did not segment below the top of the mixing layer. Tracking data indicated that the cloud continuously drifted westward during the sampling sequence.

INSTRUMENTATION

A twin-engine light aircraft was equipped to monitor gaseous HCl, total HCl, particulates, relative humidity, and temperature (ref. 9). In addition, routine flight parameters (altitude, heading, and air speed) were recorded. Total HCl measurements are based on a sequence of reactions which take place on the inner surface of a coated inlet tube to generate Br_2 which is then quantified by chemiluminescent oxidation of alkaline luminol. A comprehensive evaluation of the total HCl detector can be found in references 4 and 10.

The gas filter correlator, used to measure gaseous HCl, is a nondispersive infrared absorption instrument which employs a concentrated sample of HCl to provide a selective filter for radiation absorbed in a gas mixture containing traces of HCl. Since this selective filter only absorbs radiation at particular wavelengths (characteristic of gaseous HCl), this instrument responds only to gaseous HCl and not to HCl in the liquid phase. Details on the design and calibration of the gas filter correlator have been documented in references 4 and 11.

Air samples for the HCl instruments are obtained through aircraft nose probes designed to provide free-stream uncontaminated air samples. Isokinetic flow sampling inlets are provided for these probes, and they are alined to be parallel to the free-stream during sampling. Both HCl instruments are mounted in the nose compartment of the aircraft to minimize HCl losses in the inlet lines. In addition, the sampling inlet tube for the total HCl detector was designed to be used as the aircraft sampling probe. The gas filter correlator inlet line was teflon, and the sampling cell was teflon coated. Sample flow rates provide a sample volume exchange rate in the instrument's detection chamber of 6 per sec and 3 per sec for the total and gaseous instruments, respectively. Instrument lag times, as a result of sample flow rates and short inlet lengths, are both less than 1 sec. The lower detection limit for both instruments for the Shuttle measurements is approximately 0.2 ppm by volume.

SPACE SHUTTLE 5 AIRBORNE MEASUREMENTS

After the ground cloud stabilized at an altitude of 1.2 km, a first pass was executed approximately 30 m directly under the cloud to measure aerosol rainout; data from this pass are in figure 2. The peak value of total HCl is much greater than the gaseous HCl indicating that the rainout consists of HCl aerosols as expected. A maximum in the gaseous HCl measurements occurred at a different spacial location than the HCl aerosol maximum, indicating little correlation between the two HCl measurements.

All the following airborne sampling passes were executed through the center of the cloud, and two sets of these measurements are shown in figures 3 and 4. In the first few passes, while rapid dilution of the cloud occurred, total HCl was found to be considerably greater than the gaseous HCl, and the maximum aerosol values did not correlate spacially with the maximum gaseous HCl values. Peak values of aerosol and gaseous HCl did correlate during the later aircraft passes, shown in figure 4, as the difference between the aerosol and gaseous HCl measurements decreased with time.

ANALYSIS OF PEAK HCl MEASUREMENTS

Space Shuttle 5

In order to compare the measured HCl concentrations with the predicted exhaust cloud dilution of HCl by ambient air as a function of time, an estimate of dilution based on cloud volume growth was calculated using the data shown in figure 5. This plot presents a summary of previous Titan exhaust cloud volumes as a function of time which were obtained from optical measurements. A straight line growth curve was drawn through the data, and no deviation from this dilution curve was anticipated for the ground cloud resulting from Shuttle 5 since it was a typical launch.

Ground cloud HCl concentration dilution for Shuttle 5 as a function of time was calculated using the dilution curve of figure 5. The last total and gaseous HCl concentrations measured were used as a match point for the dilution calculations because they approach the same level at that time. This is a forced fit approach to the dilution decay but is useful in comparing the measured aerosol and gaseous decay curves. Predicted HCl dilution of the ground cloud is shown in figure 6 along with the peak HCl measured values of both total and gaseous HCl for each pass through the cloud as a function of time after launch. The calculated dilution decay of HCl is less than the aerosol decay and greater than the gaseous decay. A faster decay rate of the HCl aerosols was anticipated, since significant rainout or fallout of HCl aerosols was measured during the first pass under the cloud. The peak total HCl measured directly under the cloud is also plotted in figure 6 as a solid circle and is seen to be as high as those anticipated within the cloud at that time after launch.

The slower decay rate for gaseous HCl can be explained as a result of degassing of the aerosol HCl. As the exhaust cloud is diluted with dryer ambient air, degassing of the wet aerosols results in both a slower gaseous decay rate and a faster aerosol decay rate. The very low concentration of gaseous HCl measured under the cloud (solid square) was due mainly to degassing of the rainout aerosols and was not expected to be as high as gaseous HCl in the main cloud.

Space Shuttle and Titan HCl Data Comparison

In figures 7 and 8, decay curves drawn through the peak HCl concentrations that were measured in three Space Shuttle clouds are compared to similar data measured during three Titan launches. Total HCl concentrations are presented in figure 7, gaseous HCl in figure 8; both are plotted against elapsed time after launch. A number of first-order features are apparent from these data sets.

First, all the measured in-cloud HCl concentration data appear to be characterized by single-term power-law decay expressions as indicated by model results. HCl concentrations and decay curves are a function of meteorological conditions including: relative humidity, strength of the inversion layer, cloud coverage, and wind. These parameters determine the amount of rainout, washout, degassing, and segmentation of the ground cloud. Details on modeling of Titan ground cloud data for various standard meteorological regimes can be found in reference 8. The decay curves for Shuttle 1 consist of two cloud segments at different altitudes and different meteorological conditions.

A comparison of the total HCl measured during three Shuttle and three Titan launches indicates that the Shuttle HCl concentrations are about twice the Titan concentrations. Since approximately twice the amount of fuel is consumed in a Shuttle launch, this result was expected.

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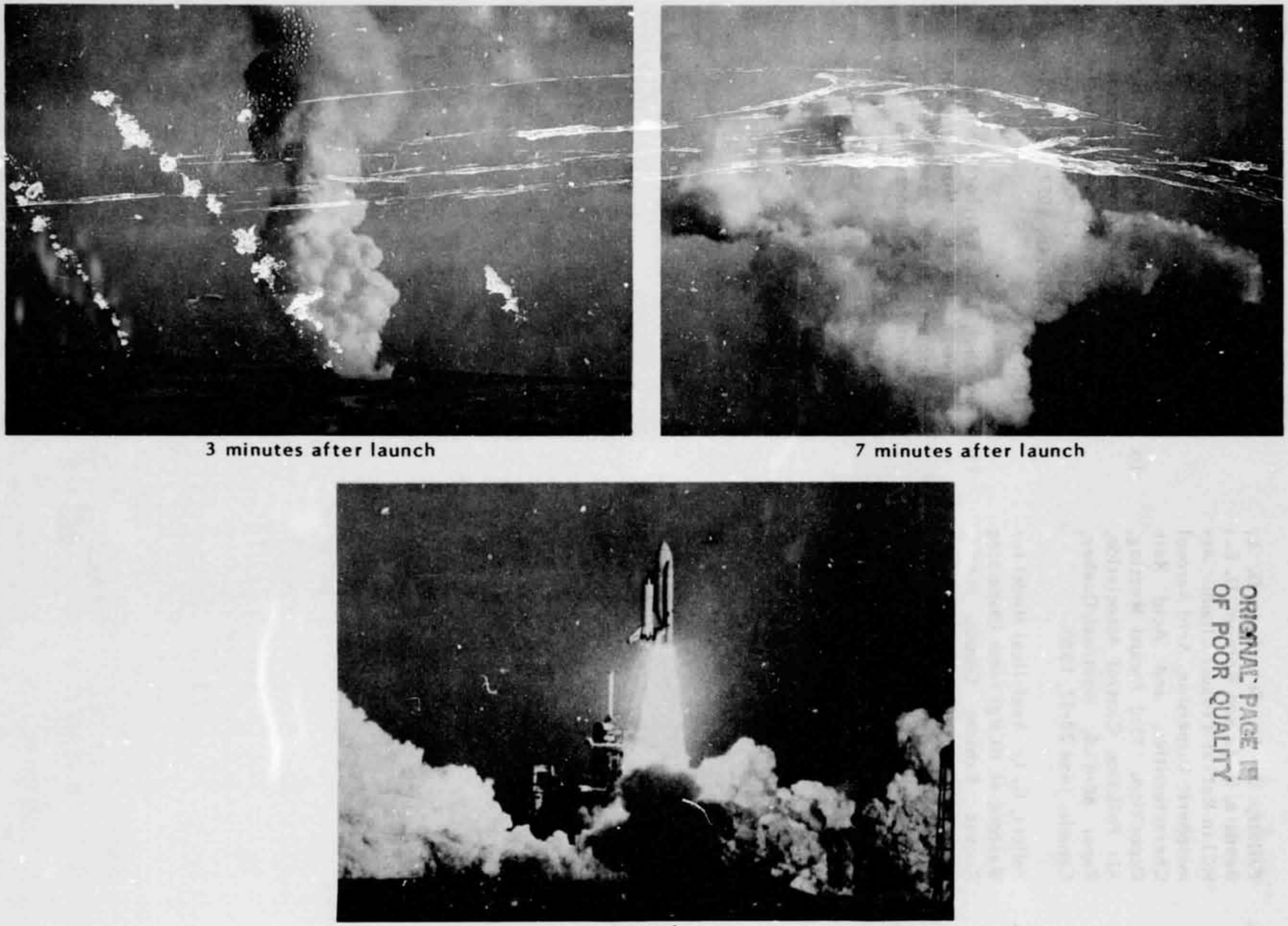

3 minutes after launch

7 minutes after launch

Launch

Figure 1.- Photographs of the Space Shuttle exhaust cloud growth with time.

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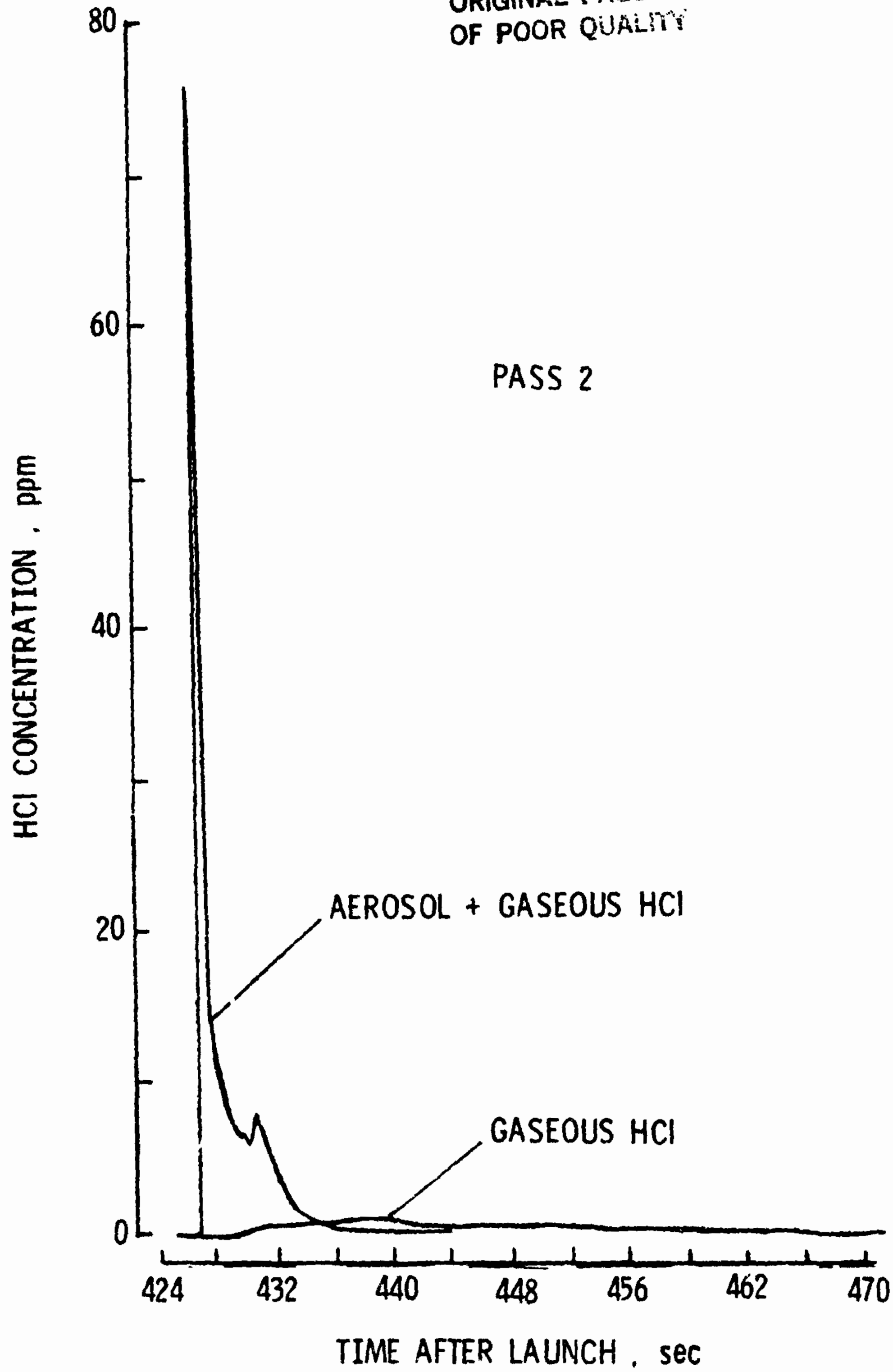

Figure 2.- Total HCl and gaseous HCl concentrations measured under the Space Shuttle 5 ground cloud (Pass 2).

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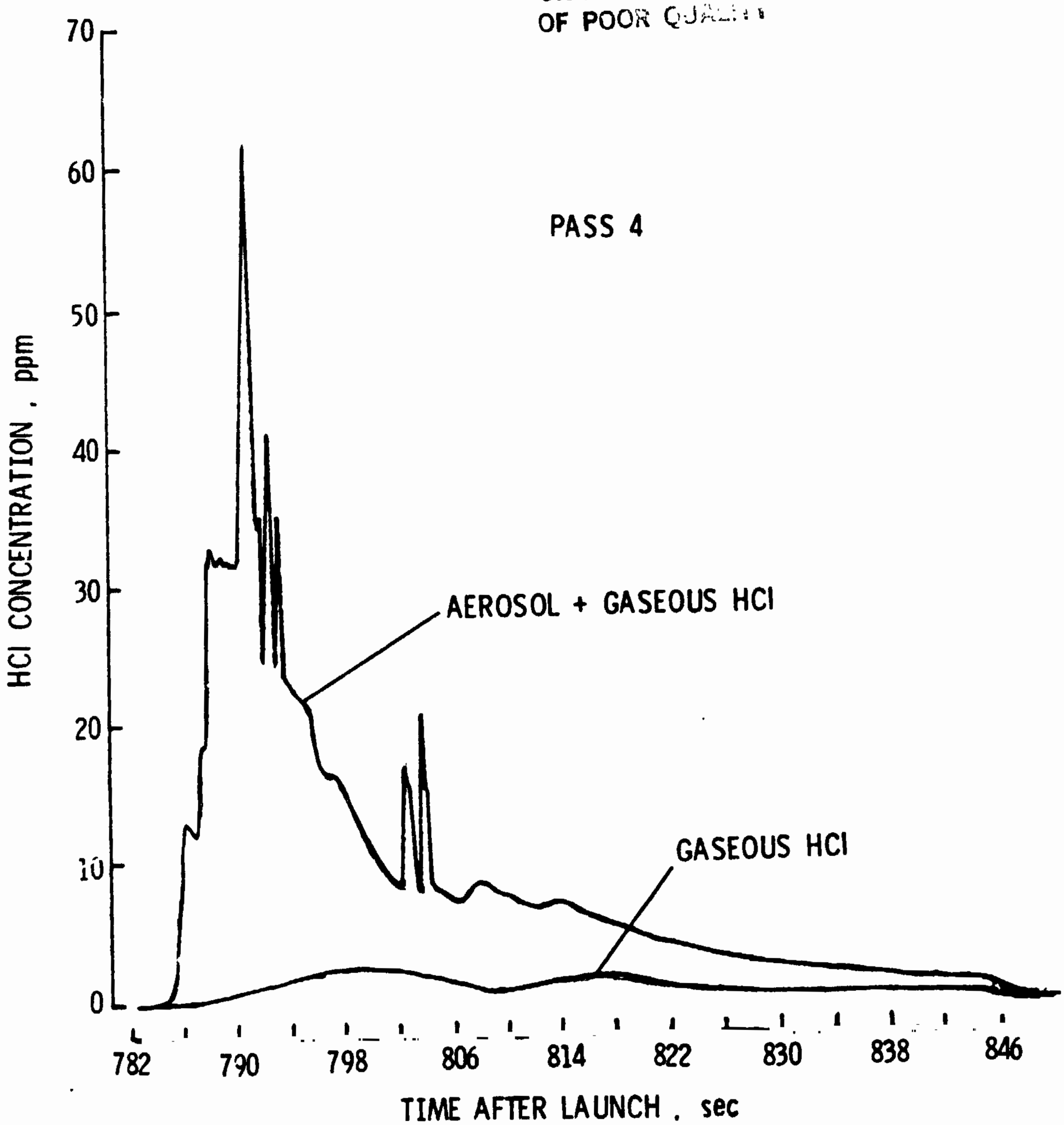

Figure 3.- Total HCl and gaseous HCl concentrations measured through the Space Shuttle 5 ground cloud (Pass 4).

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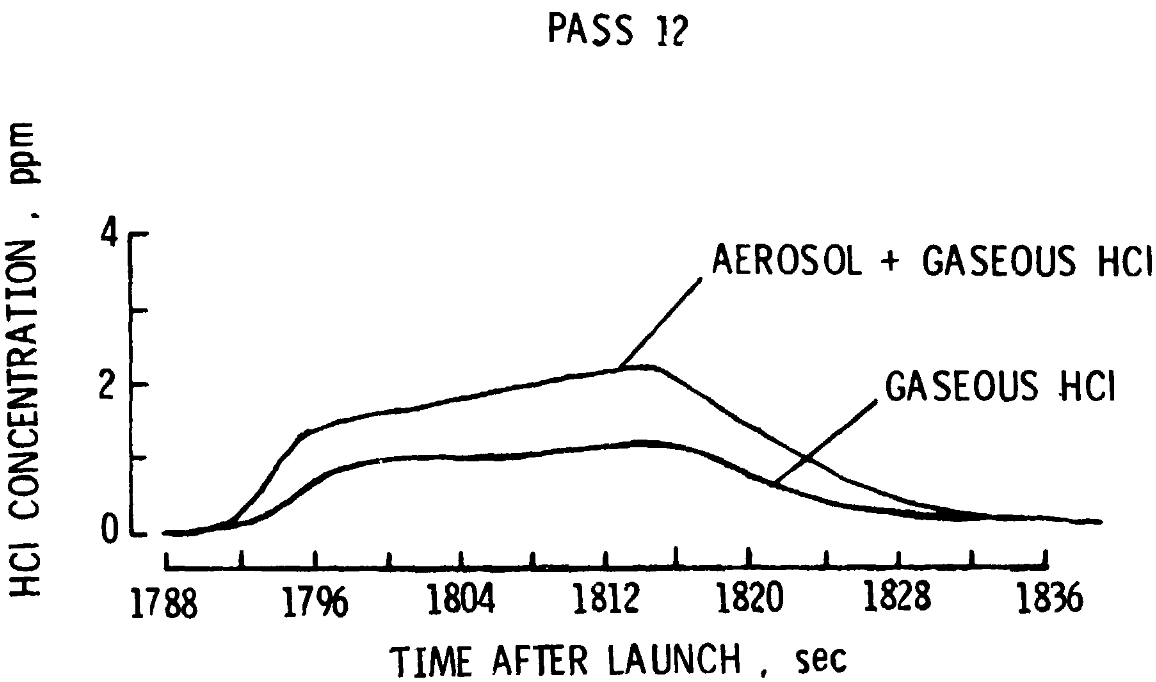

Figure 4.- Total HCl and gaseous HCl concentrations measured through the Space Shuttle 5 ground cloud (Pass 12).

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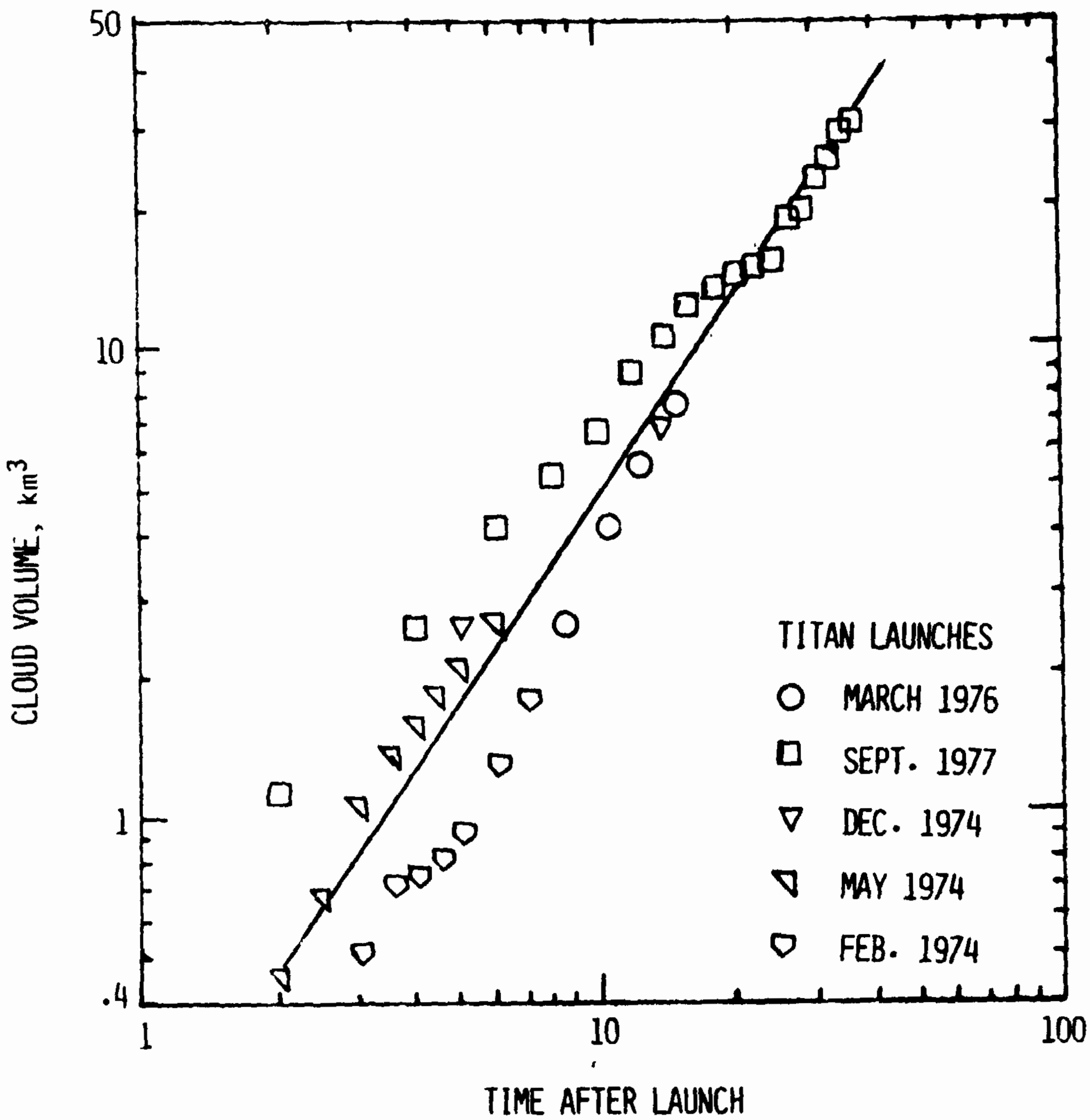

Figure 5.- Summary of Titan exhaust cloud volumes from optical measurements. Solid line indicates the interpolated dilution rate.

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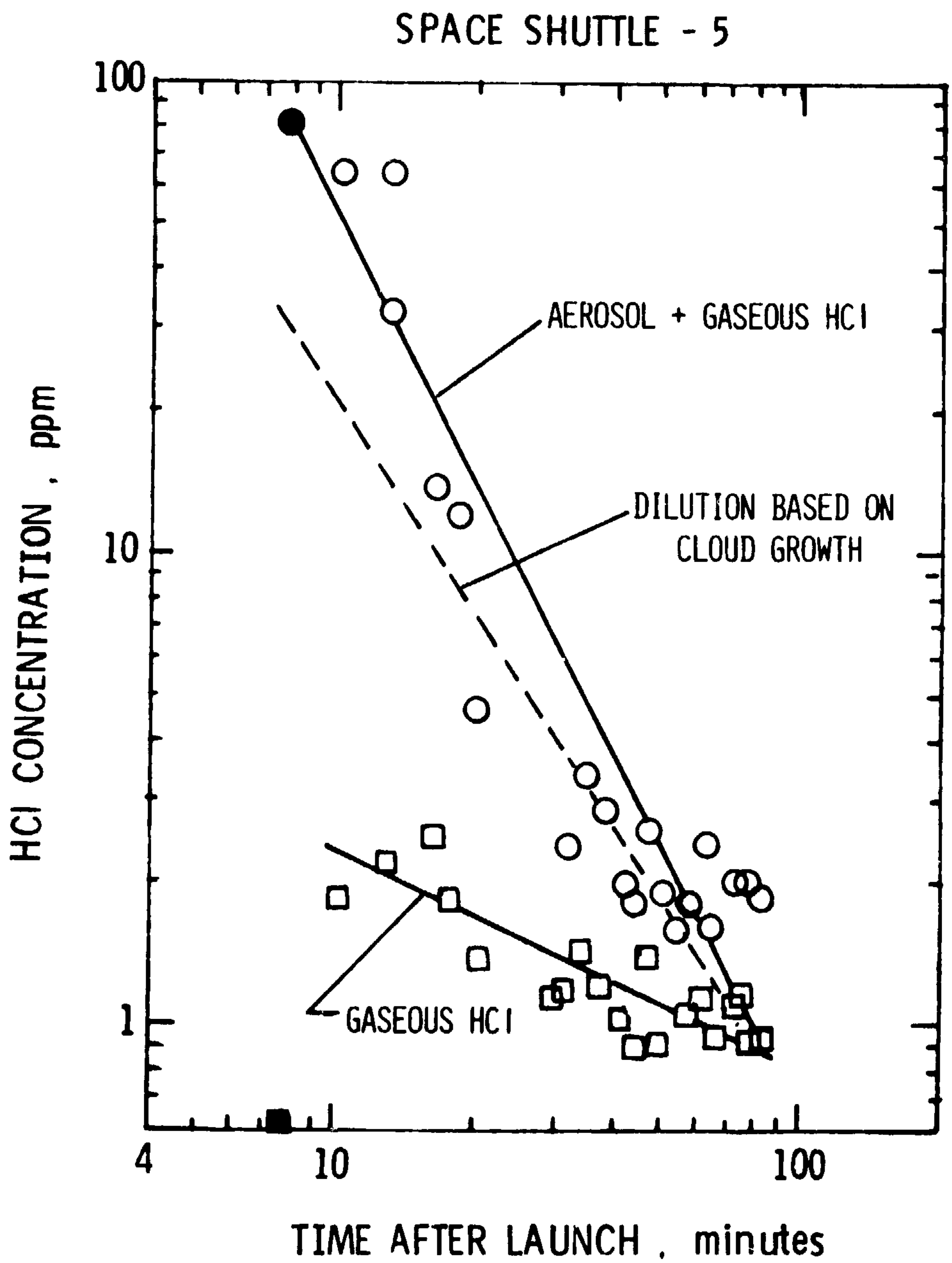

Figure 6.- Peak measured values of total and gaseous HCl for each pass through the Space Shuttle 5 exhaust cloud. Dashed curve is estimate of dilution decay based on data from figure 5.

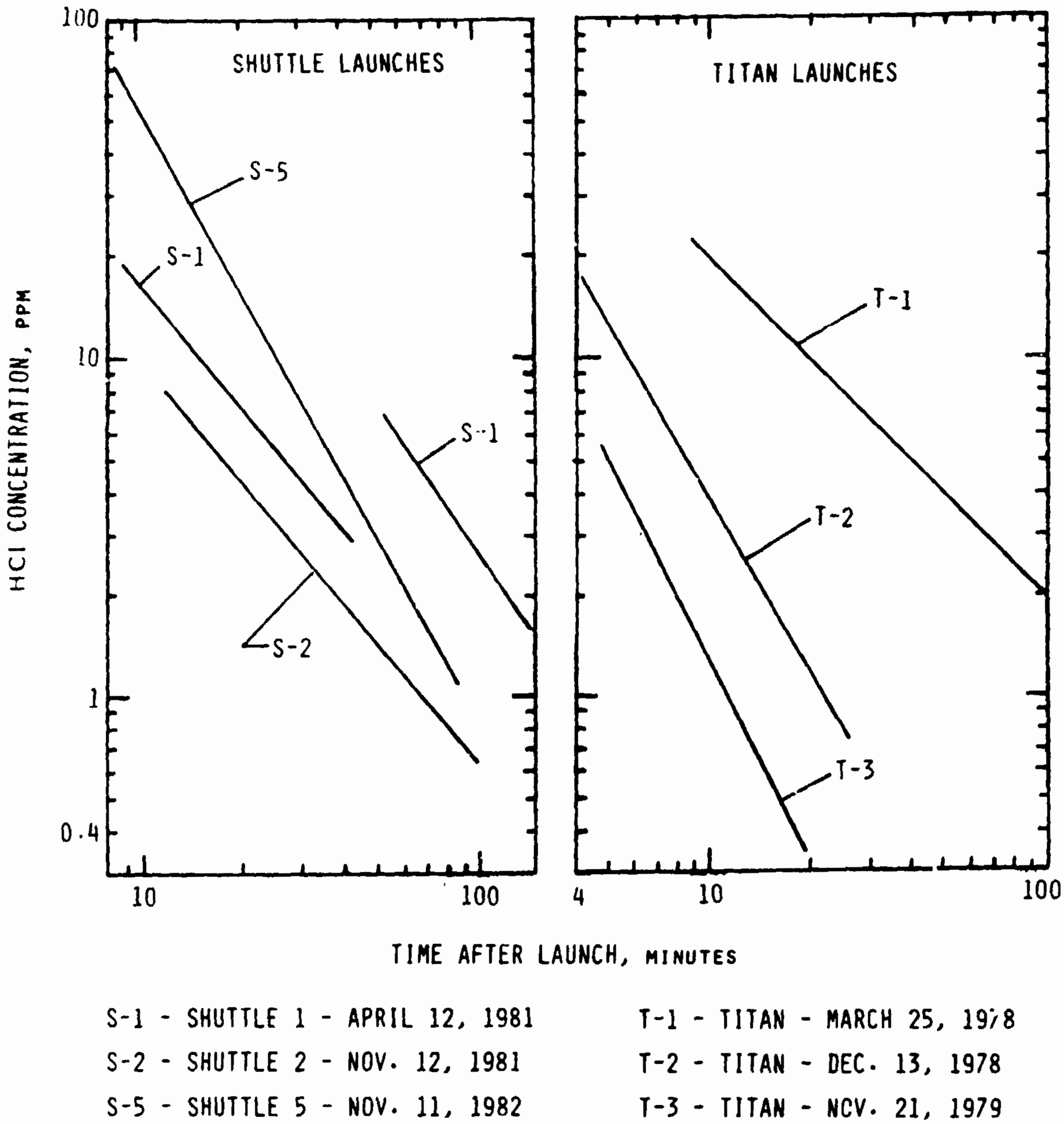

Figure 7.- Comparison of total HCl decay curves measured in three Space Shuttle and three Titan exhaust clouds.

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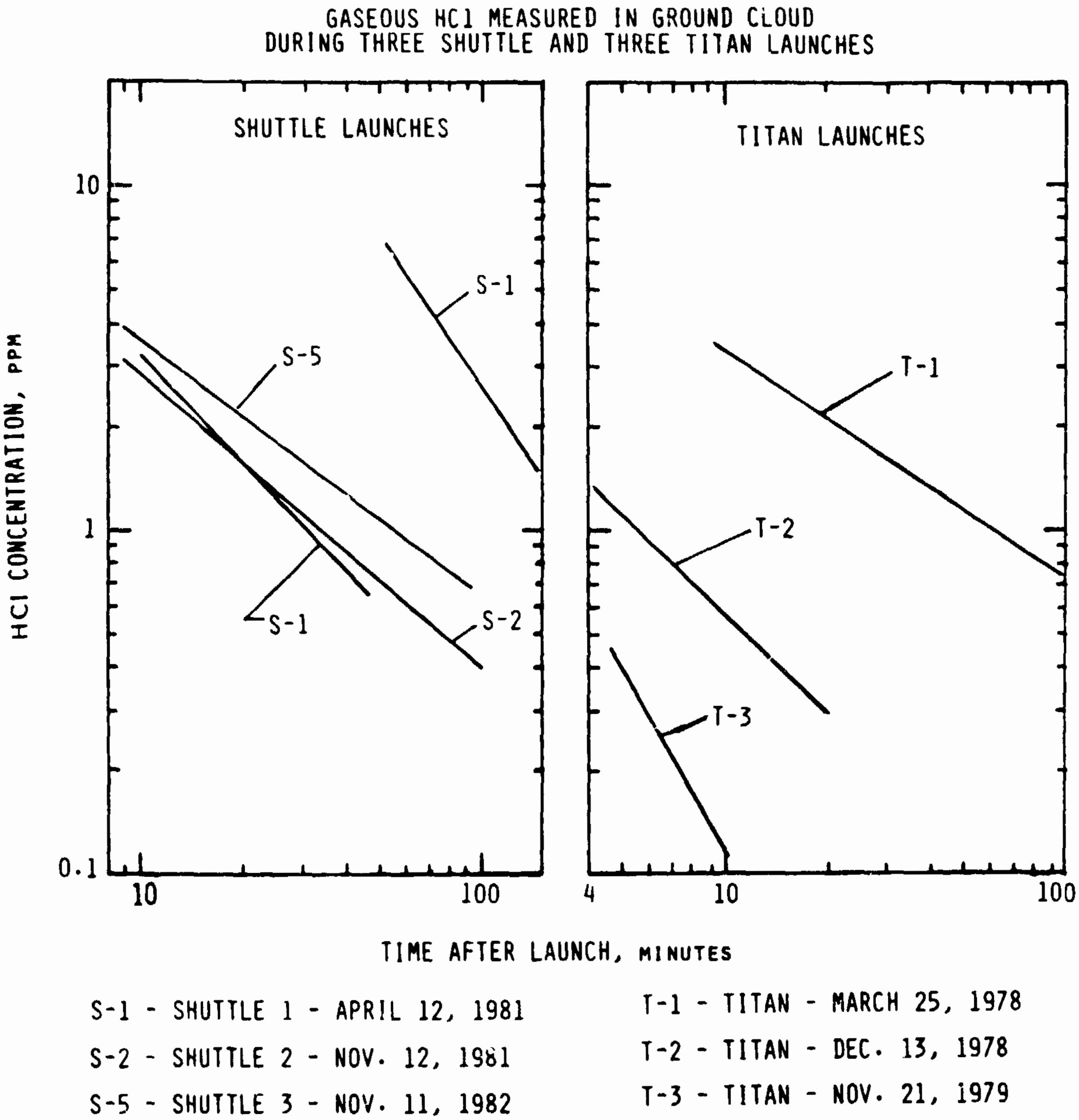

Figure 8.- Comparison of gaseous HCl decay curves measured in three Space Shuttle and three Titan exhaust clouds.

CHARACTERIZATION OF SUSPENDED PARTICLES IN THE SPACE SHUTTLE EXHAUST CLOUD - STS-1[a]

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ABSTRACT

Particles in the exhaust cloud, formed from the launching of the Space Shuttle on April 16, 1981, were sampled and characterized. Measurements were made in situ from aboard a small twin engine aircraft, instrumented with particle and gas sensors, as it made multiple passes through the cloud. Mass concentrations and particle size distributions were measured with a multistage impactor which contained a piezoelectric crystal microbalance in each stage for sensing mass as a function of particle diameter. An integrating nephelometer was used to measure scattering coefficient and to indicate when the aircraft entered and exited the cloud. Particles, collected in the various stages of the impactor, were analyzed by scanning electron microscopy and energy dispersive x-ray analysis to determine particle shape and elemental composition.

Two of several cloud segments which separated and moved in different directions at different altitudes were sampled. The size distributions measured in both cloud segments were monomodal. The first segment had a peak mass concentration at 0.11 µm geometric mean diameter, and the second segment had a peak mass concentration at about 5.4 µm geometric mean diameter. Scanning electron microscope photographs, showing agglomerates consisting of a number of individual particles stuck together, suggest that coagulation may contribute to the 5.4 µm mode. Particles, approximately spherical in shape and containing aluminum, were found in all stages of the impactor covering a size range from ~0.11 µm to greater than 40 µm geometric mean diameter. These particles are presumed to be Al_2O_3 produced from the burning of the solid propellant which contains aluminum. Among the submicron-size particles, in addition to aluminum, there were abundant amounts of sodium, sulfur, chlorine, potassium, and zinc, with traces of calcium and iron.

INTRODUCTION

Since 1972, studies on the effluents from launch vehicles with solid propellant motors (Titan III) have been conducted by the National Aeronautics and Space Administration (NASA). Measurements from aboard a light aircraft equipped with sampling instruments (ref. 1) have been made during selected launches of Titan III vehicles in their low altitude exhaust clouds (ground clouds). These studies were aimed at determining possible tropospheric and ground-level environmental effects and providing data for use in developing dispersion models for predicting exhaust cloud behavior. Since the booster for the Space Shuttle includes two strap-on solid propellant motors, and because of the expected high frequency of Shuttle launches, it is con-

[a]Presented at the Third Symposium in Particulate Sampling and Measurements.

sidered essential to study and characterize Shuttle effluents and to assess their possible environmental effects. NASA is now applying some of the measuring techniques developed for the Titan studies to measure and characterize effluents from the Shuttle. Measurements were conducted when Space Shuttle 1 was launched on April 12, 1981.

The solid propellant rocket motor consists of an ammonium perchlorate oxidizer, an aluminized synthetic-rubber binder fuel, and various other additives to stabilize mass and to control the burning rate. The major constituents after combustion are hydrogen chloride (HCl), water vapor (H_2O), and aluminum oxide (Al_2O_3) particles. During the Shuttle 1 launch, HCl and Al_2O_3 particles were sampled in the exhaust cloud. The results of the HCl measurements are reported in reference 2. In this report, results of size distribution measurements (mass versus particle diameter) of the suspended particles in the cloud are presented.

It is believed that the Al_2O_3 particles and foreign debris particles entrained in the cloud play important roles in the evolution and dispersion of the cloud. For example, very large particles (>100 μm diameter) are expected to rain out of the cloud rapidly and sediment to the ground within a few kilometers of the launch site. Submicron particles, on the other hand, may serve as nuclei for condensation of the HCl vapor, thereby forming acid droplets which could grow and precipitate out along the cloud path. Coagulation among the particles will contribute to particle growth, causing a time-varying size distribution and possibly forming particles large enough to be eventually removed from the cloud by settling. A possible deleterious effect on local agriculture may result. In addition, submicrometer- and micrometer-size particles may possibly reach stratospheric altitudes and remain suspended for long periods of time. It is, therefore, of interest to investigate the possible effects on climate, through scattering and absorption of solar and terrestrial radiation, by an accumulation and global distribution of particles in the stratosphere resulting from many Shuttle launches. Other concerns are the possible pulmonary effects on man and animals and possible participation of particles i chemical and physical processes with other constitutents of the exhaust cloud.

Our efforts were focused on measuring the size distribution of these particles by use of an airborne cascade impactor with a real-time measuring capability. Some limited postflight analyses [scanning electron microscopy (SEM)] have been performed on the size-segregated particles captured by the impactor. The scattering coefficient in the ambient air and in the exhaust cloud was measured with an integrating nephelometer. Selected results and discussion from these measurements are presented herein.

MEASUREMENTS

The Space Shuttle 1, Columbia, was launched from the Eastern Test Range on April 12, 1981. After lift-off, the exhaust plume, because of weak inversion conditions, split into several cloud segments that moved in different directions and at different altitudes. The sampling aircraft (Cessna 402) penetrated one cloud segment (cloud A) at approximately 8.5 min after lift-off and followed it with repeated penetrations at roughly 2-min to 5-min intervals for about 37 min. This cloud moved in a northerly direction while rising from an altitude of 650 m to 905 m. The relative humidity in this cloud was about 60 percent. A second cloud segment (cloud B), moving eastward at a higher altitude between 1350 m and 1880 m, was similarly sampled from 49 min after lift-off to 2 hr and 8 min after lift-off. This was a much drier cloud with a relative humidity of about 15 percent.

An integrating nephelometer aboard the aircraft measured scattering coefficient (b_{scatt}) in the ambient air and in the exhaust cloud. The scattering coefficient is related to aerosol concentration and, therefore, serves as an excellent means of mapping the cloud profile in addition to providing a rough indication of particle concentration. Figures 1(a) and 1(b) show plots of b_{scatt} versus time after launch, as the aircraft flew through the two different cloud segments. The peaks and valleys in the curve are indicative of the patchiness of the cloud, indicating that the aerosol distribution is not symmetrical. In general, the mean value of b_{scatt} per pass through the cloud decreased as time progressed, suggesting that the cloud was expanding or dispersing with time. However, it was not possible to obtain an expression for decay because the exact path through the cloud center was not flown during each pass. For example, on one pass, the aircraft may have flown through the center of the cloud, and on another pass it may have flown near the edge, where the concentration would have been lower.

The particle size distributions were measured during each pass through the cloud by sampling the particles with a quartz crystal microbalance (QCM) cascade impactor (ref 3). The QCM separates the particles into ten-size intervals by inertial impaction. The mass of the particles that impact each stage of the cascade is measured in real time by a piezoelectric microbalance. The QCM covers a size range of 0.11 μm to greater than 40 μm geometric mean aerodynamic diameter.

Table 1 gives the mass concentration per log size interval ($\Delta C/\Delta \log D$), as measured by the QCM in cloud A and cloud B at various times after lift-off. Because of readout problems associated with liquid droplets impacting in stages 1 and 2 of the impactor, no useful data were obtained on concentrations for particles larger than 10.7 μm diameter. Size distribution plots ($(\Delta C/C)\Delta \log D$ versus D) are shown in figure 2(a) for three passes through cloud B. ΔC is the mass concentration in a given stage of the impactor; C is the total concentration summed over all sizes; and D is the geometric mean aerodynamic diameter. Figure 2(a) and the data for cloud A in table 1 show that the size distributions measured in cloud A are all very similar. There is a relative abundance of very small particles. The peak concentration at 0.11 μm diameter or less represents at least 55 percent of the total mass summed over all sizes. More than 85 percent of the mass falls in the size range less than 0.17 μm diameter.

In sharp contrast to the size distributions in cloud A, the size distribution in cloud B [fig. 2(b)] has peak concentrations near 5.4 μm diameter with more than 35 percent of the mass at that size. In measurements of Titan exhaust clouds, bimodal size distributions were found (ref. 4) in contrast to the two single mode distributions found in the two separate cloud segments here. However, some of the Titan bimodal size distributions have peaks occurring at about the same sizes (0.11 μm and 5.4 μm geometric mean diameter) as were observed in the single mode distributions here (ref. 5). It is probable that the two cloud segments developed differently because they mixed with different types of air masses. There was, for example, a noted difference in altitude and relative humidities in the two clouds, with cloud A having about 60 percent relative humidity and cloud B having about 15 percent relative humidity. It appears that coagulation may have contributed to the peak at 5.4 μm in cloud B. Evidence of coagulation is seen by the agglomerate in the scanning electron microscope photograph in figure 3. These particles show only Al in the energy x-ray spectra and are presumed to be Al_2O_3 because of their shape. Note that the b_{scatt} values for cloud A are much higher than values for cloud B, which is consistent with the preponderance of small particles in cloud A versus cloud B because the nephelometer and visibility, are much more sensitive to smaller particles.

The relatively low concentrations of particles larger than 10 µm, as indicated by the size distribution plots in figures 2(a) and 2(b), suggest that larger particles may not be present in the cloud. However, particles larger than 40 µm were found in stage 1 of the cascade impactor, as shown in figures 4(a) and 4(b). These large particles consist of smaller Al_2O_3 spheres which apparently combined in the cloud by coagulation. It was not possible to quantify these particles by mass because of the readout problems in stages 1 and 2 mentioned earlier. Compared to the smaller particles, the number of these large ones is relatively small, but because of their large size, the relative mass could be significant.

The small single spherical particles surrounded by the dark spots in figure 4(a) are Al_2O_3 spheres. The dark spots are thought to be caused by liquid coatings of HCl on the particles which later evaporated leaving the dark stains. There is also etching of the nickle electrode in these regions, apparently caused by the HCl. Thus, we see evidence of the HCl condensing on the particles forming HCl droplets.

Spherical-shaped particles, showing energy dispersive x-rays for aluminum only, were found in stages 4, 5, 6, and 7, corresponding to geometric mean diameters of 5.4 µm, 2.6 µm, 1.3 µm, and 0.69 µm, respectively. Figure 5(a) is a scanning electron microscope photograph showing an example of these particles in stage 6. Figure 5(b) shows an aluminum mapping. The light spots indicate the presence of aluminum. These are presumed to be Al_2O_3 particles from combustion. Mixed with these Al_2O_3 particles in stages 5 and 6 is a background of amorphous material which shows a complex x-ray spectrum indicating the presence of: Na, Mg, Al, S, Cl, Ca, and Fe. These same materials have been found in the same size ranges in Titan exhaust clouds (ref. 6). In impactor stages 8, 9, and 10, corresponding to geometric mean diameters of 0.33 µm, 0.17 µm, and 0.11 µm, the morphology of the material becomes very complex and irregular with both solids and liquids present. X-ray energy scans show Na, S, Cl, Fe, Zn, and K, in addition to the Al. These elements are likely present in the background air.

CONCLUSIONS

Measurements in two separate segments of the Space Shuttle exhaust cloud revealed a difference in particle size distributions in the two clouds. The lower altitude cloud segment (between altitudes of 650 m and 950 m) was sampled up to 37 min after lift-off and had a peak mass concentration at 0.11 µm geometric mean diameter. A second cloud segment (between altitudes of 1,350 m and 1,880 m) was sampled from 49 min until more than 2 hr after lift-off and had a peak mass concentration at 5.4 µm. Postflight analysis of the size-segregated particles revealed the presence of some particles larger than 40 µm diameter. Evidence of coagulation among particles in the cloud is seen from scanning electron microscope photographs. The particles larger than 2.6 µm diameter are almost all Al_2O_3 spheres, whereas the Al_2O_3 spheres, 2.6 µm and smaller, are mixed with amorphous materials consisting of Na, Mg, Al, S, Cl, Ca, and Fe. In addition, there is evidence of HCl condensing on the Al_2O_3 particles forming large droplets.

Recently, there has recently been some concern shown over the possible effects of the large particles containing HCl dropping out of the cloud. Future efforts will be directed toward quantifying these large particles in the cloud, and flights underneath the cloud will be made to detect the dropout of these particles.

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TABLE 1.- MASS CONCENTRATION[a] PER LOG SIZE INTERVAL MEASURED IN EACH STAGE OF THE QCM IMPACTOR

[$\Delta C/\Delta \log D$ $\mu g\ m^{-3}\ \mu m^{-1}$]

QCM stage	GMD (μm)	Data for cloud A			Data for cloud B		
		Pass 1	Pass 3	Pass 6	Pass 11	Pass 15	Pass 20
		8.5 min after lift-off	19.1 min after lift-off	31.1 min after lift-off	57.8 min after lift-off	95.6 min after lift-off	109.8 min after lift-off
3	10.7	34	2	0	40	30	18
4	5.4	12	2	0	163	152	110
5	2.6	21	3	4	66	70	50
6	1.32	18	6	5	68	68	22
7	.69	0	4	10	27	34	18
8	.33	19	10	9	11	8	6
9	.17	172	145	133	31	18	8
10	.11	321	229	203	22	22	19

[a]Estimated uncertainty in mass concentration is <1 $\mu g\ m^{-3}$.

Symbol definition:

GMD = geometric mean diameter.
QCM = quartz crystal microbalance.

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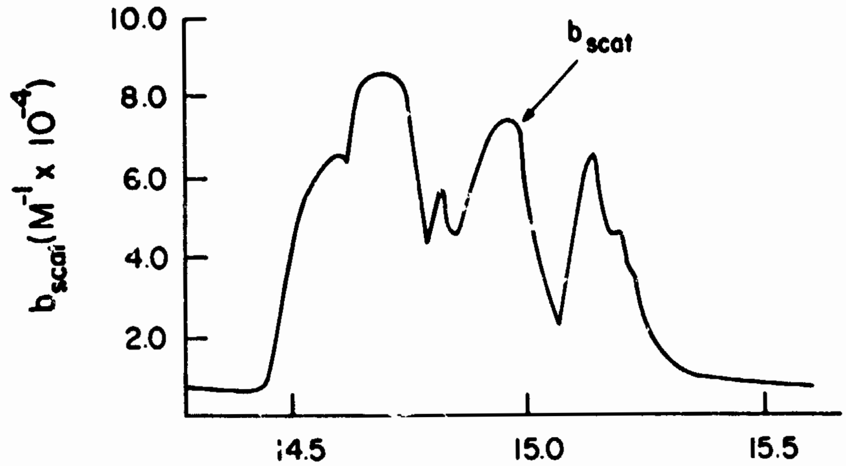
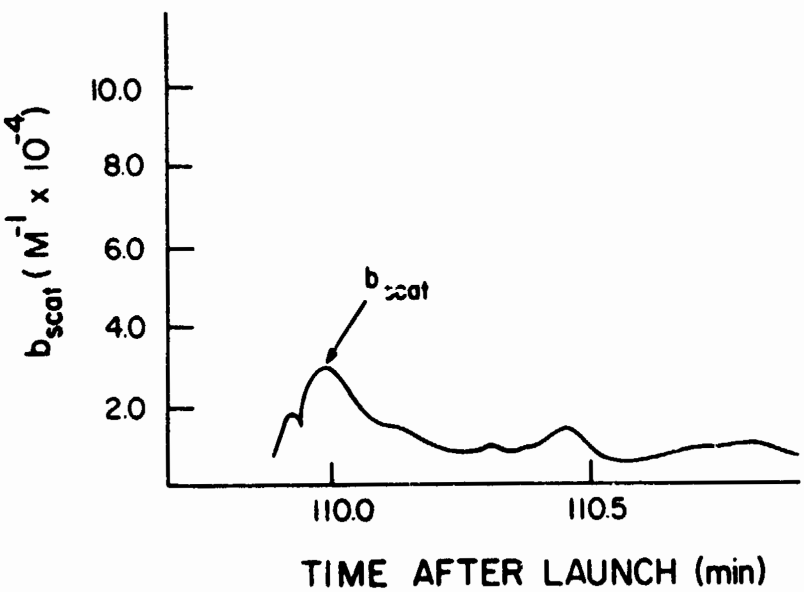


(a) cloud A



(b) cloud B

Figure 1.- Scattering coefficient plots as a function of time after lift-off of Space Shuttle 1 measured with an integrating nephelometer in cloud A and cloud B.

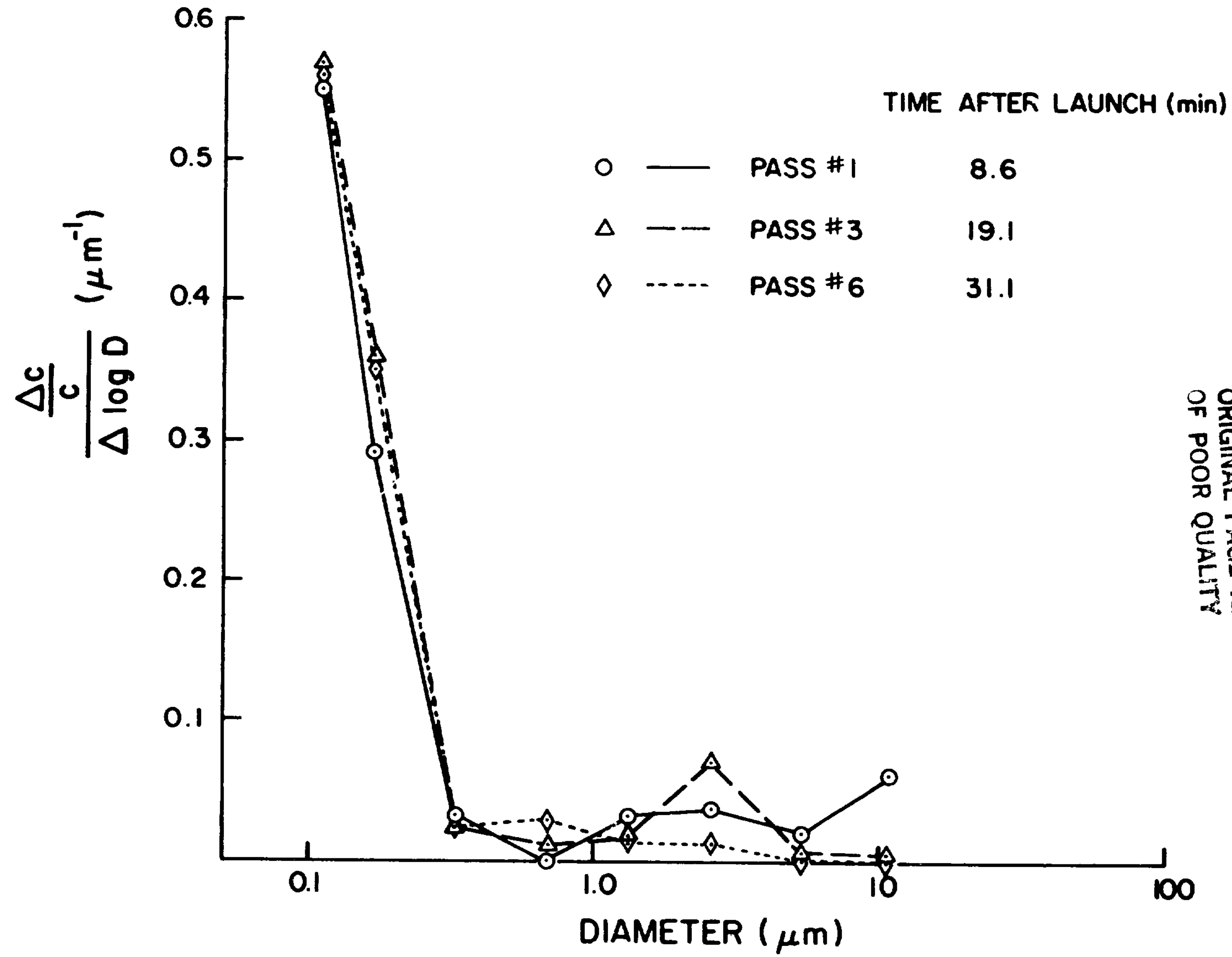


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Figure 2(a).- Size distribution plot for cloud A of normalized mass concentration per log size interval $\frac{\Delta C}{C}$ log D as a function of particle diameter D.

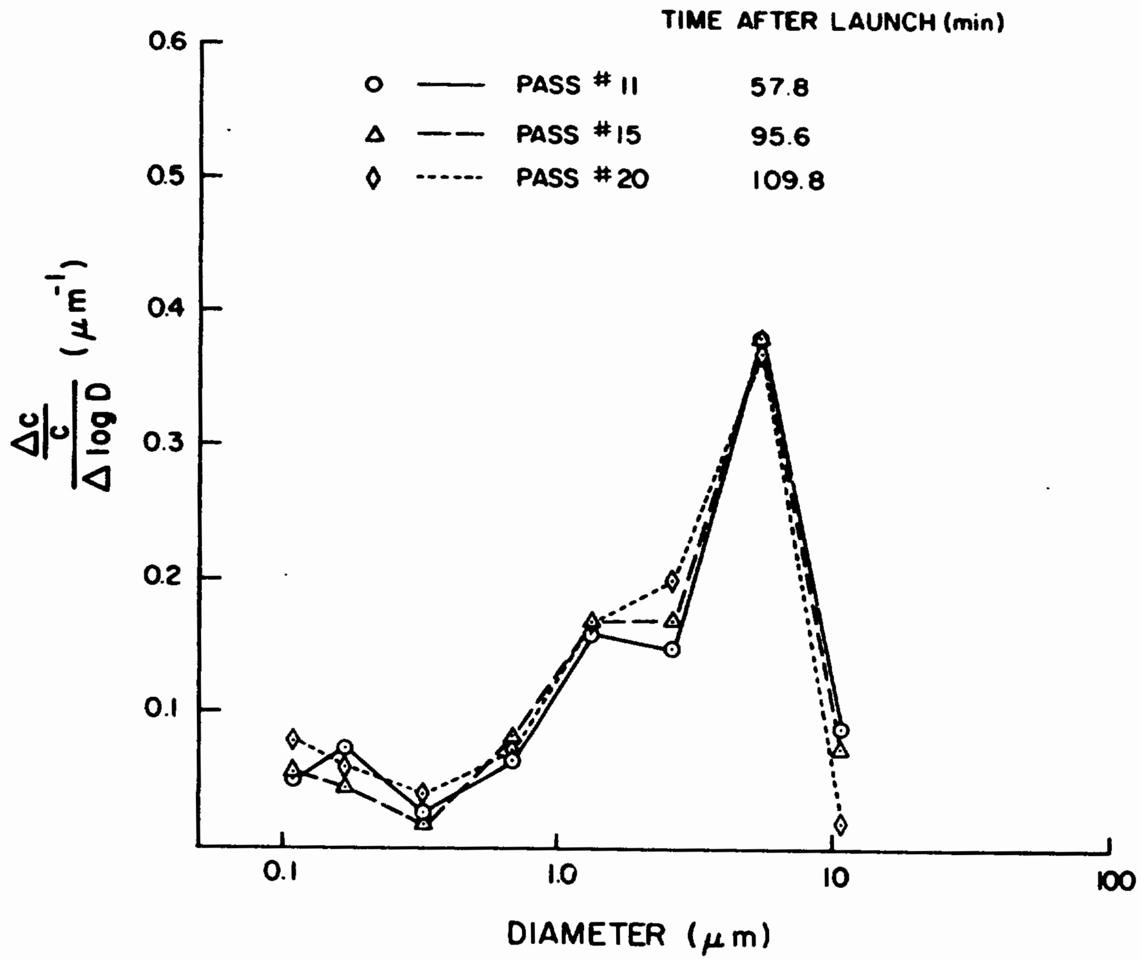
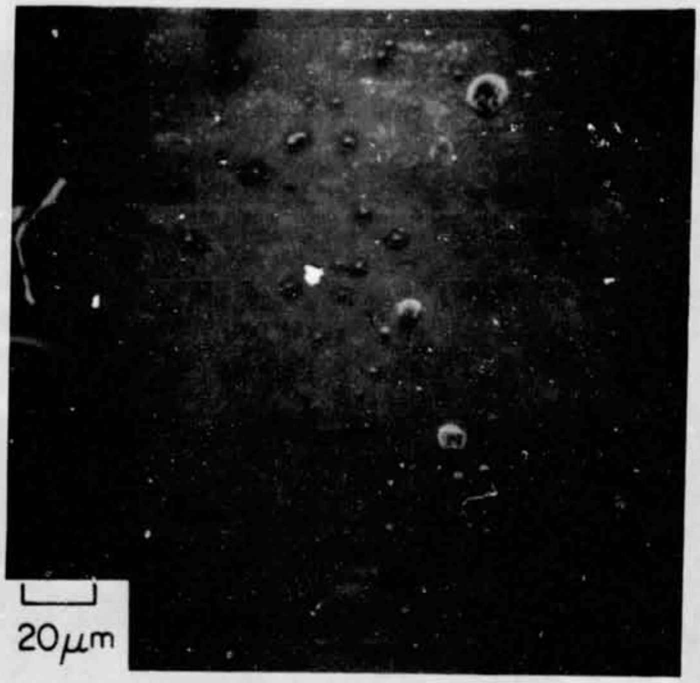
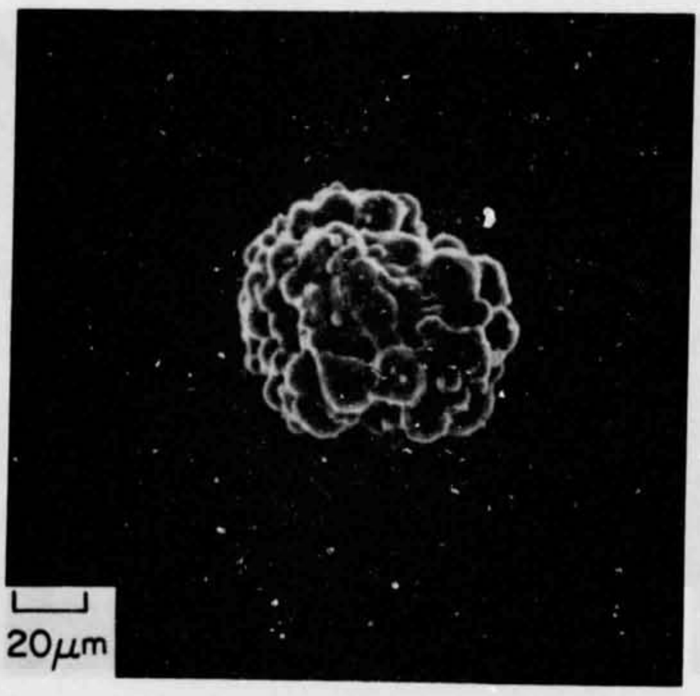


Figure 2(b).- Size distribution plot for cloud B or normalized mass concentration per log size interval $\frac{\Delta C}{C}$ log D as a function of particle diameter D.

Figure 3.- Scanning electron microscope photograph of seven aluminum oxide particles that coagulated and formed one large particle. These particles impacted in stage 4 of the QCM impactor corresponding to a geometric mean aerodynamic diameter of 5.4 μm.

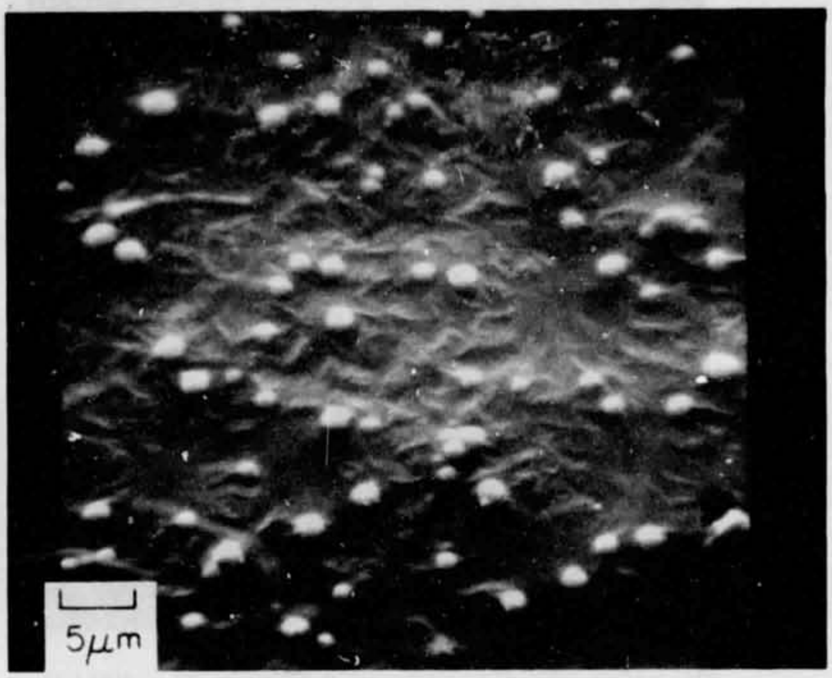


(a) Large agglomerates, some over 40 μm diameter

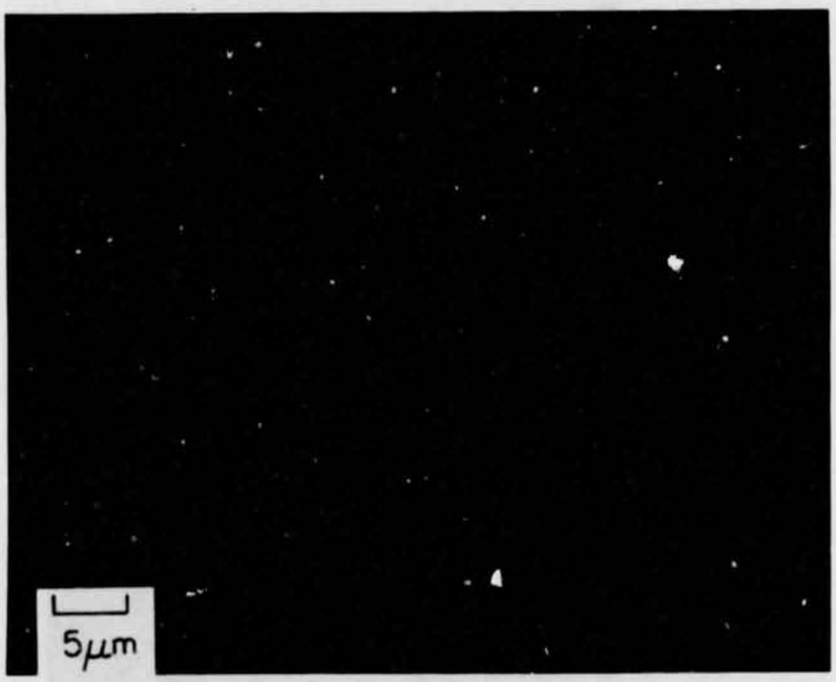


(b) Higher magnification of the large particle near the center of (a)

Figure 4.- Scanning electron microscope photograph of aluminum oxide particles collected in QCM stage 1.



(a) Scanning microscope photograph of aluminum oxide particles



(b) X-ray energy mapping for aluminum particles

Figure 5.- Scanning electron microscope photograph of aluminum oxide particles collected in stage 6 of the QCM impactor corresponding to a geometric mean aerodynamic diameter of 1.32 μm and an x-ray energy mapping for aluminum of particles in (a).

SHUTTLE ENVIRONMENTAL EFFECTS: AEROSOL PARTICULATES - STS-2 AND STS-5

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INTRODUCTION

Since 1972, the National Aeronautics and Space Administration (NASA) has been conducting launch vehicle effluent (LVE) measurements at selected NASA and U.S. Air Force launches for the purpose of investigating the environmental impact of launch vehicle emissions (mainly solid-rocket motor exhaust) on tropospheric air quality. The initial program goal was to assess the applicability and accuracy of diffusion models for predicting the dispersion of exhaust effluents from NASA launch vehicles, culminating with the Space Shuttle. Later, program emphasis shifted to developing and verifying the Shuttle environmental impact statement. Current program goals focus on obtaining data bases to assist in the determination of the environmental effects of Shuttle launches.

One approach employed by Langley Research Center personnel to meet these objectives was to measure the ambient concentration of rocket engine exhaust products within the exhaust clouds formed at launches. These exhaust products are mainly hydrogen chloride (HCl) and particulates. Early LVE measurement activities concentrated mainly on the Titan III launch vehicle (the nation's then largest solid rocket), which used a solid-rocket fuel similar to that now employed by the Space Shuttle. To obtain within-cloud measurements, NASA instrumented a twin-engine aircraft (Cessna 402) with particle and gas insitu type sensors.

Only activities associated with measuring the particulates are discussed in this paper. A summary of the Titan, STS-1, STS-2, and STS-5 activities to date are given in figures 1 through 3. These summaries, the results obtained from the measurements, and the conclusions and/or current status of the program are presented herein without the reams of supporting data and detailed analyses.

INITIAL EFFORTS

Particulate measurements were made during the 1970's of Scout, Delta, Apollo, and Titan launch clouds. Particulate samples were collected using a 6-stage quartz crystal microbalance (QCM) inertial cascade impactor with a range of 0.05 μm to 1.6 μm diameter. Later a 10-stage extended range QCM impactor was used, measuring 0.05 μm to 25.0 μm diameter particles. These cascade collectors separate the particles inertially and classify them according to aerodynamic mean diameter. The largest particles are collected in the first stage, and each succeeding stage progressively collects smaller particles. The inlet was heated to evaporate moisture from the hydroscopic particles prior to entering the instrument. Real-time electronic readout was provided.

Typical results showed that the mass concentration as a function of particle size (diameter) was bimodal (contained two major-size concentrations), with concentrations of smaller particles centered between 0.05 μm and 0.1 μm diameter and larger particles centered between 0.8 μm and 1.0 μm diameter. Further investigations, using postflight electron scanning microscopy and x-ray analysis, showed that the particles in the two modes are different, both morphologically and chemically. The largest particles retained in the first stages of the QCM were fewer in number than in the smaller-size mode. They consisted of aluminum oxide spheres and other particles containing sodium and chlorine. The particles in the latter stages consisted of a few spherical particles and a large number of agglomerates. The elemental makeup of these particles included traces of sodium, aluminum, sulfur, chlorine, potassium, calcium, iron, and zink.

STS-1 RESULTS

For results of STS-1, refer to Characterization of Suspended Particles in the Space Shuttle Exhaust Cloud - STS-1.

STS-2 RESULTS

STS-2 was launched November 12, 1981. Concern over possible effects of the large particles containing HCl droplets falling out of the cloud prompted the installation of an Optical Array Cloud Droplet Spectrometer Probe, replacing the QCM instrument for STS-2 cloud measurements. The Spectrometer Probe (PMS model OAP-200X), commonly called a 'Knollenberg', extended the range to cover particles from 20 µm to 300 µm in diameter.

Unlike the QCM, the Knollenberg instrument is a particle counter which counts particles in various size ranges. The total mass concentration is obtained by multiplying the number of particles counted by the mass of one particle (spherical shape and chemical composition are assumed) of Al_2O_3. This procedure is repeated for each size range, which in this case was 15 channels.

Mass concentrations of 1×10^3 to 1×10^4 were representative of the early passes (see figs. 4 through 9, lower plot), but the count of large particles (20 µm to 300 µm diameter) falls off rapidly with time.

The integrating nephelometer indicated scattering coefficients of from 1×10^{-3} early in the cloud to 1×10^{-4} after the cloud dispersed. These βscat values are slightly less than, but of the same order as, those measured in the STS-1 exhaust cloud.

STS-5 RESULTS

STS-5 was launched November 11, 1982. The Knollenberg instrument was further modified for the STS-5 launch to extend the range to the 28 µm to 600 µm size range. And again, the integrating nephelometer was used.

Preliminary analyses show that large particle (≈100 µm diameter) counts of approximately 50 counts per pass were recorded (similar to that for STS-2) by the spectrometer probe. The integrating nephelometer measured the mass loading of small particles (0.2 µm to 10 µm) to range from 150 µg/m^3 up to a maximum of 200 µg/m^3. A detailed analysis of STS-5 particulate data is currently in progress.

CONCLUSIONS

- Some large particles containing HCl coatings do exist, but these large particles are few in number by the time the sampling aircraft gets into the cloud.
- Small particles differ markedly from the larger particles.
- Al_2O_3 particles coagulate to form large particles within the cloud and show evidence of condensed HCl droplets.
- The particulates contain many trace elements which could be contributed from the ambient background air.

TITAN AND STS-1

- SIZE DISTRIBUTION IN THE SHUTTLE PLUME ARE SIMILAR TO THOSE IN TITAN PLUMES IN THE SIZE RANGE <10μm DIAMETER.
  - THEY ARE BIOMODAL WITH ONE PEAK BETWEEN ABOUT 0.8μm, AND SEVERAL MICRONS AND ONE PEAK BETWEEN ABOUT 0.1μm AND 0.5μm.
  - THE LARGE SIZE MODE CONTAINS MOSTLY Al_2O_3 PARTICLES, WHICH ARE VERY SPHERICAL IN SHAPE AND USUALLY COATED WITH HCl.
- THERE WERE SOME VERY LARGE Al_2O_3 PARTICLES, PROBABLY COLLECTED VERY EARLY IN THE CLOUD (≈40μm DIAMETER) ALSO COATED WITH HCl.

Figure 1.- Summary of particle information, Titan ard STS-1.

STS-2 AND STS-5

- THERE WERE SOME VERY LARGE PARTICLES BETWEEN 20μm AND 300μm MEASURED VERY EARLY IN THE CLOUD UP TO ≈45 MINUTES, BUT THE INITIAL CONCENTRATIONS BY NUMBER WERE VERY LOW < 0.1 PARTICLES/cm^3. THESE LARGE PARTICLES WERE NONEXISTANT AFTER ABOUT 45 MINUTES, PROBABLY BECAUSE OF RAPID DROPOUT.

- SINCE THE LARGE PARTICLES WERE MEASURED BY LIGHT SCATTERING TECHNIQUES, THEY WERE NOT COLLECTED AND ANALYZED, BUT THEY MOST PROBABLY CONSIST OF COMBINATIONS OF Al_2O_3, LIQUID HCl, AND PAD DEBRIS.

Figure 2.- Summary of particle information, STS-2 and STS-5.

GENERAL

- NEPHELOMETER TRACES INDICATED THAT ALL OF THESE CLOUDS WERE PATCHY AND DISPERSED, AND THEY DECREASED IN CONCENTRATION WITH TIME.

Figure 3.- General conclusion pertaining to exhaust clouds.

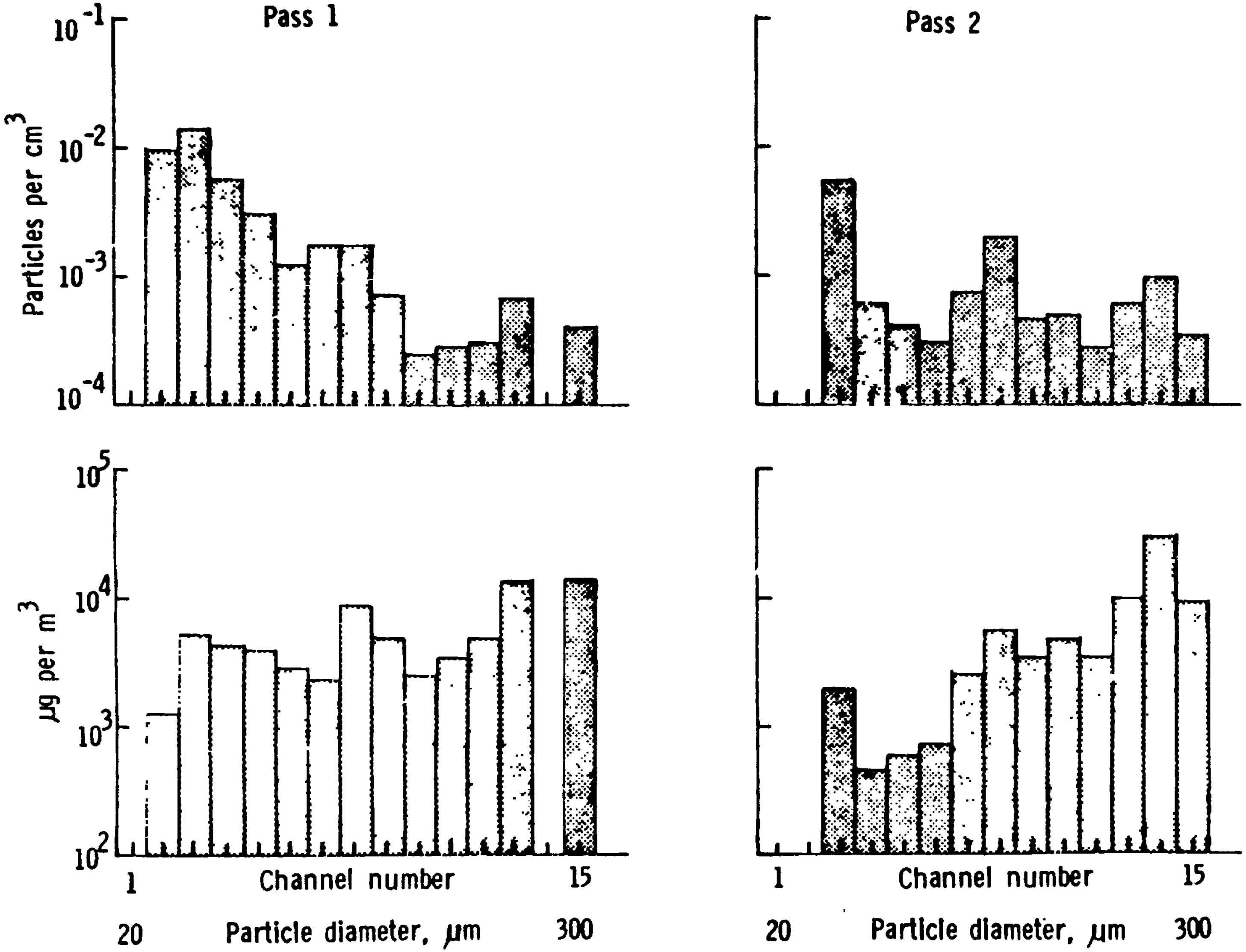

Figure 4.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 1 and 2.

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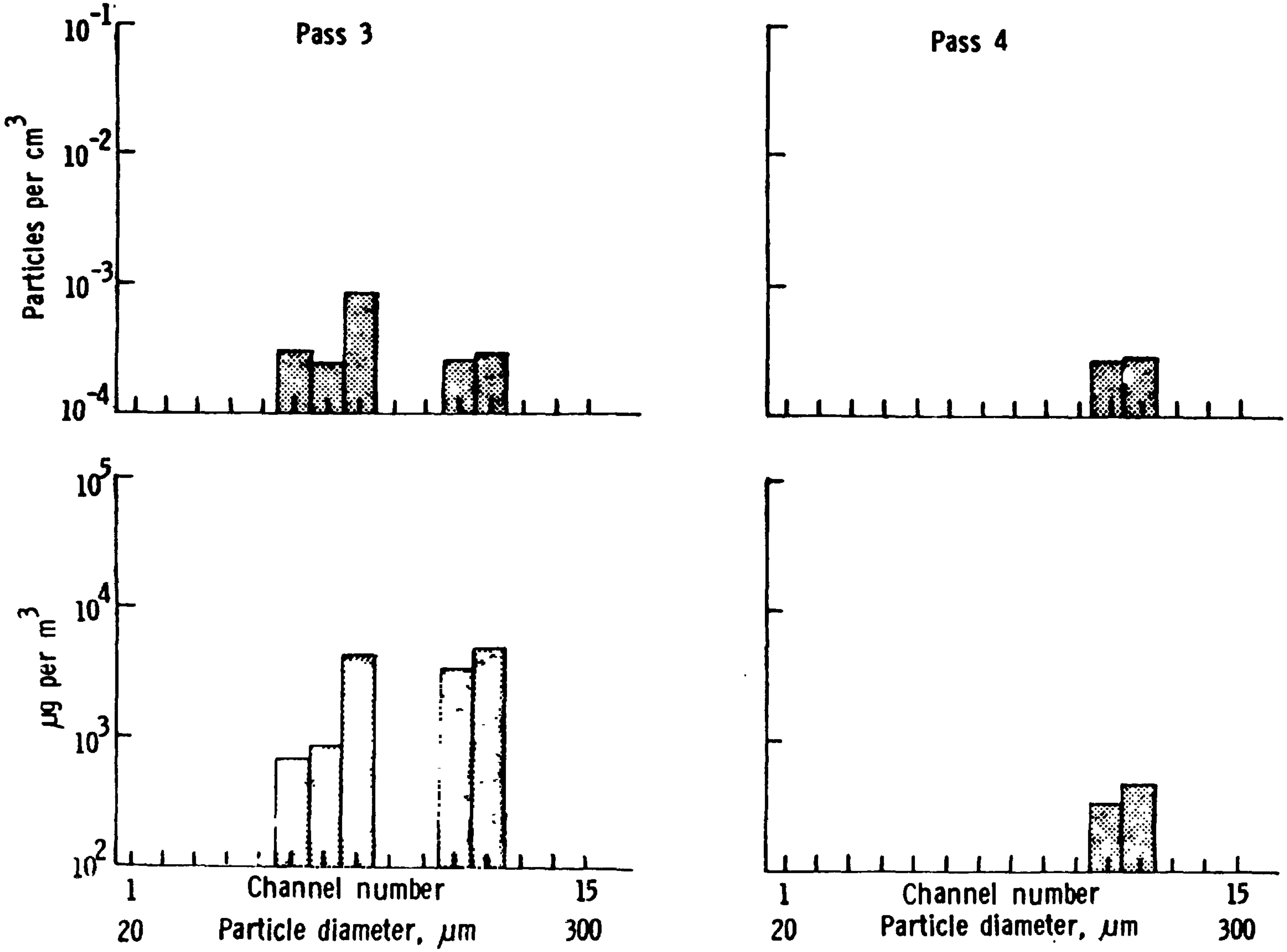

Figure 5.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 3 and 4.

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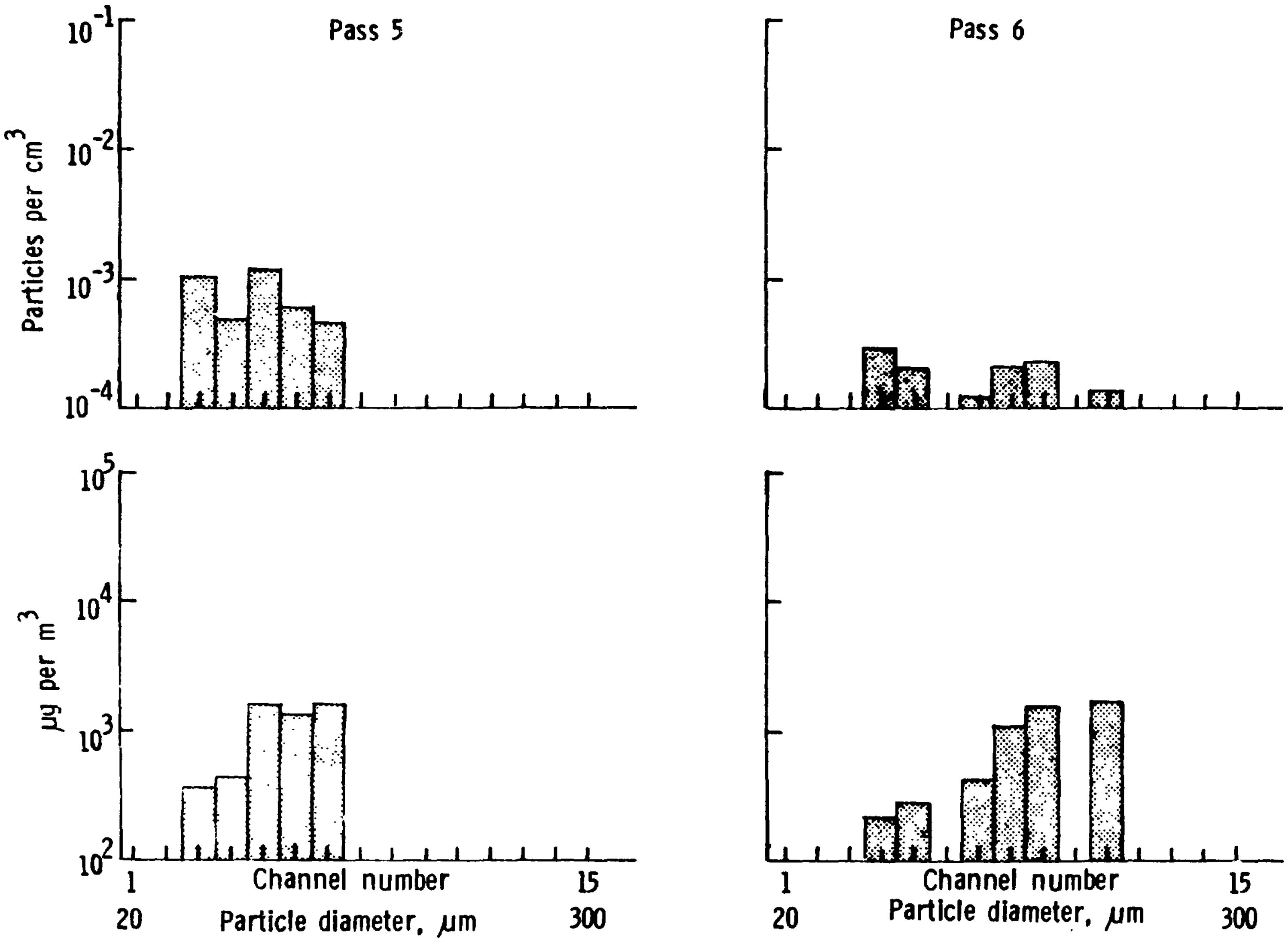

Figure 6.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 5 and 6.

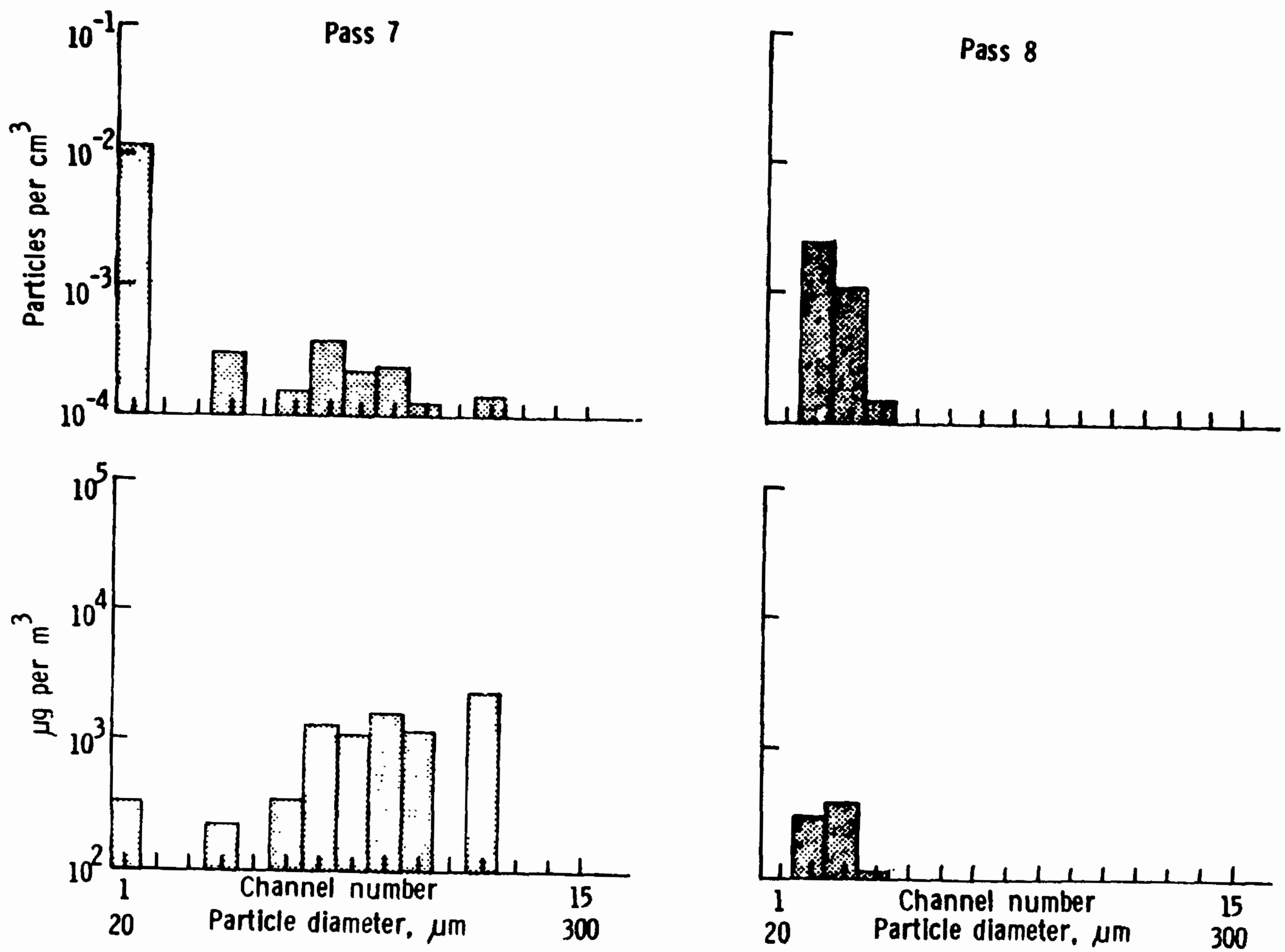

Figure 7.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 7 and 8.

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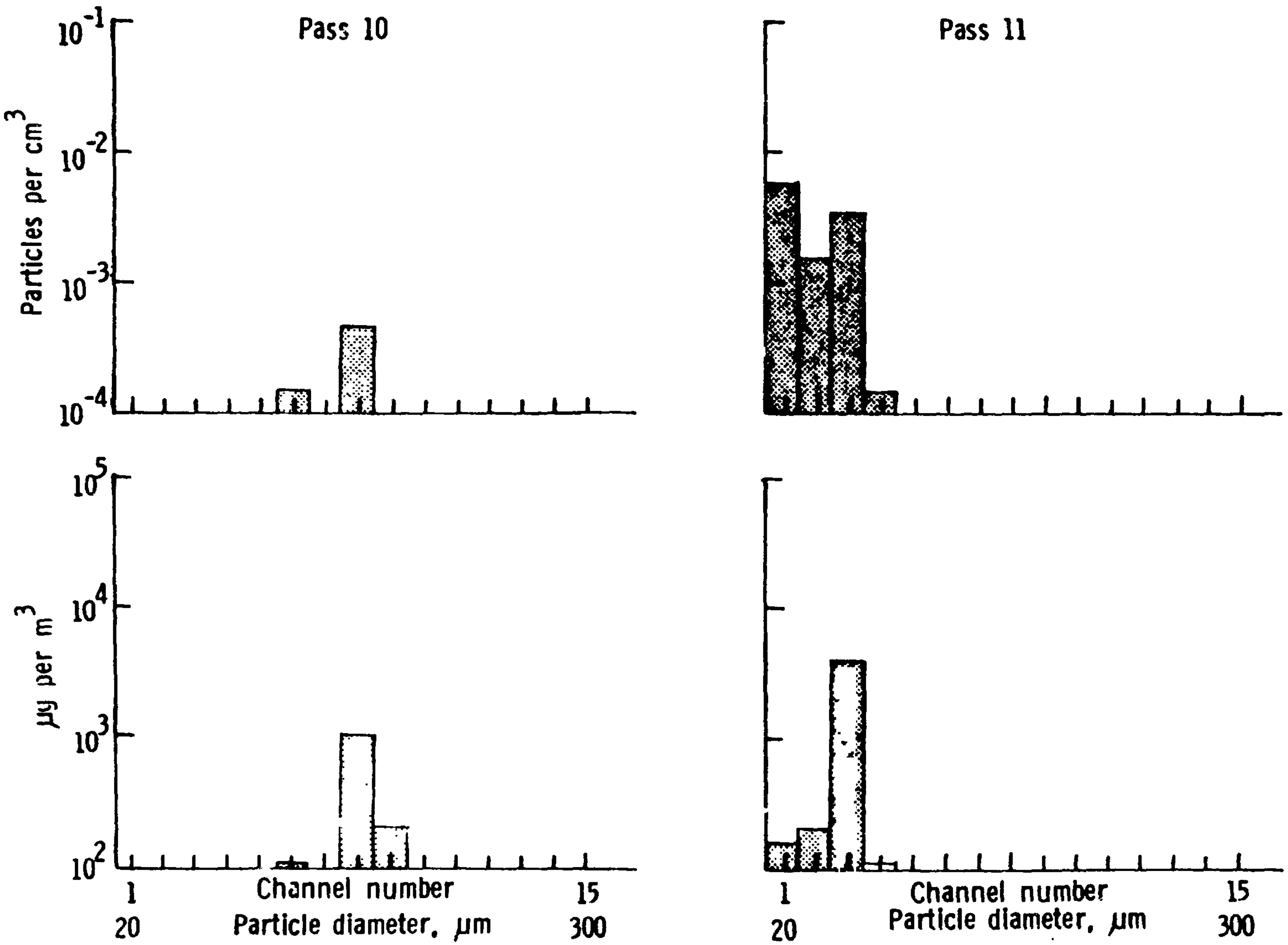

Figure 8.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 10 and 11.

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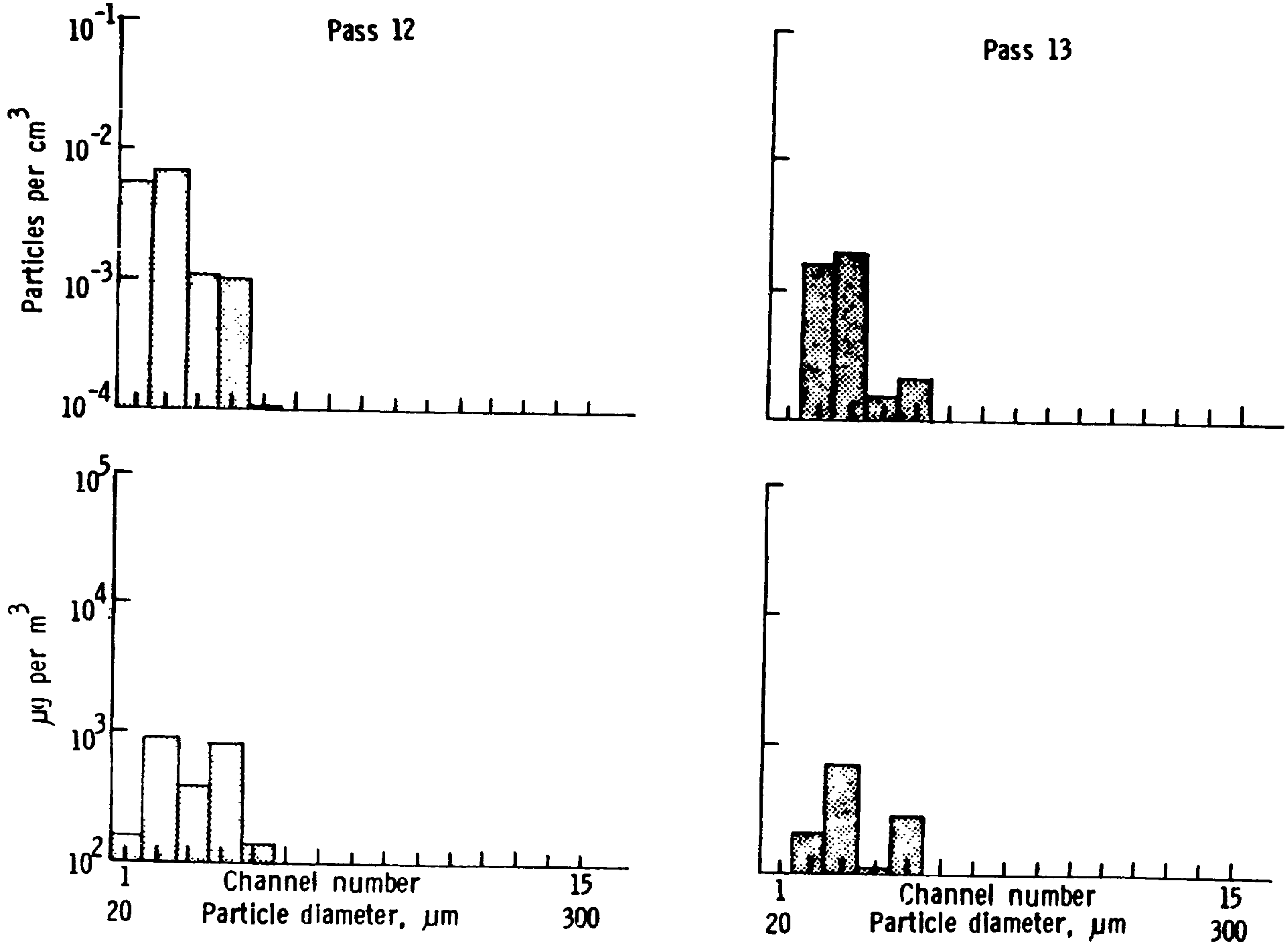

Figure 9.- Various size ranges/total mass concentrations of particles obtained from 15 channels, Passes 12 and 13.

ALUMINUM OXYCHLORIDE FORMATION ON SPACE SHUTTLE EXHAUST ALUMINA

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ABSTRACT

Aluminum oxide samples from the exhaust of Space Shuttle STS-1, STS-4, and STS-5 launches were analyzed. The water soluble fraction, pH, acid soluble fraction, and insoluble fraction were determined for each sample. The X-ray diffraction analysis of the insoluble particulate fractions (always > 72 percent of the sample weight) indicated that these fractions were α - Al_2O_3, and thus confirmed that the five samples analyzed were Space Shuttle alumina. Calcium, magnesium, potassium, ammonium, and sodium ions were measured as indicators of the amount of ground debris or sea salt particles incorporated into the samples. All samples analyzed contained significantly elevated amounts of water soluble chloride and aluminum (III) ion. Results from these analyses and from laboratory experiments, in which calcination produced aluminas were exposed to gaseous HCl and H_2O mixtures from room temperature to 220° C, suggest that the surface of the Shuttle exhaust alumina particulates should be viewed as having more of the characteristics and properties (e.g., hydrophilicity) of aluminum chlorides and oxychlorides than of aluminum oxides.

INTRODUCTION

Hydrogen chloride (HCl) and aluminum oxide (Al_2O_3) are primary exhaust effluents of ammonium perchlorate/aluminum-based solid-propellant rocket motors (SRM's). With the current and projected emphasis on large reusable SRM boosters (particularly with the Space Shuttle), the impact of these SRM effluents on the chemistry of the troposphere and stratosphere must be carefully evaluated. The Space Shuttle SRM's release as exhaust about 276,000 kg of Al_2O_3 and about 163,000 kg of HCl during each launch (ref. 1). According to the Space Shuttle Environmental Impact Statement (ref. 2), about 63 percent of the SRM effluent is released in the troposphere and the remainder in the stratosphere, up to about 43km altitude. While the potential impact of the Shuttle exhaust on the atmosphere must be examined from many vantage points, this paper will focus on the particulate exhaust alumina and its likely surface composition after chemical interaction with HCl and H_2O in a Shuttle (or SRM) exhaust plume. Some of the chemistry of the $HCl/H_2O/Al_2O_3$ system will be examined, as well as how this chemistry may lead to modifications of the particulate alumina surface. In this paper, previously documented laboratory and field results for SRM alumina will be compared with new results from laboratory experiments and from the analysis of actual samples of Space Shuttle alumina. The modifications to the particulate alumina surface from reaction with HCl and H_2O, discussed in this report, may be of major importance in assessing the role of these particles as nucleation sites for atmospheric water and ice. Such considerations are of current interest (ref. 3).

Aluminum oxide from SRM exhaust has been shown to consist of both the alpha and gamma crystalline phases (refs. 4 and 5), with the majority of particles falling in the 0.05 to 0.3 micrometer range (refs. 6, 7, and 8).

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Bailey and Wightman (ref. 9) have studied the sorptions of HCl and H_2O, separately, on both alpha and gamma aluminum oxide particles. They found that water-vapor adsorption involved only physisorption; however, HCl was chemisorbed, and this was approximately 60 percent irreversible under nitrogen at atmospheric pressure. Cofer and Pellett (ref. 10) characterized the simultaneous sorptions of gaseous HCl and H_2O on calcination-produced gamma and alpha alumina at room temperatures and pressures and concluded that a nearly unimolecular layer of a hydrated chemisorbed chloride phase resulted. The chemisorbed chloride phase was predominately water soluble as a chloride. Mole ratios of about 3.3/1 soluble chloride to aluminum (III) ion were obtained, suggesting that substantial chloride dissolved as an aluminum salt and that water soluble aluminum chlorides and/or oxychlorides were likely formed from surface reactions of HCl and H_2O with the alumina. Cofer (ref. 11) further demonstrated with laboratory experiments that the surface chloride phase was significantly more hydrophilic than the corresponding 'pure' alumina surface. Dillard et al. (ref. 12) identified aluminum chloride as one of the major aluminum-containing species in SRM exhaust from samples collected in the boundary layer.

EXPERIMENTAL

Five samples of Space Shuttle exhaust alumina were chemically analyzed. Three of the samples were collected from the first level of the fixed service structure where the alumina had accumulated during launch in the corners of the steel I-beams. These samples were collected within 4 hours after launch of STS-1, STS-4, and STS-5 and consisted of about 3 grams of aluminum oxide per sample; these samples are designated STS1P, STS4P, and STS5P in this text. Another sample of about 0.5 gram (STS5W) was collected from the leading wing surface of a twin-engine light aircraft, used somewhat routinely to penetrate and monitor SRM effluents (ref. 13) in the stabilized ground clouds (typically about 1.5 km altitude) after launches at the John F. Kennedy Space Center (KSC). The fifth sample, designated STS5G, was collected from grass samples about 300 meters directly behind the flame trench. Copious amounts of dust (presumably Al_2O_3) had been observed to have accumulated on the surface of the grasses after Shuttle launches. Cuttings of this grass were shaken over a container to collect the Al_2O_3. Eleven and two-tenths grams of material were collected. Since the reactions of gaseous HCl and H_2O with aluminas had been found in the laboratory to produce water soluble aluminum chloride and/or oxychlorides (ref. 10) and the same basic chemistry was anticipated for the alumina in the cooled SRM exhaust plume, an aqueous chemical anaysis protocol was employed for the Shuttle samples. An attractive aspect of aqueous analysis is that the solvated ions measured during analysis are the same ions most apt to chemically influence the nucleation/condensation processes of H_2O on the surface of the particulates in the actual atmosphere.

Samples weighing 1.73 g, 2.0 g, 2.13 g, and 0.51 g of STS1P, STS4P, STS5P, and STS5W, respectively, were placed in 100 ml of 18 megohm resistivity water, agitated for 20 minutes, and allowed to settle; then pH measurements were made with a standard glass pH electrode. Sample STS5G was processed as above except that the entire sample (11.2 g) was placed in 1000 ml of H_2O. After pH measurements, aliquots of each solution were analyzed by ion chromatography for sodium, potassium, ammonium, nitrate, chloride, and sulfate, and then by atomic absorption for calcium, magnesium, and aluminum. The solutions were then filtered to remove the insoluble particle fractions, weighed, and then acidified in hot concentrated aqua regia and agitated for 4 hours. These solutions were then filtered, dried, and weighed to determine the weight of the acid soluble fraction of the particles. The acid insoluble residue was then analyzed by X-ray diffractometry.

RESULTS

The pH's that resulted from quenching the five Shuttle samples in deionized H_2O (initial pH = 5.6) are shown in table 1. It is apparent that the three pad samples produced significantly less acidic solutions than the samples collected from the plane wing and grass cuttings. Although this result cannot be explained with certainty, the following speculation is offered. The launch pad structures are sprayed with cooling water (~250,000 gal) during launch and then washed down with water (~100,000 gal) after each launch. The interaction of the cooling water with the SRM exhaust around the structure during launch quite likely removes much of the gaseous HCl, and consequently, less HCl is available to adsorb and/or react with the alumina. Secondly, even though the alumina was collected from somewhat protected parts of the structural I-beams, some of the highly soluble portions of the alumina (specifically the chlorided portions) may have been leeched during the wash down of the structure. It is suggested, therefore, that the acidity of the wing and grass samples are probably a better reflection of the inherent acidity of SRM alumina than the pad sample.

In table 1, the water soluble fraction of the samples can be seen to fall generally in the 1 to 6 percent range. A notable exception to this occurred with STS5W, where 20 percent of the sample was water soluble. The sodium content of the wing sample, however, was exceptionally high (see table 2). Since the aircraft flew continuously in the marine boundary layer, it is suggested that a significant part of the water soluble weight fraction of this sample resulted from the concurrent collection of sea salt aerosol on the plane wings, and that water soluble weight fractions for SRM exhaust alumina in the 1 to 6 percent range are more reasonable.

Since it has been suggested that large amounts of ground debris (soil, etc.) may be entrained into SRM ground clouds during launches (ref. 14), an aqua regia digestion step was incorporated into the analysis. While silica (sand) and α - alumina would be relatively impervious to acid attack, carbonates (sea shell fragments, bits of concrete, etc.) would not, and an acid soluble fraction would result. Any unreacted γ - alumina (unreacted with respect to HCl) would also undergo dissolution in aqua regia. Both STS1P and STS5G appear to have significant aqua regia soluble weight fractions. While the grass sample was visually observed to have a small amount of sea shell fragments and sand associated with it, no such observation was made with the pad sample.

Over 72 percent by weight of the material analyzed from each of the Shuttle samples was insoluble in water and in hot concentrated aqua regia. It can be seen in table 1 that the insoluble fraction of each of the Shuttle samples (except for STS5G) is essentially α - aluminum oxide. The identification of these fractions as α - aluminas is not a trivial point, since it furnishes conformation that the samples collected were in fact Shuttle exhaust alumina. A γ - aluminum oxide peak was not observed, but would not be anticipated since γ - alumina would most likely have dissolved during the acid digestion. The small α - quartz peak observed with STS5G came as no surprise since a small amount of sand had been observed in this sample.

The weight percentages of water soluble chloride measured from the five Shuttle alumina samples (except for the wing sample, for which sea salt contamination has already been hypothesized) are in remarkably good agreement with those predicted (~2 percent) by Cofer and Pellett (ref. 10) from their earlier laboratory experiments.

The complete analysis of the water soluble ions that resulted after deionized water quenching of the Shuttle samples is shown in table 2. Particular attention should be given to the calcium, sodium, and aluminum ions since they are felt to be indicative of sea shell and concrete debris, sea salt contamination, and alumina dissolution, respectively. For example, STS5G was observed to have had small bits of sea shell fragments associated with it and, as would be expected, released a proportionately large amount (relative to the other cations) of calcium when dissolved in water.

The soluble chloride ion concentrations were high relative to the other individual ions in all cases. In addition, the chloride ion concentrations were abnormally high relative to soluble chloride concentrations and ratios found for particulates collected before and after Shuttle launches with high volume samplers (ref. 15). In short, the Shuttle alumina samples were heavily chlorided.

The interpretation of the data in table 2 must be done with the understanding that chloride ions (or any ions), once solvated in a multi-ion aqueous solution, cannot be identified with respect to their original association (i.e., which positive ions were originally associated with which negative ions before dissociation). From examination of both the pH's that resulted from quenching the five Shuttle samples in water and the concentrations of cations that resulted, it can be concluded that only the equilibrium solubility of the aluminum (III) ion in the three pad samples (pH's > 5) would be subject to any potential pH influences, as follows.

Fundamental to the interpretation of these data is the assumption that the solvated aluminum (III) ion measured in these solutions originated from the Shuttle alumina, and more specifically, that the water soluble part of the alumina was rendered soluble by prior reactions with HCl. The assumption appears reasonable since neither the α nor the γ phases of alumina are water soluble, but the γ variety has been shown to undergo dissolution to aluminum (III) ion in hydrochloric acid (ref. 16). Pellett et al. (ref. 17) have discussed the likelihood of a liquid hydrochloric acid aerosol phase developing in the boundary layer during SRM launches. The laboratory results of Cofer and Pellett (ref. 10) also confirm that water soluble aluminum (III) ion resulted after exposure of γ - aluminas to gaseous HCl and H_2O mixtures. Since α - alumina is resistant to acid attack, it is additionally suggested that the bulk of the aluminum (III) ion measured from the Shuttle samples originated primarily from the γ - aluminum oxide fraction of the SRM exhaust.

While the aluminum (III) ion concentrations appearing in table 2 may not seem particularly large relative to the other cations listed, it must be recognized that the capacity of the solvated aluminum (III) ions for monovalent chloride ion is very large. For example, in sample STS5G, the mass of soluble calcium (II) ion measured appears much larger than that of aluminum (III); however, when the oxidation states (2/3) and the atomic weights (40/27) of each element are considered, the aluminum (III) ion will accomodate 27 percent more chloride in solution than the calcium ion. In this sense, the aluminum (III) ion was found to dominate all other cations in solution except for the wing sample, which had the very large sodium content attributed to the parallel collection of sea salt aerosol.

The maximum amount of chloride that can be attributed to aluminum, that is, entering solution as an aluminum salt (more specifically as aluminum trichloride) is presented in table 3 as a percentage of the total amount of chloride found in solution. These results suggest that about half of the chloride in solution could have been originally associated with the alumina. While this assertion must certainly be viewed as speculative, reaction of SRM alumina with acid (in particular HCl) remains the most obvious and reasonable mechanism to explain the significant concentrations of solvated aluminum (III) ion analyzed in these solutions.

The analytical results obtained on the five Shuttle samples appear to be in good agreement with the earlier results on laboratory aluminas (ref. 10) in the following ways. Both the laboratory aluminas and the actual field samples were heavily chlorided after exposure to HCl. The chloride was of a water soluble form in both cases. Significant amounts of solvated aluminum (III) ion resulted when the samples were quenched in water. These observations lead the authors to suggest that aluminum salts (aluminum chlorides and/or oxychlorides) were formed on the surface of the SRM alumina as the result of interactions of HCl, H_2O, and alumina in the SRM plume.

CONCLUSIONS

Chemical analysis of the five Shuttle exhaust samples indicated that the particulate SRM alumina was heavily chlorided. The chloride was predominately in a water soluble form, of which a significant portion quite likely originated as aluminum chlorides and/or oxychlorides. Concentrations of water soluble aluminum (III) ion measured were large and suggested that the surface of the SRM alumina particles was rendered soluble by prior reactions with HCl and H_2O in the SRM exhaust cloud.

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TABLE 1.- BULK SAMPLE PROPERTIES

Sample	pH (a)	Water soluble fraction, %	Acid soluble fraction, %	Insoluble fraction, %	X-ray composition insoluble fraction	H_2O soluble chloride, %	H_2O soluble aluminum, %
STS1P	4.9	5.6	16.4	78.0	a - Al_2O_3	4.8	0.4
STS4P	5.3	2.0	9.2	88.8	a - Al_2O_3	1.6	0.2
STS5P	5.1	1.0	4.6	94.4	a - Al_2O_3	0.6	0.1
STS5W	3.4	20.0	7.4	72.5	a - Al_2O_3	11.7	1.1
STS5G	3.2	3.1	24.1	72.8	a - Al_2O_3 a - Quartz (trace)	2.1	0.3

[a]1 gram/50 ml H_2O.

TABLE 2.- WATER SOLUBLE COMPOSITION
(mg/gm sample)

Sample	Cl^-	Al^{3+}	Na^+	K^+	Ca^{2+}	Mg^{2+}	$SO_4^=$	NO_3^-	NH_4^+
STS1P	48	4.0	1.6	0.2	2.5	0.3	1.7	-	0.08
STS4P	16	1.9	0.3	0.05	1.8	0.05	0.2	-	0.02
STS5P	6.2	1.3	1.0	0.4	0.9	0.1	0.1	-	0.10
STS5W	118	10.8	45	9.0	7.0	1.6	7.8	0.01	0.02
STS5G	22	2.8	0.7	1.6	4.0	0.9	0.7	0.4	0.08

TABLE 3.- MAXIMUM ASSOCIATION OF CHLORIDE WITH ALUMINUM

Sample	H_2O soluble chloride, %	H_2O soluble aluminum, %	Percentage Cl^- as $AlCl_3$ (a)	Percentage of Cl^- as $AlCl_3$ to total Cl^- (a)
STS1P	4.8	0.4	1.6	33
STS4P	1.6	0.2	0.8	50
STS5P	0.6	0.1	0.4	66
STS5W	11.7	1.1	4.3	37
STS5G	2.1	0.3	1.2	57

[a]Percentages based on water soluble Al (III).

MICROPHYSICAL PROPERTIES OF THE SHUTTLE EXHAUST CLOUD[a]

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INTRODUCTION

A data base describing the properties of the exhaust cloud produced by the launch of the Space Transportation System (STS) has been assembled from a series of ground- and aircraft-based measurements made during the launches of STS-2, STS-3, and STS-4. The aircraft observations were made during the STS-3 launch with a National Oceanic and Atmospheric Administration (NOAA) WP-30 Orion hurricane research aircraft, with special instrumentation added for cloud condensation nucleus (CN) and ice nucleus (IN) counting, Aitken particle counting, and pH determination. Ground observations were made at a field array of approximately 50 sites and also in the direct exhaust from the Solid Rocket Booster (SRB) flame trench at all three launches. Additional data were obtained from ground-based measurements during firings of the 6.4-percent model of the SRB at the Marshall Space Flight Center (MSFC). [See the companion paper by Anderson and Keller in these proceedings.] Information on a variety of cloud microphysical properties is now available for the National Aeronautics and Space Administration's (NASA's) continuing assessment of any possible adverse impacts of the exhaust products on human health and/or the environment.

EXHAUST CLOUD EVOLUTION

During a normal burn, the two SRB's exhaust the following major gaseous and particulate constituents (ref. 1), with amounts given in kg s^{-1}.

carbon dioxide	3873
aluminum oxide	2829
water vapor	2688
hydrogen chloride	1993
nitric oxide	122
iron chloride	91

The Space Shuttle Main Engines' (SSME's) exhaust product is primarily water vapor[b] (1805 kg s^{-1}) [ref. 1]. Note that due to afterburning of hydrogen, more water vapor results from the two SRB's than from the SSME's.

During the time from ignition to shortly after liftoff (~ 8 sec), the exhaust jets of the two SRB's and the SSME's interact mechanically with the deluge water which is introduced at the launch pad prior to ignition and which continues to flow during liftoff. Although the primary purpose of the ~1.4×10^6 ℓ of deluge water used at John F. Kennedy Space Center (KSC) is to attenuate the pressure wave which results from ignition of the SRB's, it is also used for sound and fire suppression.

[a]Presented at the Ninth Conference on Aerospace and Aeronautical Meteorology, Omaha, Nebraska, June 6-9, 1983.

[b]Amounts after chemical addition of air.

During the mechanical interaction of the exhaust jets with the deluge water, a significant portion of the deluge water is vaporized and a smaller fraction is atomized. Heat and water balance calculations show that the maximum amount which can be vaporized is about 2×10^5 ℓ and the amount atomized is of the order 10^4 ℓ. It should be noted that the vaporized deluge water represents a greater portion of the total water vapor source for the exhaust ground cloud than the combined water vapor output of both SRB's and the SSME's.

In the turbulent near-pad environment, the micron-size aluminum oxide SRB exhaust particles acquire large velocities relative to the millimeter-size atomized drops. Therefore, each large drop scavenges an enormous number of small particles. Electron micrographs of 'hits' on copper plates indicate that the number of Al_2O_3 particles scavenged by each large drop is typically of the order 10^4.

Since near-pad turbulence efficiently mixes HCl exhaust gas with the ambient air, the atomized drops, as well as the small drops which form by condensational growth as the cloud cools, readily scavenge HCl gas and quickly become acidic (pH ~0.5). Most of the large acidic drops are deposited in the immediate pad vicinity. Some of the acidic drops, however, are lifted in the updrafts of the buoyant exhaust cloud as it rises to stabilization height and moves with the prevailing winds. Typical rise rate of the cloud near the ground, measured from the time-sequenced photographs, is 5 m s^{-1} to 9 m s^{-1}. Drops fall from the exhaust cloud when the updraft velocity in their portion of the cloud decays below the terminal velocity for that particular drop size. Drop fallout begins at cloud initiation and continues (sometimes intermittently depending on the evolution of the updrafts) until the drop concentration is depleted. Since stabilization height of the exhaust cloud is a function of atmospheric stability and because drop evaporation rate is a function of humidity, the atomization-scavenging-transport process results in an acidic deposition footprint on the ground which varies in location from one launch to another depending on winds, humidity, and atmospheric stability. The feasibility of neutralization of the ground cloud by addition of a buffer solution to the deluge water is being investigated.

AIRCRAFT MEASUREMENTS

A list of the relevant instrumentation onboard the aircraft that was used in making cloud microphysical measurements in the STS-3 exhaust cloud on March 22, 1982, is given in table 1. For the aerosol measurements, outside air was drawn through the cabin, sampled from an aerosol manifold, and vented to the outside. This system was designed and installed on the aircraft specifically for this flight to allow sampling from a continuous flow or from disposable 70 ℓ electrically conductive sampling bags.

During the first 1 1/2 hr after Shuttle launch, the aircraft made 20 cloud penetrations with about 2-min intervals between most penetrations in the first hour. Following this time block, 27 min were spent in clear air upwind of the cloud, collecting background data. Penetrations of the then diffuse cloud were resumed, and it was tracked for a total of over 4 hr as it moved northeastwardly over the water. The aerosol was sampled from a total of 23 bags, providing 17 samples of the exhaust cloud along with 6 ambient samples for comparison. Useful information on background CCN and IN concentrations in the Cape Canaveral area were also obtained during prelaunch instrument checkout flights.

The initial exhaust cloud penetration was made 4 min after launch (L + 4 min) at a radar-measured altitude of 700 m. A second penetration was made at L + 7 min at 970 m and a third penetration at L + 9 min at 750 m. Each of these first three passes revealed maximum vertical updraft velocities slightly greater than 4 m s^{-1} (i.e., approximately the terminal fall speed of a 1-mm diameter water drop) and large acidic (pH < 0.5) drops ranging in concentration from about 1 m^{-3} to 100 m^{-3}. Maximum drop diameters detected on the first pass were slightly greater than 1 mm. Drops as large as 0.7-mm diameter were detected even on the third pass, but subsequent passes revealed no particles as large as 0.2 mm. Updraft velocities were also insignificant by the time of the fourth pass (L + 12 min). The cloud was never observable with either the 5-cm pulse position indicator (PPI) or 3-cm right hand indicator (RHI) onboard radars. The temperature of the cloud on the first three passes was on the order of 1° C to 2° C warmer than ambient. Compared to typical natural clouds in Florida, there was very little cloud water measured by the Johnson-Williams (JW) nimbiometer or formvar replicator (maximum JW ~0.3 g m^{-3}).

Prelaunch background CCN concentration over land was 1.5 cm^{-3} x 10^3 cm^{-3} at 0.25-percent supersaturation. In-cloud CCN concentration peaked at 15 min after launch at 20 times the background value. Prelaunch Aitken particle concentration was 10^4 cm^3. In-cloud measurements following launch showed a peak concentration about 4 times the background value at L + 15 min. In contrast to natural clouds, the exhaust cloud CCN concentration was nearly equal to the total aerosol concentration, thus demonstrating the hydrophilic nature of virtually all the aerosol. This close relationship between total aerosol concentration and CCN was maintained for the first 40 min after launch, however, became less definite as the cloud aerosol mixed with the environment. After the first hour, concentrations of both CCN and Aitken particles decayed toward background levels. Background levels late in the flight were somewhat lower than those before the launch, reflecting the difference between the natural aerosol over land and that over the ocean some distance from land.

IN were counted by two different methods: the filter technique and a National Center for Atmospheric Research (NCAR) continuous IN counter. For the IN filter measurements, two identical membrane filters were mounted in parallel for each bag sample. Care was taken to minimize the effects of high CCN concentrations on the IN counts. The total volume sampled per filter was 20 ℓ. The two sets of filters were processed in separate laboratories at water saturation and a temperature of -20° C. The NCAR continuous IN counter was operated at -20° C, with a net sample flow of 10 ℓ m^{-1}. The IN measurements during this launch showed no enhanced IN activity in the cloud compared to the surrounding air. The NCAR continuous counter had an average IN count in the cloud of 31 IN ℓ^{-1} + 20 IN ℓ^{-1} and outside the cloud 26 IN ℓ^{-1} ± 16 IN ℓ^{-1}. The difference is not statistically significant; i.e., a count over 60 IN ℓ^{-1} in the cloud would be significant. IN concentration values obtained with the membrane filters were lower than those determined with the NCAR counter (expected because of the differences in principles of measurement). They varied from 0.3 IN ℓ to 3 IN ℓ^{-1} but were always similar to the natural concentrations measured under the same conditions; i.e., same altitude and whether over land or water. These results were contrary to expectation of several hundred IN ℓ^{-1}, based on past laboratory work and on flight samples taken during the launch of smaller rockets using similar SRM's; e.g., Titan III.

To clarify these discrepancies, laboratory tests were made with small pieces of SRB propellant. The tests showed a time delay in nucleation, indicating that the active particles were activated by contact nucleation. However, these active particles, 1 μm or so in diameter, showed only traces of aluminum. This may indicate that, in laboratory tests, the propellant binder is involved in nucleation, but in an actual burn it may be destroyed. Further testing is being conducted.

From the available exhaust cloud measurements, we conclude that in the case of the ground cloud where plenty of large water drops are present and considerable scavenging and fallout of aerosol takes place, possible adverse impacts of the remaining aerosol (CCN and IN) on natural precipitation processes, which may occur in the launch area hours after the launch, are remote. Under certain atmospheric conditions, however, there could be short term adverse effects on visibility. In the case of the column cloud, no CCN or IN measurements have been made.

REFERENCE

1. Environmental Impact Statement - Space Shuttle Program. Final, NASA TM82278, Washington, D.C., April 1978.

ACKNOWLEDGMENTS

The aerosol measurements were made by Dr. Garland Lala and Dr. Gerhard Langer. This study was supported by the work and contributions of numerous other individuals and various organizations within the government and their support contractors. Of special assistance were NOAA Research Facilities Center; NOAA National Hurricane Research Laboratory; State University of New York at Albany; Universities Space Research Association; Air Force Space Command, Los Angeles; the KSC Biomedical Office and Environmental Management Staff, JSC Space Environmental Office; and the MSFC Test Laboratory.

TABLE 1.- AIRCRAFT CLOUD PHYSICS INSTRUMENTATION

Specialized instrument parameter	Instrument type
CCN	SUNY static diffusion chamber
Aitken particle	SUNY Gardner counter
IN	SUNY membrane filters NCAR continuous counter
Drop size/concentration	PMS FSSP PMS 2-D cloud probe PMS 2-D precipitation probe DRI formvar replicator
Cloud liquid water	Johnson-Williams hot wire nimbiometer
pH	Foil impactor with litmus paper SUNY precipitation water sampler
Air temperature	Rosemount total temperature (platinum resistance)
Dewpoint	General Eastern (cooled mirror)
Vertical winds	Accelerometer coupled to pitch and attack angles
Winds	Omega (INS TAS computed)
Pressure	Garrett (static and dynamic)
Altitude	Stabilized radar altimeter
Radar	C-band PPI, 360° horizontal scan X-band RHI, 360° vertical scan
Cloud size/shape	16-mm photography (nose, sides, and downward)

Symbol definitions:

CCN - cloud condensation nucleus
DRI - data rate indicator
IN - ice nucleus
INS - inertial navigation system
NCAR - National Center for Atmospheric Research
PMS - Performance Monitoring System
PPI - pulse position indicator
RHI - right hand indicator
TAS - true airspeed

ACIDIC DEPOSITION PRODUCTION MECHANISM

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INTRODUCTION

A consequence of the launch of STS-1 on April 12, 1981, was a light deposition of acidic material observed on foliage and pH papers at sites as far as 7.4 km from the launch pad. To explain the origin of this fallout, a study was undertaken consisting of the following data: field measurements during the launches of STS-2 through STS-4; cloud measurements by a hurricane research aircraft[a] equipped with special cloud microphysics instrumentation; fallout studies of 6.4-percent Shuttle model firings at Marshall Space Flight Center (MSFC); and scientific and numerical analyses. In this paper, results are documented that relate to the primary objective of the study: the production mechanism of the acidic deposition.

Numerous individuals, organizations within the U.S. Government, and support contractors contributed to this study. Of special assistance were the following: NOAA Research Facilities Center; NOAA National Hurricane Research Laboratory; State University of New York at Albany; Universities Space Research Association; U.S. Air Force Space Command, Los Angeles, California; Biomedical Office and Environmental Management Staff, John F. Kennedy Space Center (KSC); Space Environment Office, Lyndon B. Johnson Space Center (JSC); and the MSFC Test Laboratory.

The primary characteristics of the acidic deposition are as follows:

1. Deposition occurs with every launch. Acidic deposition was observed after STS-1, STS-2, STS-3, STS-4, and STS-5 and in 6.4 percent of the model tests of the Western Test Range (WTR) configuration.

2. The pH is less than 0.5. Samples collected at pad perimeter measure 0.5 (STS-2) and 0.36 (STS-4). The pH paper on aircraft foil impactor confirms pH approximately 0.5 (STS-3).

3. Deposition is composed of water (large fraction), Al_2O_3 particles, and HCl. A sample collected at the pad indicates 70 percent liquid and 30 percent solids. Micrographic analysis of deposits on copper plates supports this estimate.

4. Deposition forms very rapidly. Millimeter-sized drops were present in the cloud at the first aircraft penetration, L + 4 minutes. Because of the pattern of deposition near the pad, one infers formation time less than 60 sec.

5. The deposition outside the pad perimeter has drop diameters up to 2,000 µm. Figures 1, 2, and 3 illustrate size distributions measured by airborne instruments and the copper plate method. Particles smaller than 100 µm have usually dried before reaching the ground.

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[a]National Oceanic and Atmospheric Administration (NOAA) WP-3 at the Research Facilities Center, Miami, Florida, provided the cloud measurements.

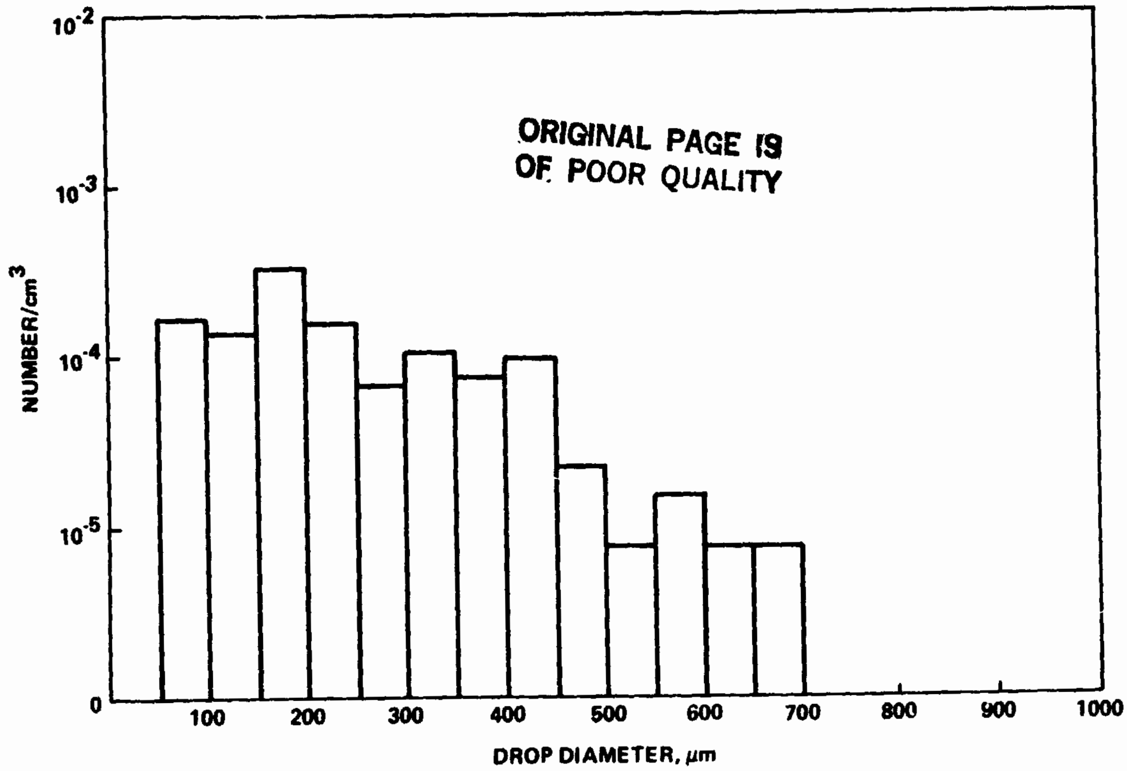
DISCUSSION

These observations lead to the conclusion that the deposition is formed by atomization of the deluge water at the launch pad. This results from mechanical interaction of the exhaust jet with the water. The atomization produces water drops which very rapidly (within a few seconds) scavenge sufficient HCl and Al_2O_3, explaining the observed pH and solid fraction. Measured updrafts in the cloud exceed 4 m/s. This is sufficient to lift the millimeter-sized deposition drops with the cloud to levels where they are carried downwind and deposited in both the near- and far-field.

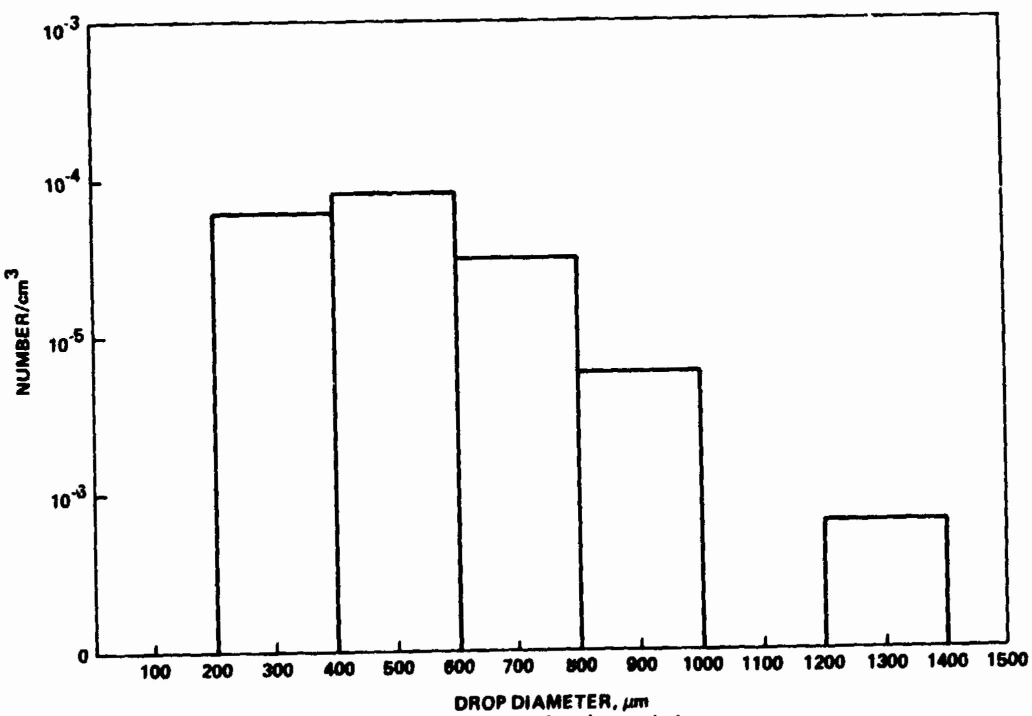
Other possible formation processes were considered, but they are incapable of explaining the observations. Upper limit rate computations of formation by condensation or condensation-coalescence processes indicate that these processes are too slow to account for the rapid production rate. Most conclusively, these processes cannot account for 6.4-percent model tests where the very small clouds last for only 2 to 3 min. Direct production by the vehicle is ruled out by the high liquid fraction observed, among other reasons. However, these processes are, or at least can be, occurring and influencing the observations in a subsidiary way. Certainly, scavenging (coalescence) is the mechanism for the incorporation of Al_2O_3 into the deposition. It is a sufficiently rapid process when the collector drop begins at a large size. Also, there is some tenuous evidence for the production of a few large particles in the column cloud - either by coalescence or direct production from the vehicle, perhaps by erosion of the solid-rocket booster (SRB) nozzles.

CONCLUSION

One may conclude from this study that the acidic deposition will continue to occur with each Shuttle launch. Given a fixed vehicle, a pad, and deluge water configuration, the quantity produced in normal, fair-weather meteorological conditions will remain relatively constant. The location at which it is deposited will vary with the low-level wind conditions and atmospheric stability at launch time.

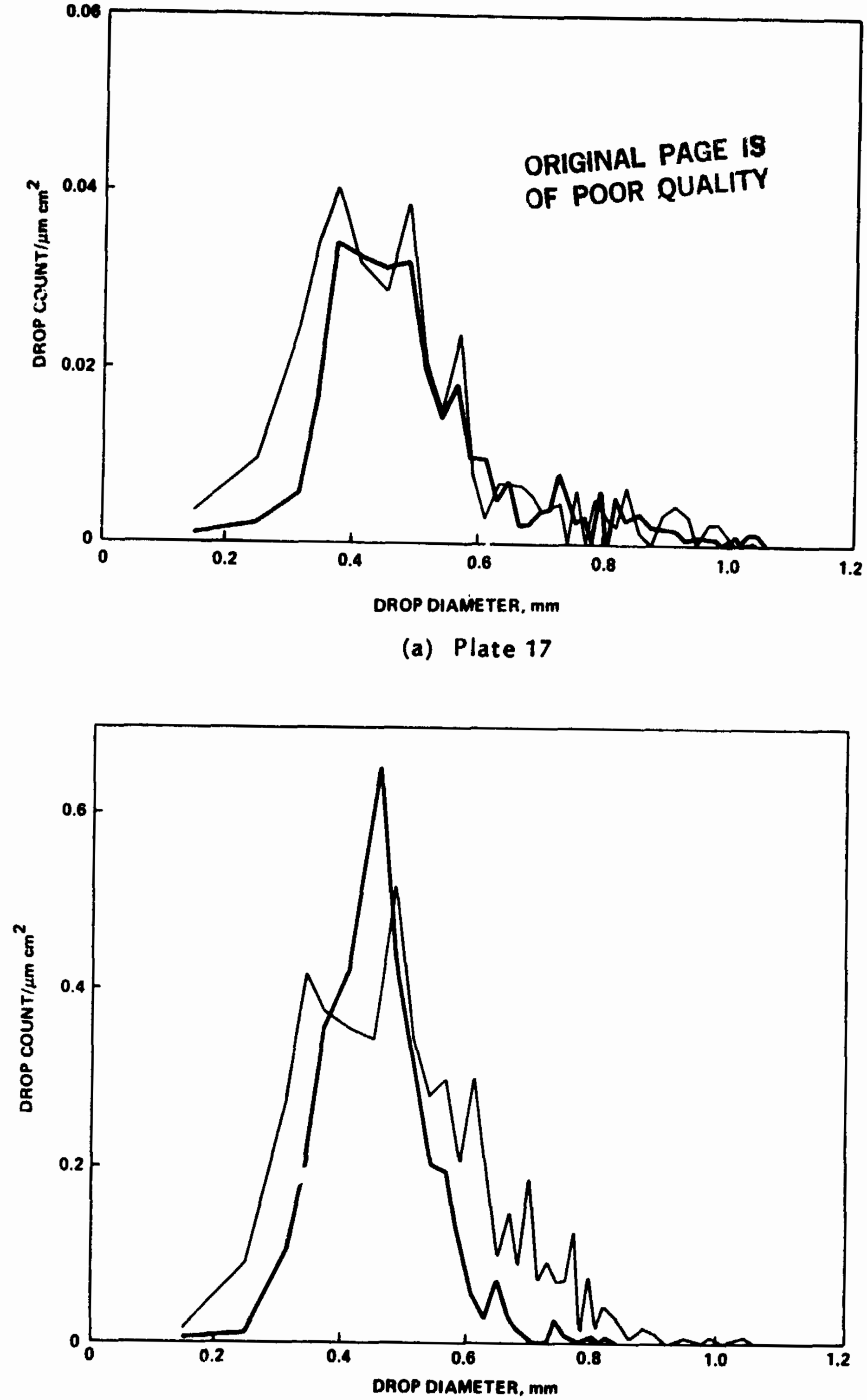


(a) Sample deposition



(b) Another sample deposition

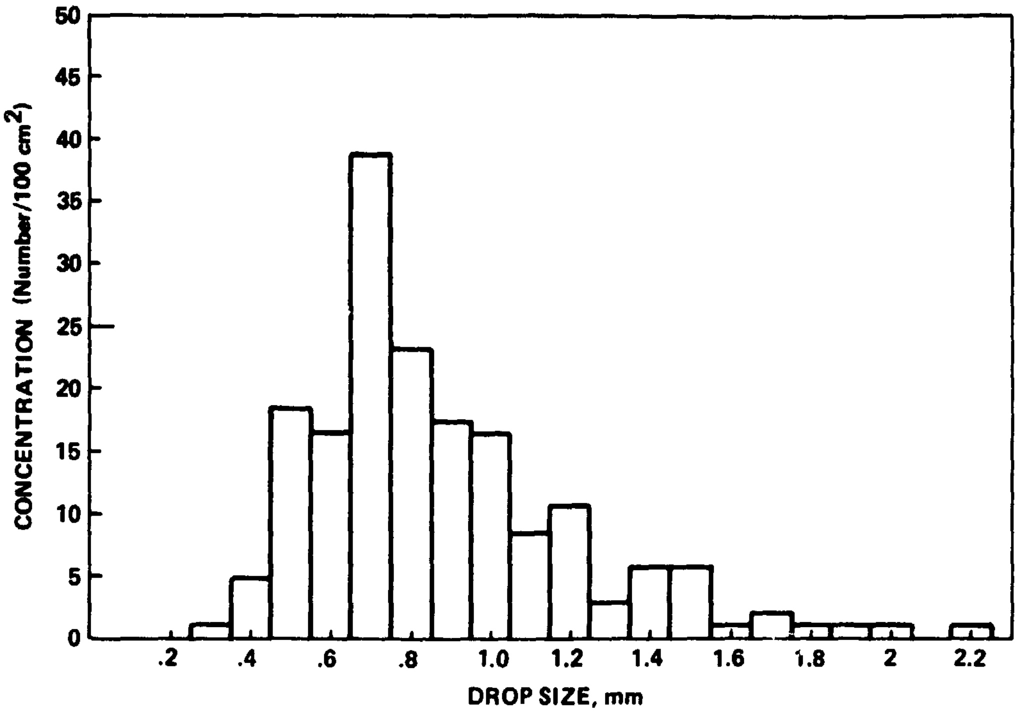
Figure 1.- Size distributions measured by airborne instruments.



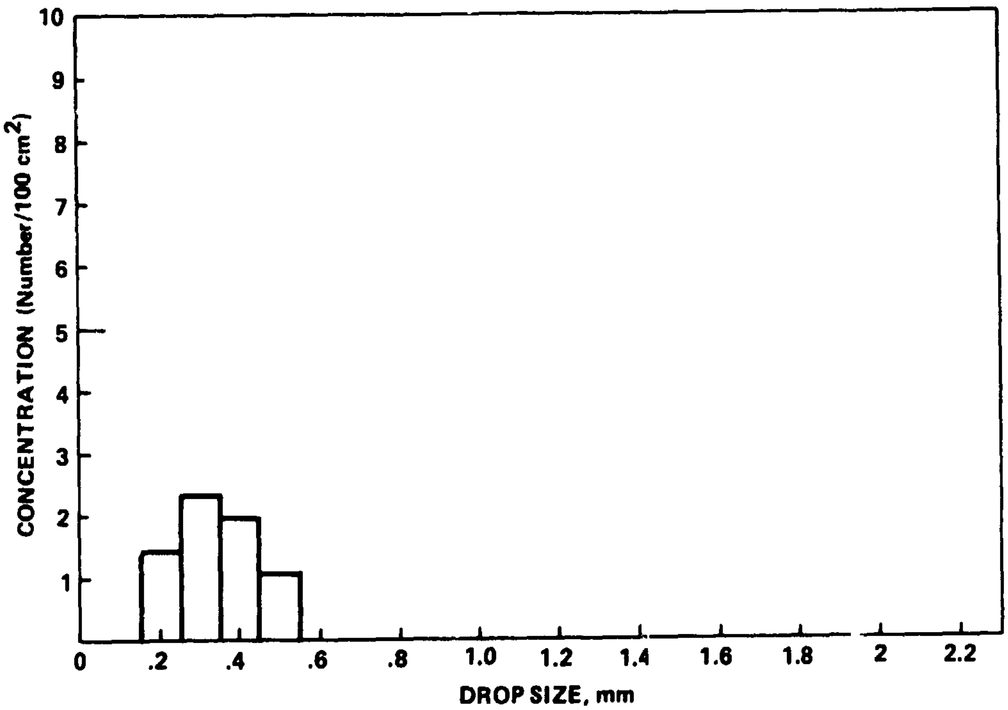
(a) Plate 17

(b) Plate 15

Figure 2.- Drop count and drop diameter measured by copper plate method.



(a) Plate 44



(b) Plate 50

Figure 3.- Size distribution measured by the copper plate method.

PREDICTION STRATEGIES FOR EXHAUST CLOUD IMPACTS: FALLOUT OF ACIDIC DROPLETS AND INADVERTENT WEATHER MODIFICATION

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INTRODUCTION

Each launch of the Space Shuttle results in the release of a significant amount of hydrogen chloride (HCl) gas and aluminum oxide (Al_2O_3) aerosol into the atmosphere. This paper presents recent exhaust cloud measurement results and offers strategies for predicting and/or determining possible impacts of these releases.

This study was supported by the work and contributions of numerous individuals and various organizations within the U.S. Government and the support contractors. Of special assistance were the following: the National Oceanic and Atmospheric Administration (NOAA) Research Facilities Center; the NOAA National Hurricane Research Laboratory; State University of New York, Albany; Universities Space Research Association; U.S. Air Force Space Command, Los Angeles Calif.; Biomedical Office and Environmental Management Staff, John F. Kennedy Space Center (KSC); Space Environmental Office, Lyndon B. Johnson Space Center (JSC); and the Marshall Space Flight Center (MSFC) Test Laboratory.

NORMAL CIRCUMSTANCES

During a normal burn, the two solid-rocket boosters (SRB's) exhaust the following major gaseous and particulate constituents (ref. 1). [Amounts are given in kg S^{-1}.]

carbon dioxide* (3873)
aluminum oxide (2829)
water* (2688)
hydrogen chloride (1993)
nitric oxide* (122)
iron chloride (91)

The Space Shuttle main engine's (SSME's) exhaust product is primarily water vapor* (1805 kg S^{-1}), reference 1.

During the time from ignition to shortly after liftoff (f 8 sec), the exhaust jets of the two SRB's and the SSME's interact mechanically with the deluge water which is introduced at the launch pad prior to ignition and which continues to flow during liftoff. Although the primary purpose of the f 3.8×10^5 gal of deluge water used at KSC is to attenuate the pressure wave which results from ignition of the SRB's, it is also used for sound and fire suppression. During the mechanical interaction of the exhaust jets with the deluge water, a signficant portion of the deluge water is vaporized and a smaller fraction is atomized. The amount vaporized will depend on the characteristics of the exhaust jet/deluge water interaction and the ambient humidity conditions. Heat and water balance calculations, however, show that the maximum amount which will be vaporized is about 10^5 gal, and the amount atomized is of order 10^4 gal. It should be noted that the vaporized deluge water represents a greater portion of the total water vapor source for ground cloud than the combined water vapor output of both SRB's and the

*Amounts after chemical addition of air.

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SSME's. Evidence supporting the atomization concept is presented in the companion paper by Keller and Anderson in these proceedings.

In the turbulent near-pad environment, the micron-size aluminum oxide exhaust particles acquire large velocities relative to the millimeter-size atomized drops. Therefore, each large drop scavenges an enormous number of small particles. Electron micrographs of 'hits' on copper plates indicate that the number of Al_2O_3 particles scavenged by each large drop is typically of order 10^4.

Since near-pad turbulence efficiently mixes HCl exhaust gas with the ambient air, the atomized drops, as well as the small drops which form by condensational growth as the cloud cools, readily scavenge HCl gas and quickly become acidic (pH ~0.5). Many of the large acidic drops are deposited in the immediate pad vicinity and later revolatilize, releasing HCl gas for hours after launch. Some of the acidic drops are lifted in the updrafts of the buoyant exhaust cloud as it rises to stabilization height and moves with the prevailing winds. Drops fall from the exhaust cloud when the updraft velocity in their portion of the cloud decays below the terminal velocity for that particular drop size. Drop fallout begins at cloud initiation and continues (sometimes intermittently depending on the evolution of the updrafts) until the drop concentration is depleted. Following STS-3 aircraft measurements at a height of 750 m revealed vertical updraft velocities of 4 m S^{-1} and the presence of 700μm-diameter acidic (pH $\leq$ 0.5) drops in a concentration of 1 m^{-3} as late as L + 9 min.

Since stabilization height is a function of atmospheric stability and drop evaporation rate is a function of humidity, this atomization-scavenging-transport process results in an acidic deposition footprint on the ground which will vary in location from launch to launch, depending on these parameters: winds, humidity, and atmospheric stability. The deposition footprint location can be predicted by using an existing one-dimensional time-dependent cloud model coupled with fallout trajectory calculations. The one-dimensional time-dependent cloud model can be used to determine the cloud base height and cloud top height as a function of time. Using this information and the measured winds, one can compute the approximate cloud path as a function of time. Since details of the updraft structure in the cloud and how it evolves with time cannot be accurately predicted, realistic-sized particles (i.e., 2-mm diameter and smaller drops have been measured at the ground and with aircraft) can be assumed to begin falling simultaneously from the cloud base height and the cloud top height at reasonable time increments in the cloud's motion, thus giving a conservative estimate of the extent of the deposition footprint. Taking into consideration the effect of evaporation on the drops' terminal velocity and making use of the measured (or predicted) wind field to compute the particle trajectories, one can compute the fallout footprint for each particle class size. The mean wind and vector variation must be known or predicted as a function of height. It should be emphasized that since it takes several minutes for the drops to reach the ground (i.e., stabilization height is typically 1200 m, and drops as large as 1-mm diameter have a terminal velocity of only about 4 m S^{-1}), if strong winds and wind shears exist, the drops can be transported significant distances and may impact the ground far from the ground track of the exhaust cloud. It should also be noted that the deposition fallout footprint prediction will only be as good as the wind, humidity, and temperature data used.

In addition to acidic deposition, gaseous HCl diffusion from the exhaust source and revolatilization of HCl from the near-field acidic deposition must be considered for each launch. It should be noted that the approximately 2×10^5 gal (3.8×10^5 l) of 0.1 N HCl (pH = 1.0) liquid captured in the KSC holding ponds after each launch contains 2800 kg of HCl. Since this represents only 1.4 sec of SRB burn time, ample gaseous HCl is produced in a normal burn to substantially lower the pH of one two or three times the present amount of deluge water. During revolatilization of the near-pad deposition, the HCl gas release rate is a function of deposition coverage and evaporation rate. Evaporation rate depends on surface characteristics (e.g., vegetation) as well as humidity and wind speed. It should be noted that deposition coverage in the Western Test Range (WTR) configuration may be double that at KSC because of the split-flame trench configuration and increased amount of deluge water.

SPECIAL CIRCUMSTANCES

Under special ambient atmospheric circumstances, more adverse exhaust cloud impacts may possibly result. If the atmosphere is very stable (e.g., a strong low-level inversion and heavy fog may be present), preliminary runs with a two-dimensional time-dependent cloud model (analysis by R. A. Sarma and G. D. Emmitt) indicate that an acidic cloud may be trapped near the ground (fig. 1). This could result in very high HCl gaseous and aerosol concentrations at ground level which might possibly pose a threat to personnel, vegetation, or facilities.

In the other extreme case, the atmosphere may be conditionally unstable at launch time. In this case, sustained exhaust cloud growth or merger with nearby convective clouds may possibly result in acid rain; i.e., continued precipitation produced by a natural mechanism but incorporating the exhaust cloud byproducts. Existing two- or three-dimensional cloud models should be utilized to place bounds on the relevance of these possible problems.

The existing two-dimensional time-dependent cloud model which was used in preliminary investigations was developed over the past 14 years at the Institute for Atmospheric Sciences, South Dakota School of Mines and Technology. It has a 20-km by 20-km domain in the XZ-plane with 200-m-grid spacing in both the vertical and horizontal. The initial conditions to the model are given in the form of a sounding - a vertical profile of temperature, dew point, and wind speed. Natural clouds are initialized in the model by providing small perturbations in temperature and/or water vapor fields near the surface. It is also possible to enhance or inhibit convection by imposing a convergence or divergence field near the surface. For the Space Shuttle case, modifications have been developed to simulate the distributions of heat, water vapor, and hydrogen chloride introduced into the atmosphere along the flight path and the distributions of liquid water and vapor introduced by the deluge water at the launch pad. It has also been modified to address scavenging/revolatilization of HCl within the cloud. The graphic output displays the cloud outline, the streamlines, and the HCl contours in ppm at user-specified time intervals. Figure 1 is an example of the output at 21 min after launch for a simulated fog case.

INADVERTENT WEATHER MODIFICATION

There has been considerable discussion of the potential for weather modification resulting from the combustion products of the Shuttle (refs. 2, 3, and 4). Since Al_2O_3 particles are introduced into the atmosphere during each Shuttle launch, primarily into the lower troposphere but also extending upward through the stratosphere, it has been suggested that these particles may alter precipitation processes in the troposphere or alter terrestrial radiation balance and climate through increased cloudiness in the upper troposphere or lower stratosphere. These concerns are based on the fact that the Al_2O_3 particles are hydrophilic in nature and, therefore, good cloud condensation nuclei (CCN) and on the possibility that they might also be good ice nuclei (IN).

Aircraft measurements made in the STS-3 exhaust ground cloud were the first, resulting from a Shuttle launch, to be made of CCN, Aitken nuclei, and IN. These measurements were made by a hurricane research aircraft equipped with special cloud microphysics instrumentation. (The NOAA WP-3 Research Facilities Center, Miami, Florida, made the measurements.) The number concentration of Aitken nuclei in the ground cloud peaked at about 15 min after launch at four times the background values and then decayed to near-background levels within 1 hour. Cloud condensation nucleus concentrations also peaked at about 15 min after launch but at 20 times the background values and then also decayed to near-background levels within 1 hour. During the first 30 min after launch, the CCN-number concentrations which were measured at a water supersaturation of 0.25 percent with a microprocessor-controlled thermalgradient-diffusion cloud chamber were nearly equal to the Aitken nuclei-number concentrations measured with a Gardner counter. This demonstrates the hydrophilic nature of virtually all the aerosol in the ground cloud. [G. Lala, State University of New York, Albany, developed and operated the cloud chamber; Aitken nuclei equal total aerosol.]

Few, if any, extraneous IN were measured in the STS-3 ground cloud by either the filter technique or with a continuous National Center for Atmospheric Research (NCAR) IN counter operated at -20°C. [G. Langer, Universities Space Research Assoc., operated the IN counter and made the analysis.] However, laboratory combustion tests of solid-rocket motor material in a large cloud chamber suggest that 'contact' ice nucleation may be important under some conditions. Unfortunately, contact nucleation is not readily measurable with existing state-of-the-art field instruments.

From these measurements, we conclude that in the case of the ground cloud where plenty of large water drops are present and considerable scavenging and fallout of aerosol takes place, possible adverse impacts of the remaining aerosol (CCN and IN) on natural precipitation processes, which may occur in th launch area hours after the launch, are remote. Under certain atmospheric conditions, however, there could be short-term adverse effects on visibility. In the case of the column cloud, no CCN or IN measurements have been made. It should be noted that due to the low concentration of natural IN in the upper troposphere and in the stratrosphere, the addition of extraneous IN in these regions would be much more significant than the addition of a few IN in the lower troposphere. At this time, the potential for inadvertent weather modification should not be summarily dismissed.

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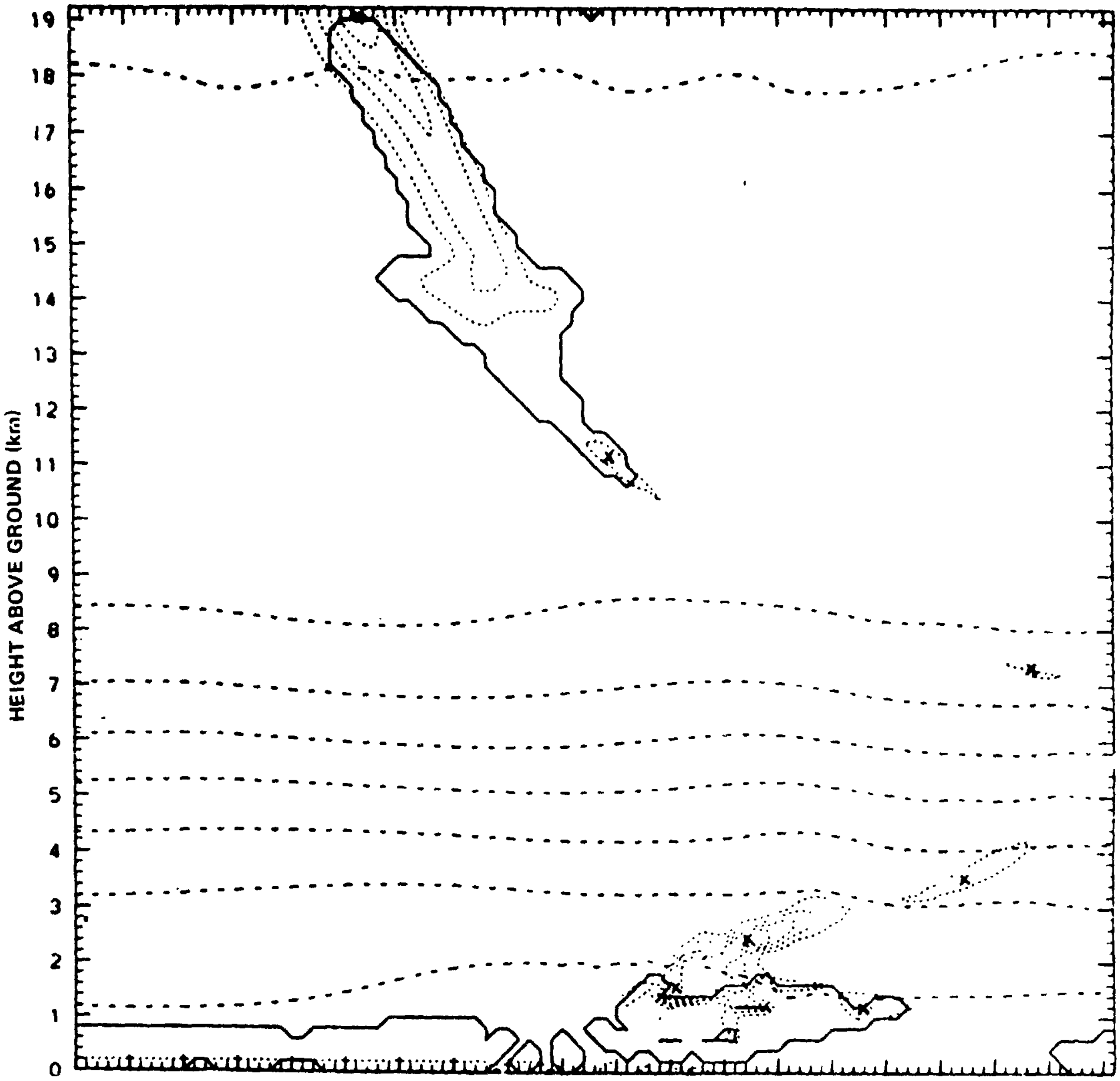

Figure 1.- Cloud outline (solid lines), streamlines (dashed lines), and HCl contours (dotted lines) for the fog case at 21 min after launch. The HCl contours start at 25 ppm and are in intervals of 25 ppm; x's denote local maxima of HCl concentration. Each large mark along the axes represents 1 km.

NEAR-FIELD DEPOSITION OF ACIDIC DROPLETS FROM TITAN III AND SPACE SHUTTLE LAUNCHES

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SUMMARY

Water-saturated mineral oil was used as a medium for capturing wet deposition from solid rocket exhaust clouds. The oil minimized absorption of gaseous HCl by captured droplets and retarded subsequent droplet evaporation prior to analysis. Wet depositions obtained in conjunction with three Titan III launches (two with rainfall) and the STS-1 Space Shuttle launch were analyzed for ionic concentrations. Microcoulometry was used for chloride, atomic absorption for sodium and (sometimes) calcium, and ion chromatography for most of the available anions and cations in one STS-1 sample. In general, wet deposition was found to be relatively sparse (typically 100 to 1,000 drops/m^2) and infrequent (sampled in 4 out of 10 launches) within the near-field tes sectors (up to 12 km downwind) that were deployed 2 hr to 4 hr prior to launch. While several samples had chloride and sodium concentrations approximating diluted seawater, some consisted primarily of hydrochloric acid in concentrations up to 0.1 molar, equivalent to a pH of one. This occurred 4 km downwind of a Titan III launch at onset of rainfall, for which an acid chloride deposition footprint was deduced, and 5 km downwind of the STS-1 Shuttle launch. It is concluded that highly acidic near-field deposition can occur for both Titan III and Shuttle launches. However, we are not yet able to define the detailed roles of HCl and H_2O co-condesation on agglomerates of alumina and soil particles, coagulation of the resultant acid aerosol, and the highly localized dynamics of cloud rise with entrainment of massive deluge water sprays released at the pad.

INTRODUCTION

The potential for deposition of hydrochloric acid rain, resulting from precipitation scavenging of exhaust clouds from large solid rocket motors (SRM), has been under study by the National Aeronautics and Space Administration (NASA) for more than 8 years. (See refs. 1 through 14 for summary of recent literature.) Deposition of acidic droplets and associated particles has been monitored during the last 8 years of Titan III launches as part of the environmental impact assessment activity for Space Shuttle. The probability that highly acidic deposition will occur during Shuttle launches may be greater than that for Titan III launches because the twin SRM boosters for the Space Shuttle exhaust about 2.4 times as much HCl within the first 1,500 m altitude (~48 tons). In addition, because much larger water deluge sprays are deployed at the Shuttle launch pad for cooling and acoustic baffling purposes (300,000 gal), the potential for near-field deposition may also be increased.

In this paper, we report near-field deposition of acidic droplets (containing alumina/soil particles) that were measured at downwind distances up to 12 km in connection with three Titan III launches and a recent (April 12, 1981) Space Shuttle launch. Although this wet deposition tended to be relatively sparse and infrequent, captured droplets sometimes contained hydrochloric acid in concentrations up to 0.1 molar, equivalent to a pH of one. Thus, when launch-associated deposition occurred with pH's approaching unity (measured in 2 of 10 launches), it was more than 1,000 times as acidic as 'normal' acid rain (pH = 4.6) in the Cape Canaveral area. Normal acid rain is about ten times more acidic than pollutant-free natural rain.

COLLECTION AND ANALYSIS OF WET DEPOSITION SAMPLES

Postlaunch samples were collected in plastic containers (typically 150 cm^2 capture area) filled ~3 cm deep with water-saturated mineral oil. The purpose of the mineral oil was to prevent diffusion of HCl (g) to aqueous droplets after capture of wet deposition and also to retard subsequent evaporation prior to analysis. The mineral oil had been thoroughly shaken with distilled water, and the resulting emulsion allowed to separate for a day into two phases. Just prior to launch, water-saturated mineral oil phase was decanted into clean plastic containers and lids were affixed. For the September 9, 1975, Titan III launch, these containers, along with covered sheets of pH paper, were mounted on sampling platforms about 2 m above ground at each of the nine primary sampling sites. Technicians located at each site removed the plastic covers when rain commenced 20 min to 30 min after launch, and replaced them several minutes later when samples (generally 0.2 ml to 2 ml) were collected and the SRM exhaust cloud had clearly passed overhead. Since nearly all sites were unmanned for the May 12, 1977, and December 13, 1978, Titan III launches and the STS-1 Shuttle launch, the covers in these site deployments were usually removed 1 hr to 3 hr prior to launch and replaced 1 hr to 3 hr after launch.

A microcoulometric technique was used for the chloride determinations, and atomic absorption analysis was used to determine sodium, the principal sea salt cation. Since the quantities of rainwater analyzed were sometimes only a fraction of a milliliter, microtechniques for sample handling and serial dilution had to be developed and tested with known samples. For example, when samples consisted of only one small droplet, a 50 µl microsyringe was used first to capture the droplet and measure its initial volume (between bounding oil-water menisci; typical error, ±5 percent) and then to add a measured volume to (50 µl to 100 µl) of distilled water to the resuspended droplet. Subsequent serial dilutions were accomplished upon removal of an aliquot of the diluted original droplet. For the Shuttle STS-1 launch, ion chromatography was used as a supplemental independent technique to determine both cations and anions in the single most acidic sample, identified earlier by microcoulometry and atomic absorption.

ACID CHLORIDE FOOTPRINT FOR THE SEPTEMBER 9, 1975, TITAN III

Visual, photographic, and time-lapse pulse position indicator (PPI) radar observations indicated that this Titan III exhaust cloud encountered a rainshaft or spray from a cellular element of a large convective storm, which moved from the east and intersected the ling area about 20 min to 30 min after launch. Aircraft measurements indicated that abrupt depletion of in-cloud HCl occurred after ~30 min (ref. 6). The results of the quantitative chloride determinations are illustrated in figure 1, where isopleths of rainwater Cl^- concentration are shown for the experimental sector, which includes 28 km^2 for $1 < p(Cl^-) < 3$. Although this plot originally represented the total Cl^- values uncorrected for sea-salt contamination, the calculated corrections based on assumed proportionality of sea-salt chloride to measured Na^+ were found to be relatively small and effectively negligible for all eight samples (illustrated later in figure 6). Thus, the combined Cl^- and Na^+ composition data suggest that the $H^+ \cong$ excess $Cl^- \cong$ total Cl^- is a good approximation, and therefore, the acid chloride footprint effectively represents H^+ deposition due to rain-scavenged HCl. The actual construction of the isopleths stemmed from an initial finding that geographic gradients in $p(Cl^-)$, where $p(Cl^-) = \log [1/Cl^-(\text{molarity})]$, tended to be linear and spatially consistent when various pairs of adjacent points were compared. Thus, the illustrated $p(Cl^-)$ isopleths reflect this spatial linearity assumption. The respective locations of all sample data points, numbers 2 to 9, accurately depict the total Cl^- measured. Sample container number 1 was blown over by wind and lost.

The pH papers deployed at sites 6 and 8 indicated wet depositions with pH's of approximately unity, and thus provide independent confirmation of the hypothesized proportionality between excess chloride (over Na^+) and initially deposited H^+ from aqueous HCl. It should be noted in this connection that the wet deposition also contained small amounts of ground debris and alumina particles. Thus, slow dissolution and neutralization reactions with soil (ref. 9) and alumina (refs. 7, 8, and 9) are considered likely mechanisms for postlaunch pH increases in the collected samples, which appeared to have occurred over periods of hours to a few days prior to initial spot checks with pH paper and quantitative analysis.

For the September 9, 1975, Titan III launch, if we assume that 50 percent of the total chloride deposition occurred outside the experimental sector in a more or less symmetrical pattern, the collective results suggest that approximately 7 km^2 of surface, centered about 4 km downwind, received rain having an initial pH of <1.5. The occurrence of this event during the second half-hour postlaunch appeared to stem from precipitation scavenging of the stabilized SRM ground cloud by leading elements of the large convective storm that moved westward through the area.

CHLORIDE MEASUREMENTS FOR THE MAY 12, 1977, TITAN III

Launch monitoring personnel observed a light drizzle after the May 12, 1977, Titan III launch. However, they were uncertain whether it occurred soon enough to scavenge the exhaust cloud over the deployed experimental test sector. Relatively small quantities of wet deposition were obtained after this launch (volumes ranged 0.02 ml to 1.5 ml), and the chloride and sodium ion concentrations that were determined are illustrated on the site maps shown in figures 2 and 3, respectively. Note that the chloride concentrations are generally much lower than observed in the September 9, 1975, Titan III case, and no distinct hot spot and/or pattern is apparent downwind of the launch site. Comparisons between corresponding ion concentrations indicate that the mass ratios of chloride to sodium differ relatively little from that for seawater (1.85). These results appear to be consistent with the occurrence of a light sea breeze drizzle sometime after the SRM exhaust cloud passed through the experimental area.

CHLORIDE MEASUREMENTS FOR THE DECEMBER 13, 1978, TITAN III

The December 13, 1978, launch occurred at 7:40 p.m. Eastern Standard Time (EST). A condition of partial cloudiness existed just prior to launch time due to thin stratus at about 1,200 m altitude. This was dissipated by an influx of drier air, following a frontal passage in northern Florida, which led to clear sky conditions within the first half-hour after launch. Nighttime photography of the exhaust cloud (fast film, full moon conditions) from three different angles indicated that the lower half of the ground cloud (up to 600 m) drifted in a south-southeastward (SSE) direction towards sites 2 and 8 shown in figure 4. The upper half of the cloud drifted in a southwestward (SW) direction over site 20. The amounts of wet deposition sampled were very small (ranging 0.02 ml to 0.5 ml), and the chloride and sodium ion concentrations were again much lower than in the September 9, 1975, Titan III case, except for small to moderate excess chloride concentrations observed at sites 2, 8, and 20 (shown later in figure 6). Since rain did not appear to occur after this launch, the near-field wet deposition observed at sites 2 and 8 appeared to originate as rainout and/or fallout from lower elements of the exhaust cloud itself.

WET DEPOSITION FROM STS-1 SHUTTLE LAUNCH

The first launch of the Space Shuttle STS-1 occurred at 7:00 a.m. EST, April 12, 1981. More than 30 mineral oil samples were deployed, but only seven were found to have one or more droplets of wet deposition. These seven sites are depicted on the map shown in figure 5. Chloride concentrations obtained from microcoulometry and both sodium and calcium ion concentrations determined by atomic absorption analysis are summarized in table 1. Inspection of these results indicates that site A-8, mineral oil bucket No. 20, was the only wet deposition sample (initial volume, 0.5 ml) that was significantly high in excess chloride. Once this fact was determined, ion chromatography and pH measurements were also made on sample No. 20, and the results are summarized in table 2. The ion chromatography technique indicated that chloride was the only significant anion present, and notably, nitrate and sulfate were negligible. Note that calcium and magnesium were not determined by ion chromatography, since the required column was not available. The pH measurement was obtained by using a miniature combination pH electrode on a 1/25th dilution of the original sample. The corresponding estimate for pH of the original wet deposition (0.70) agrees remarkablely well with the pH calculated by an ion balance (0.98) based on the ion chromatographic data. Thus, we conclude that the wet deposition at site A-8 consisted primarily of Shuttle-derived hydrochloric acid having a pH of approximately unity. Minor components undoubtedly consisted of SRM-produced alumina, sea salt, and entrained soil particles containing K^+ and Ca^{++}.

SUMMARY OF MEASUREMENTS

A graphical summary of all the chloride and sodium measurements reported in this paper is depicted in figure 6. A region of excess chloride is shown to the right of the NaCl and seawater lines, and curves parameterized in terms of p(X's Cl^-) are shown to illustrate the equivalent pH of an idealized HCl plus diluted seawater solution. Significant departures from the seawater line are evident in this plot for nine samples in which $2.5 > p(X's\ Cl^-) > 1$.

Most of the remaining samples in figure 6 exhibited compositions closely resembling that of diluted seawater. Although excess sodium ion is frequently seen in the vicinity of coastal areas, and particularly in cases where sea salt aerosol has been mixed with parcels of polluted continental air for some time, none of the Titan III results show appreciable excess sodium, and only three of the seven STS-1 results show some excess. The apparent reason for this excess sodium is that all of the deposition samples were collected under the influence of onshore winds, at locations very near to the ocean-land interface.

CONCLUSION

The following concluding statements are based upon the results of this study coupled with background information derived from the literature cited.

1. Near-field wet deposition having pH's approaching unity can occur in conjunction with Titan III and Shuttle launches.

2. Rainfall overriding an SRM exhaust cloud can result in HCl washout and highly acidic initial deposition.

3. Acidic wet deposition from a SRM cloud in the absence of overriding rain tends to be relatively sparse (e.g., 10^2 to 10^3 drops/m^2), and also infrequent for any given area outside a so-called sacrifice zone immediately adjacent to the launch complex. However, it is clearly capable of damaging surface receivers in its path.

4. In-cloud condensation and coalescence processes, which can lead to acidic wet deposition, are enhanced by high relative humidity of cloud dilution air, large amounts of entrained deluge water and soil particles, and large size (>50 μm) alumina exhaust agglomerates.

5. The relative importance of near-field in-cloud processes, along with local cloud rise dynamics and meteorology, is not well understood.

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TABLE 1.- COMPOSITION OF WET DEPOSITION FROM THE SHUTTLE STS-1 LAUNCH, APRIL 12, 1981; SUMMARY OF MICROCOULOMETRIC (Cl^-) AND ATOMIC ABSORPTION (Na^+, Ca^{++}) ANALYSES

Site number	Sample number	Chloride (ppm)	Sodium (ppm)	Calcium (ppm)
A-7	L-15	150	83	33
L-8A	L-8A	122	122	23
L-4	L-4	7705	4613	180
A-8	20	5415	680	140
P-6	42	60.9	39	11
A-4	43	42.9	51	6.3
A-20	52	34.9	43	11

TABLE 2.- COMPOSITION OF ACIDIC WET DEPOSITION FROM SITE A-8, STS-1 LAUNCH, APRIL 12, 1981, CAPE CANAVERAL, FLORIDA

[Site A-8, mineral oil bucket No. 20, was located 5 km northwest of Pad 39A, on a line generally parallel to the coast.]

1. ION CHROMATOGRAPHY

   Cl^- = 4800 ppm (g/g)

   Na^+ = 460 ppm

   K^+ = 240 ppm

   $NH4^+$ = 54 ppm

   $NO3^-$ = negligible

   $SO4^-$ = negligible

   MICROCOULOMETRY

   Cl^- = 5420 ppm

   ATOMIC ABSORPTION

   Na^+ = 680 ppm

   Ca^+ = 140 ppm

2. pH calculated by ion balance . . . . 0.98 (ion chromatography)

3. Experimentally determined pH:

   1/25 dilution (measured) 2.10

   Original solution (calculated ideal) 0.70

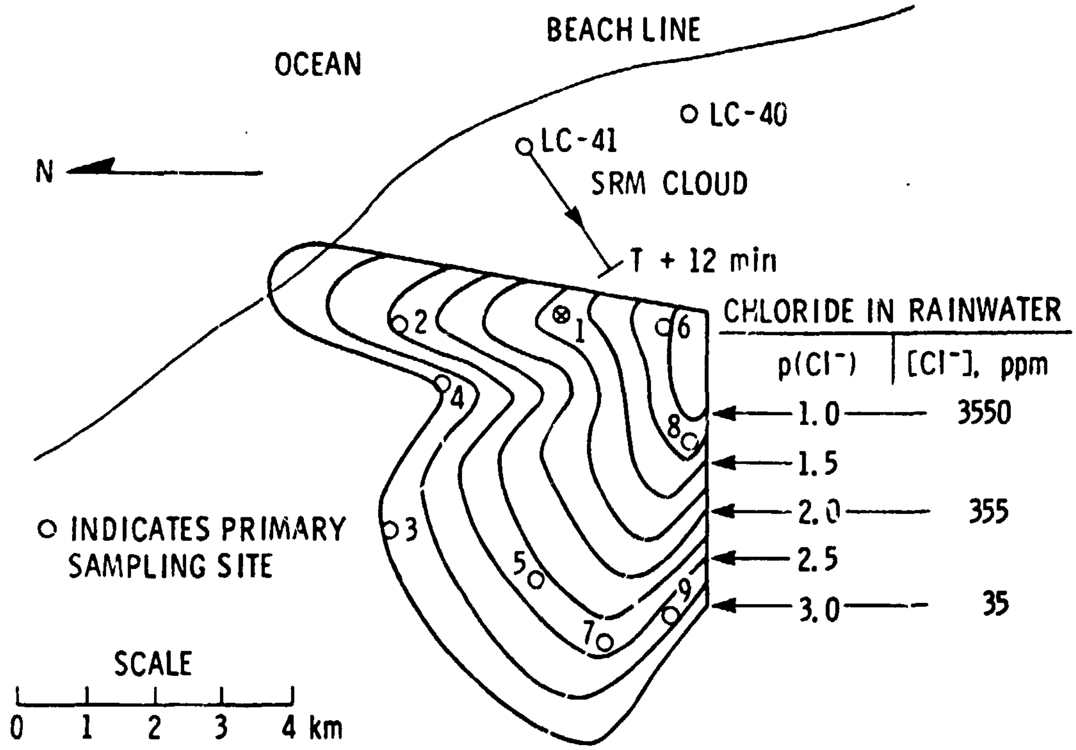

Figure 1.- Acid chloride footprint representing wet deposition from precipitation scavenging of a Titan III SRM exhaust cloud about 30 minutes after launch on September 9, 1975. Samples numbered 2 to 9 are accurately represented by isopleths; sample no. 1 was lost. The pH papers at sites 6 and 8 supported the excess chloride measurements, indicating wet depositions with pH's of approximately unity.

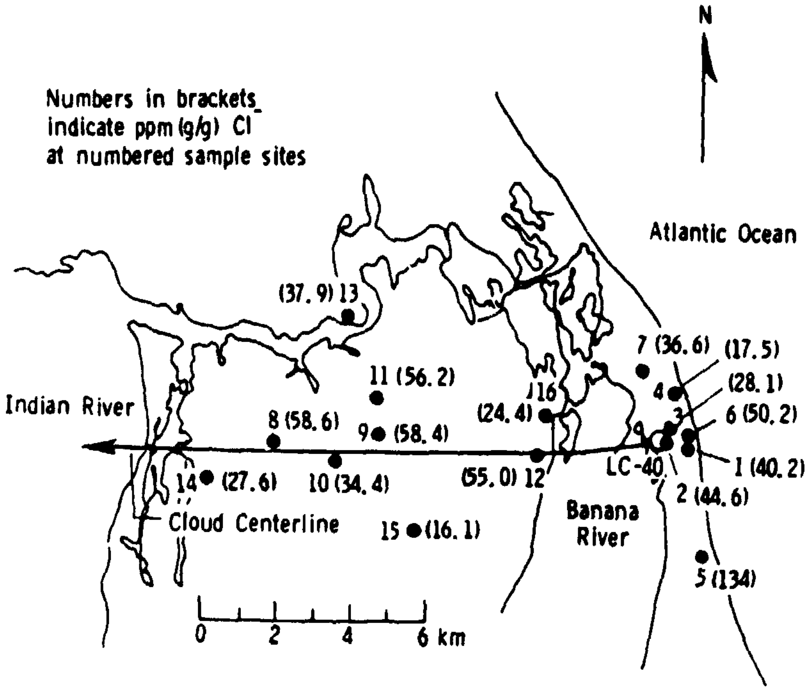

Figure 2.- Wet deposition of chloride from a precipitation event which occurred shortly after the May 12, 1977, Titan III launch from LC-40, Cape Canaveral.

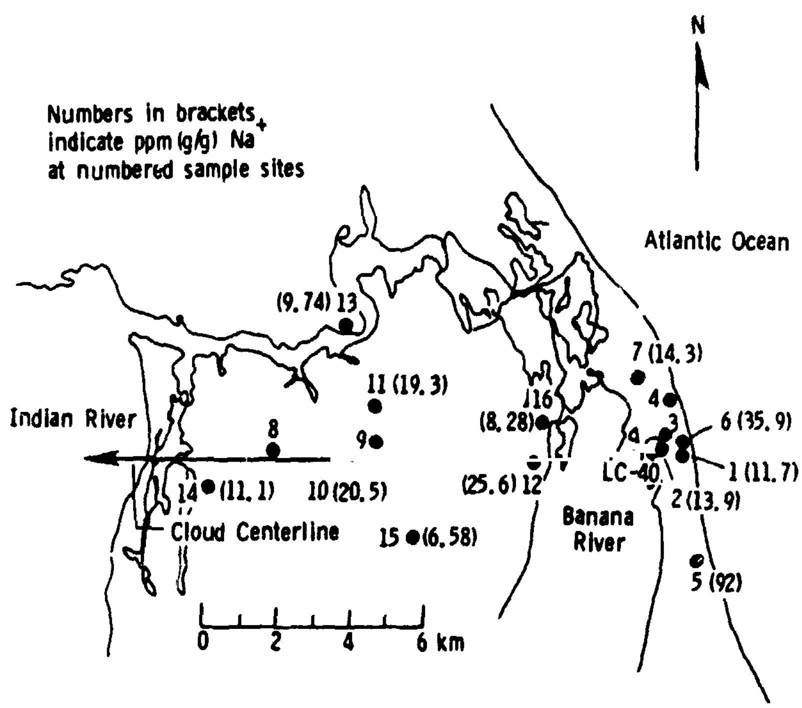

Figure 3.- Wet deposition of sodium from a precipitation event which occurred shortly after the May 12, 1977, Titan III launch from LC-40, Cape Canaveral.

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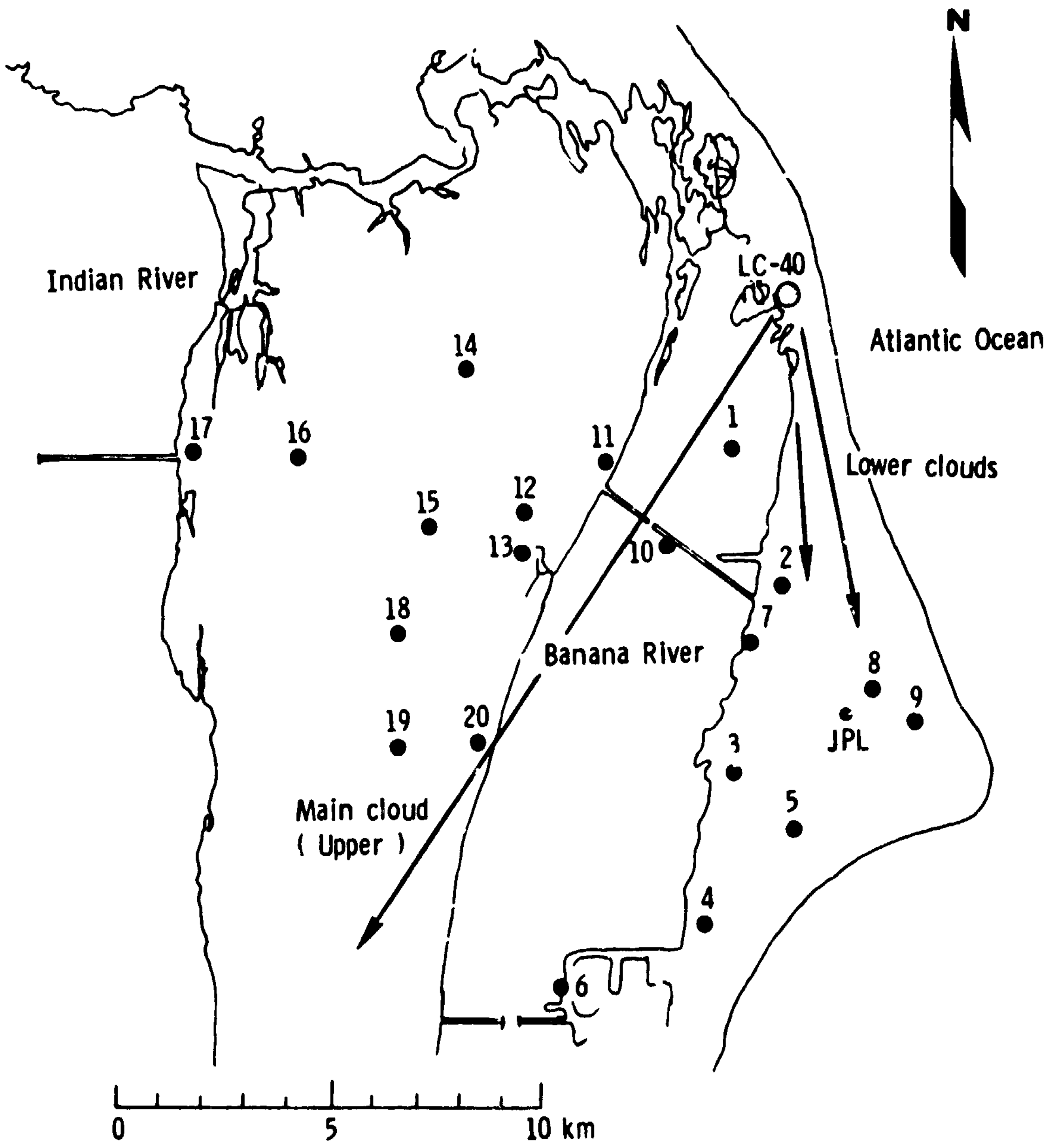

Figure 4.- Siting map for the December 13, 1978, Titan III launch from LC-40, Cape Canaveral. Sampling devices deployed at each location included mineral oil 'buckets', pH paper, HCl dosimeter tubes, and millipore total-suspended particulate filters.

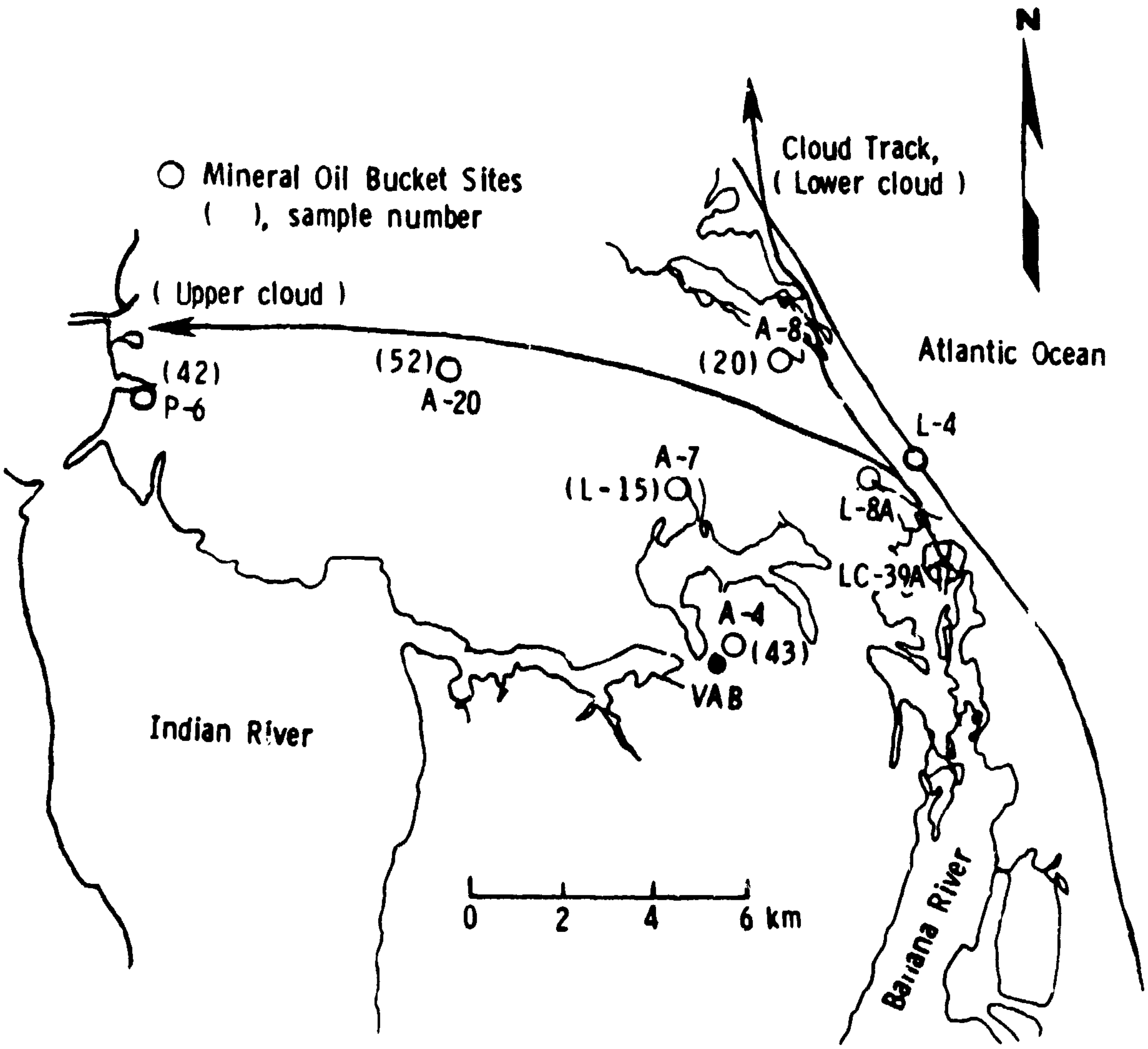

Figure 5.- Siting map for Shuttle launch STS-1, April 12, 1981, showing locations where wet deposition was obtained in mineral oil "buckets".

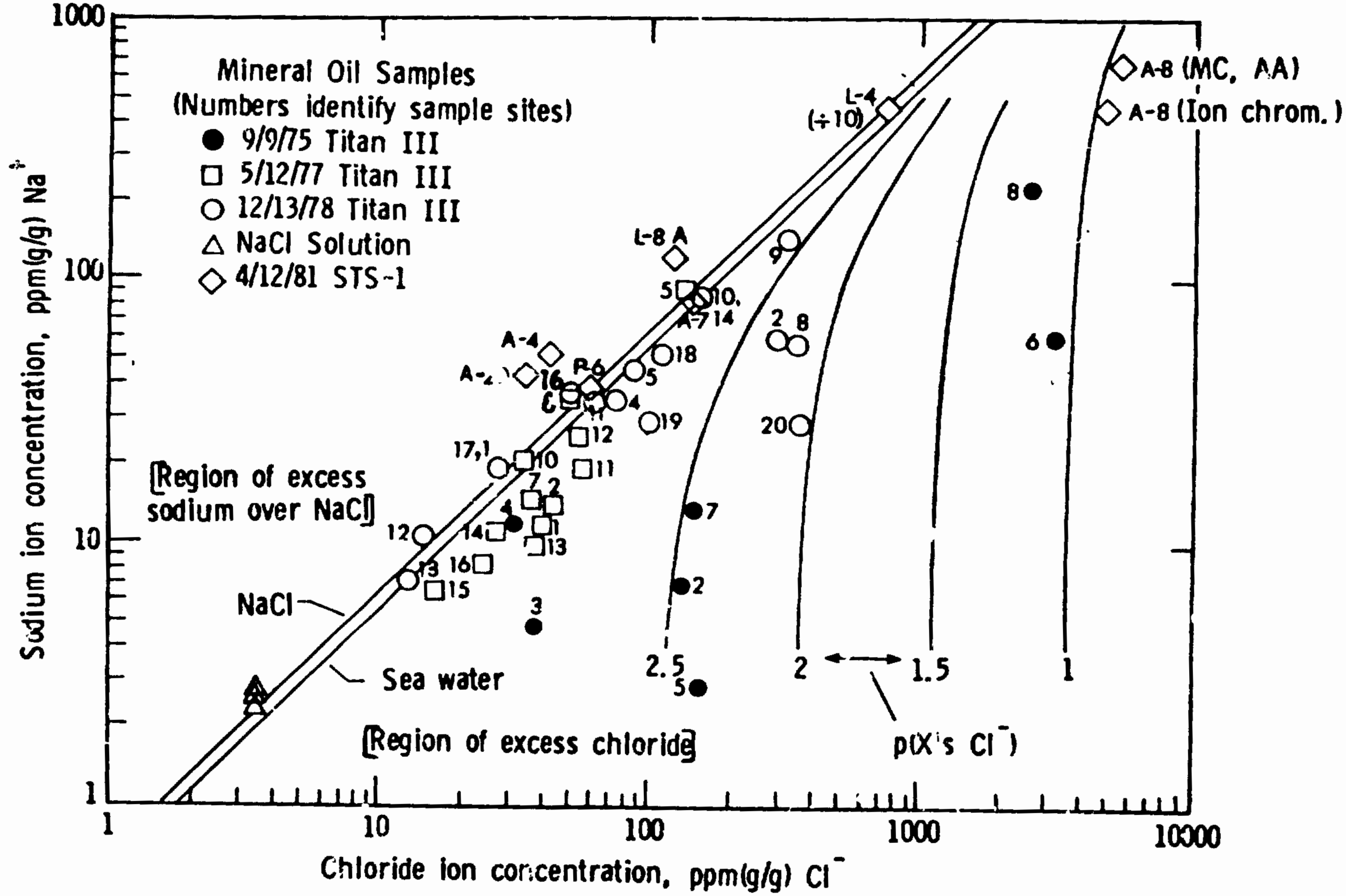

Figure 6.- Composite characterization of chloride, sodium, and excess chloride concentrations, obtained from wet deposition samples collected in mineral oil "buckets" at Cape Canaveral, Florida. This correlation summarizes all the data obtained in association with three Titan III launches and the STS-1 Space Shuttle launch.

MODELING OF THE EXHAUST CLOUD

- AEROSPACE VEHICLE EFFLUENT DIFFUSION MODELING FOR TROPOSPHERIC AIR QUALITY AND ENVIRONMENTAL ASSESSMENT
  MSFC Space Science Laboratory Staff

- NASA/MSFC EXHAUST EFFLUENT DIFFUSION PREDICTIONS AND MEASUREMENTS FOR STS-1 THROUGH STS-4
  MSFC Space Science Laboratory Staff

- A COMPARISON OF IN-CLOUD HCl CONCENTRATIONS PREDICTED FROM THE NASA/MSFC MULTILAYER DIFFUSION MODEL TO MEASUREMENTS FOR THE FIRST SPACE SHUTTLE LAUNCH, APRIL 12,1981
  Glasser

- OBSERVATIONS AND CUMULUS MODELS OF SHUTTLE EXHAUST CLOUDS
  Barnes

- AN APPLICATION OF MODEL TESTING FOR THE STUDY OF ROCKET EXHAUST PROPERTIES
  Anderson and Keller

- THE 6.4-PERCENT MODEL OF THE SPACE SHUTTLE
  Compton

- USAF SPACE SHUTTLE DISPERSION MODELING WORKSHOP
  Naugle

- ROCKET EXHAUST DIFFUSION MODEL EVALUATION AT THE AIR FORCE WESTERN SPACE AND MISSILES CENTER
  Dargitz

- GROUND CLOUD MICROPHYSICAL TERRAIN EFFECTS
  Compton

AEROSPACE VEHICLE EFFLUENT DIFFUSION MODELING FOR TROPOSPHERIC AIR QUALITY AND ENVIRONMENTAL ASSESSMENT

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) has pursued the development of relatively simp'e, operationally useable, computerized dispersion models for predicting the behavior of rocket exhaust clouds in the troposphere. These models are used to assess the environmental impact of exhaust products from rocket engines with respect to air quality standards, toxicity thresholds, and potential bioecological effects. The concept of using generalized multilayer dispersion models for these applications was first outlined in the 1970's, and the models have been continuously updated and improved since that time. In 1973, a joint program for rocket exhaust prediction and launch monitoring was initiated by NASA for all Titan launches from the John F. Kennedy Space Center (KSC). In this program, Marshall Space Flight Center (MSFC) had the responsibility for supplying dispersion predictions, Langley Research Center (LaRC) had responsibility for making concentration measurements of rocket exhaust products at the surface and aloft through the use of aircraft sampling techniques, and KSC provided local support for these activities. This program revealed the need for the development of a real-time dispersion prediction capability, and the results of the program provided measurements for use in verifying the accuracy of model predictions, as well as a data base which could be used in making model improvements.

The details of the current version of the Rocket Exhaust Effluent Diffusion (REED) code, which has been used to assess the environmental impact of Space Shuttle operations and to support the first five launches of the Space Shuttle, are briefly described.

THE NASA/MSFC REED CODE

The burning of rocket engines during the first few seconds prior to and immediately following vehicle launches results in the formation of a large cloud of hot, buoyant exhaust products near ground level which subsequently rises and entrains ambient air until the temperature and density of the cloud reach an approximate equilibrium with ambient conditions. By convention, this cloud is referred to as the ground cloud. The rocket engines also leave an exhaust trail from normal launches which extends throughout the depth of the troposphere. Given the input of existing (climatological) or predictions of meteorological parameters, the NASA/MSFC REED code is designed to calculate peak concentration, dosage and deposition (resulting from both gravitational settling and precipitation scavenging) downwind from normal launches, and launch aborts for use in the following:

1. Mission planning activities and environmental assessments
2. Prelaunch forecasts of the environmental effects of launch operations
3. Postlaunch environmental analysis

Overview of the NASA/MSFC REED Code

Figure 1 is a schematic diagram showing the major components of the REED computer program. Requisite meteorological inputs to the computer program are obtained from the vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure, and dewpoint or relative humidity between the Earth's surface and 3,000 m. This information is obtained during launch support activities from rawinsonde measurements routinely made at scheduled times throughout the prelaunch countdown and after the launch has occurred. The REED program accepts the rawinsonde data from either a disc or data tape file. As shown in figure 1, the rawinsonde data file can be manually edited to provide for any changes in the vertical profiles that weather forecasters assigned to the launch support team expect to occur between the time of the latest available rawinsonde measurements and the projected time of launch. Similarly, the meteorological inputs for the layers near the surface may also be manually adjusted to reflect changes in the low-level data available from the Wind System. The Wind System is a series of 30 m towers located throughout KSC and one 150 m meteorological tower instrumented to measure wind direction, wind speed, turbulence, and air temperature.

The REED program is controlled by operator input and internal management routines based on operator response to plain language queries displayed on a cathode ray tube (CRT) terminal. In figure 1, this complex interactive function is simply designated by CRT Program Control. Once the operator has elected to perform calculations for the launch of a particular vehicle (e.g., the Space Shuttle, Titan, or Delta Thor) and designated a normal launch or one or two launch-abort modes, the program automatically selects a proper set of source inputs for use in algorithms designed to calculate the following parameter values:

1. Position in space of the rising ground cloud as a function of time after launch until the internal cloud temperature equals the ambient air temperature (cloud stabilization time)

2. Dimensions of the ground cloud as a function of height

3. Distribution of vehicle exhaust products within the cloud as a function of height

At this point, the rawinsonde meteorological data, cloud rise, cloud dimension, and exhaust product distribution calculations are output to a printer and, if desired by the operator, also output to a plotted display of the vertical profiles of wind direction, wind speed, temperature, and virtual potential temperature, as well as the dimensions of the stabilized cloud. The operator then has the option of modifying the default values selected and calculated by the program to represent the major meteorological layer structure parameters (the height of the base and top of an elevated inversion layer, for example) and the turbulence parameters that will be used in the dispersion calculations.

After the final selection of model input parameters has been made by the operator, the program performs the selected type of calculations (dosage/concentration, gravitational deposition, or deposition due to precipitation scavenging, etc.). When these calculations are completed, the results are printed and, at the operator's option, plotted. If the dosage/concentration option were selected, the print output includes peak concentration at 1 km intervals downwind from the launch pad, the cloud arrival and departure times at 1 km intervals downwind from the pad, and the total dosage and time-mean concentration for the period of interest at these distances. The operator has the option of requesting the REED program to plot these results versus distance from the pad and/or isopleths of these quantities on a map of KSC. The print output for the gravitational deposition model contains maximum ground-level deposition versus distance from the pad. If selected by the operator, plots are made of maximum gravitational deposition versus distance from the pad and of deposition isopleths on a map of KSC. Finally, if the operator chooses to calculate deposition due to precipitation scavenging, maximum deposition or maximum surface water pH is also printed and plotted.

Shown in figure 1 are three major run modes that an operator can choose for making calculations with the REED code (operational, research, and production). The operational mode is designed for use during launch support operations and automatically calculates various user-inputs. For example, in the operational mode, the REED code uses an algorithm to calculate appropriate turbulence parameters near the surface, although an option is provided permitting the operator to modify the values. Either the values calculated by the REED code or the operator-input values are then used to automatically construct a vertical profile of turbulence for the first 3,000 m above the surface which is used in the dispersion calculations. When the research mode of the REED is selected, more information is usually input by the operator. For example, the operator can specify values of the turbulence parameters at each height where rawinsonde data are available. Finally, the production mode of the REED code is used to process multiple rawinsonde soundings which are read from the tape or disc file. While the production mode can be run interactively from the CRT terminal, the primary purpose of the production mode is to facilitate batch processing of multiple case without operator attention. The graphics package is not used with the production mode.

Launch Types and Vehicle Parameters

The REED code is designed to provide dispersion estimates for normal launches and two types of launch failures. For a normal launch, the assumption is made that all engines and the pad deluge system operate normally. In the case of a launch failure (single engine burn on pad), one solid engine of the Space Shuttle, Titan III, and Delta vehicles is assumed to fail to ignite, causing the vehicle to remain on the pad in a hold-down configuration while the other solid engine ignites and burns with the pad deluge system operating manually. In the other failure mode (slow burn on pad), an on-pad explosion is assumed to rupture the casings of the solid engines, scattering solid propellant over the area in the vicinity of the launch pad. The scattered solid propellant continues to burn over an extended period at a constant rate. It is assumed that the heat liberated by the explosion of liquid propellant (Space Shuttle and Delta Thor vehicles) does not contribute to plume rise because this heat is liberated over a very short time period compared to the burn time of the scattered solid propellant.

The fuel expenditure, heat content, and burn time data, currently used in the REED code, are presented in table 1. The fuel expenditure rates for normal launches were obtained by averaging the fuel expenditure rates for the engines over the approximate period from lift-off until the vehicle is about 3,000 m above the surface. The fuel expenditure rates for the single engine burn are an average for the normal firing period of the engine. For the slow burn, the rates in the table are an average over the estimated total burn time of the scattered propellants. The effective fuel heat contents, which are used in calculating buoyant cloud rise for normal launches and plume rise for launch failures, include the effects of heat produced by afterburning as well as heat losses due to radiation.

Table 2 shows the exhaust cloud constituents, expressed as a fraction of the total weight of the exhaust products. These fractions have been adjusted to yield the weight of HCl, Al_2O_3, CO_2, and CO in the exhaust cloud when multiplied by the appropriate fuel expenditure rates in table 1.

Meteorological Layers

The REED model output can be no better than the meteorological parameter accuracies used as an input, be they measured or predicted values. The primary meteorological input to the REED code is in the form of rawinsonde observations. Each level of information (standard, mandatory, and significant levels) in the rawinsonde data stream (*Kth* observation level) is used in the REED calculations to obtain the wind and temperature profiles. The REED code is currently constructed to perform dispersion calculations in two major, meteorologically defined layers. The base of the lower layer (L = 1) is assumed to be at the Earth's surface, and the top of the layer is assumed to be given by the base of an elevated inversion (top of the mixing layer). The boundaries of the upper layer (L = 2) are set by the operator. For example, if calculations are desired of dosage/concentration at the altitude of a sampling aircraft flying in an elevated inversion, the boundaries of the upper layer are defined by the base and top of the elevated inversion.

The selection of the boundaries of the two major layers is critical to the outcome of the dispersion calculations. Both gases (vapor) and particulates (Al_2O_3) are assumed to be reflected at the base of the lower layer according to a user-specified input for the fraction of material reflected (1 = complete reflection, 0 = no reflection). Material is never reflected at the base of the upper layer when gravitational settling or precipitation scavenging calculations are made, but gases are always reflected at the base of the upper layer. Thus, gases are assumed to be trapped in the upper layer for dosage/concentration calculations. The boundaries of these two major layers are also used in the determination of vertical turbulence profiles.

REED Code Cloud and Plume-Rise Models

The determination of the stabilized height of the ground cloud for normal launches and of the plume generated by launch failures is an important factor in the dosage/concentration calculations because, in general, the maximum dosage/concentration calculated at the Earth's surface is inversely proportional to the cube of the stabilized height. In the case of normal launches of solid-fueled vehicles or vehicles with large solid boosters, vehicle hold-down times are minimal and the vehicle residence times in the first several hundred meters are relatively short. The ground cloud is, therefore, comprised of buoyant gas emitted over a time period on the order of 10 sec. Experience to date shows that the buoyant rise of ground cloud under these circumstances is best calculated using an instantaneous cloud-rise model. Limited experience in predicting the buoyant rise from the normal launch of Delta vehicles, with their large liquid-fueled first stage, indicates that an average of the rise predicted by a continuous plume-rise and instantaneous cloud-rise model is appropriate. No plume-rise data are available for aborted launches of the vehicle types specified in the REED code. However, static tests of rocket engines indicate a continuous plume rise model is appropriate in these cases.

The buoyant rise models used in the REED program are based on the work of Briggs (refs. 1 and 2); the models are the instantaneous cloud-rise model and the continuous plume-rise model.

Source Dimensions, Material Distribution, and Spatial Position of the Stabilized Ground Cloud

The dispersion models are derived under the assumption that vertical finite line source can be used to represent the source of material in each of the K layers defined by the rawinsonde measurement levels and that the alongwind, crosswind, and vertical (r_z) radii of the cloud at the stabilization time are consistent with the cloud-rise model.

A. Source dimensions are determined for a normal launch as the dimensions in the plane of the horizon defined in terms of the standard deviations of the material distribution. The assumption made is that the distribution of material in the plane of horizon is bivariate Gaussian and that the concentration of exhaust products at one radius from the centroid is 10 percent of the concentration at the centroid.

B. Material distribution is determined for normal launches as the distribution of material within the ellipsoid and is assumed to be uniform in the vertical. For launch failures, the program assumes that the material has a Gaussian distribution in the vertical about the stabilization height.

C. Spatial position of the stabilized cloud is the spatial position in the plane of the horizon of the cloud in the K*th* layer at the stabilization time, with respect to the origin at the launch pad, and is given in polar coordinates.

Turbulence Profile Algorithm

The REED dispersion model code uses profiles of empirically derived standard deviations of the azimuth wind angle and elevation angle as prime predictors of cloud growth. The program calculates default turbulence profiles, which can be adjusted by the program operator. The algorithm used to calculate the turbulence profiles begins by calculating a reference standard deviation of the wind azimuth angle, assumed representative of a measurement made over a 10 min period at the lowest height available from the rawinsonde data input (4.9 m at KSC). The program assumes that turbulence over the layer depths of interest is approximately isotropic.

REED Code Dispersion Models

The dispersion models used in the REED code are based on Gaussian model concepts, which experience has shown to be suited for most practical applications. The Gaussian approach, when properly used, 'is peerless as a practical diffusion modeling tool. It is mathematically simple and flexible, it is in accord with much though not all of working diffusion theory, and it provides a reliable framework for the correlation of field diffusion trials as well as the results of both mathematical and physical diffusion modeling studies' (ref. 3). In the REED dispersion code, the exhaust materials is assumed to be uniformly distributed in the vertical and to have a bivariate Gaussian distribution in the plane of the horizon at the point of cloud stabilization. It follows from these assumptions that the models are of the general form identified with Gaussian models for vertical line sources of finite extent.

Dosage and Concentration Models

The dosage and concentration formulas are written in a rectangular coordinate system with the origin at the ground beneath the cloud stabilization point in the *Kth* layer. The x axis is directed along the axis of the mean wind direction in the *Lth* layer, and the y axis is directed crosswind or perpendicular to the mean wind direction. In the programs, the origin of the coordinate system is placed at the launch pad.

Gravitational Deposition Model

This model determines the weight of material per unit area deposited on the ground as a result of the gravitational settling of particles (drops) with velocity from the source in the *Kth* layer.

Precipitation Scavenging Model

This model determines the weight of material from the *Kth* layer deposited on the ground as a result of washout by rain.

SUMMARY

A ground cloud is formed by an aerospace vehicle such as the Space Shuttle rockets during launch. This cloud consists of the exhaust products from the solid rocket motors and liquid engines, the products of afterburning in the exhaust plume, the air that is mixed with exhaust gases, and much of the heat energy that is generated.

The direction, movement, and diffusion of the ground cloud have been the subject of an intensive analytical study during the past several years. A mathematical model has been developed which uses the characteristics of the rocket exhaust products and launch site meteorology to predict the rise, growth, and dispersal of the ground cloud. The model's output is critically dependent upon the accuracy and representatives of the meteorological inputs given for the time and location of concern. To validate the model, seven Titan launches were monitored at KSC using aircraft-, ground-, and sea-based instrumentation to measure cloud concentrations and fallout of hydrogen chloride, carbon dioxide, and aluminum oxide particles. These are the primary exhaust products of the solid rocket motors which are of concern. There was reasonable agreement between measurements and the model predictions, considering the range of uncertainties of data inputs and statistical nature of the model output.

Additional information on the REED code and its operation can be found in references 3 and 4. References 5, 6, and 7 pertain to air quality standards and exposure to air pollutants.

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TABLE 1.- FUEL EXPENDITURE AND HEAT CONTENT DATA

Property	Vehicle type			
	Space Shuttle	Titan III	Delta 2914	Delta 3914
(a) Normal launch				
Fuel expenditure rate W (g s^{-1})	1.5219×10^7	5.4375×10^6	8.3607×10^5	1.0576×10^6
Effective fuel heat content H (cal g^{-1})	1479.1	2021.1	1766.0	1449.9
(b) Single engine burn				
Fuel expenditure rate W (g s^{-1})	3.8451×10^6	2.7188×10^6	NA	NA
Effective fuel heat content H (cal g^{-1})	1062.4	1010.6	NA	NA
Burn time t_B (s)	132.0	60.0		
(c) Slow burn				
Fuel expenditure rate W (g s^{-1})	9.8873×10^5	1.3594×10^6	2.7294×10^5	3.7073×10^5
Effective fuel heat content H (cal g^{-1})	1000.0	1000.0	690.0	411.2
Burn time t_B (s)	1027.0	240.0	69.0	126.0

Symbol definition:

NA = Not applicable

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TABLE 2.- EXHAUST CLOUD CONSTITUENTS (FRACTION BY WEIGHT)

Constituent	Vehicle type			
	Space Shuttle	Titan III	Delta 2914	Delta 3914
HCl	0.1146	0.1932	0.1218	0.1589
Al_2O_3	0.1828	0.2819	0.2214	0.1936
CO_2	0.2503	0.2665	0.2055	0.2783
CO	0.00042	0.0222	0.0156	0.0331

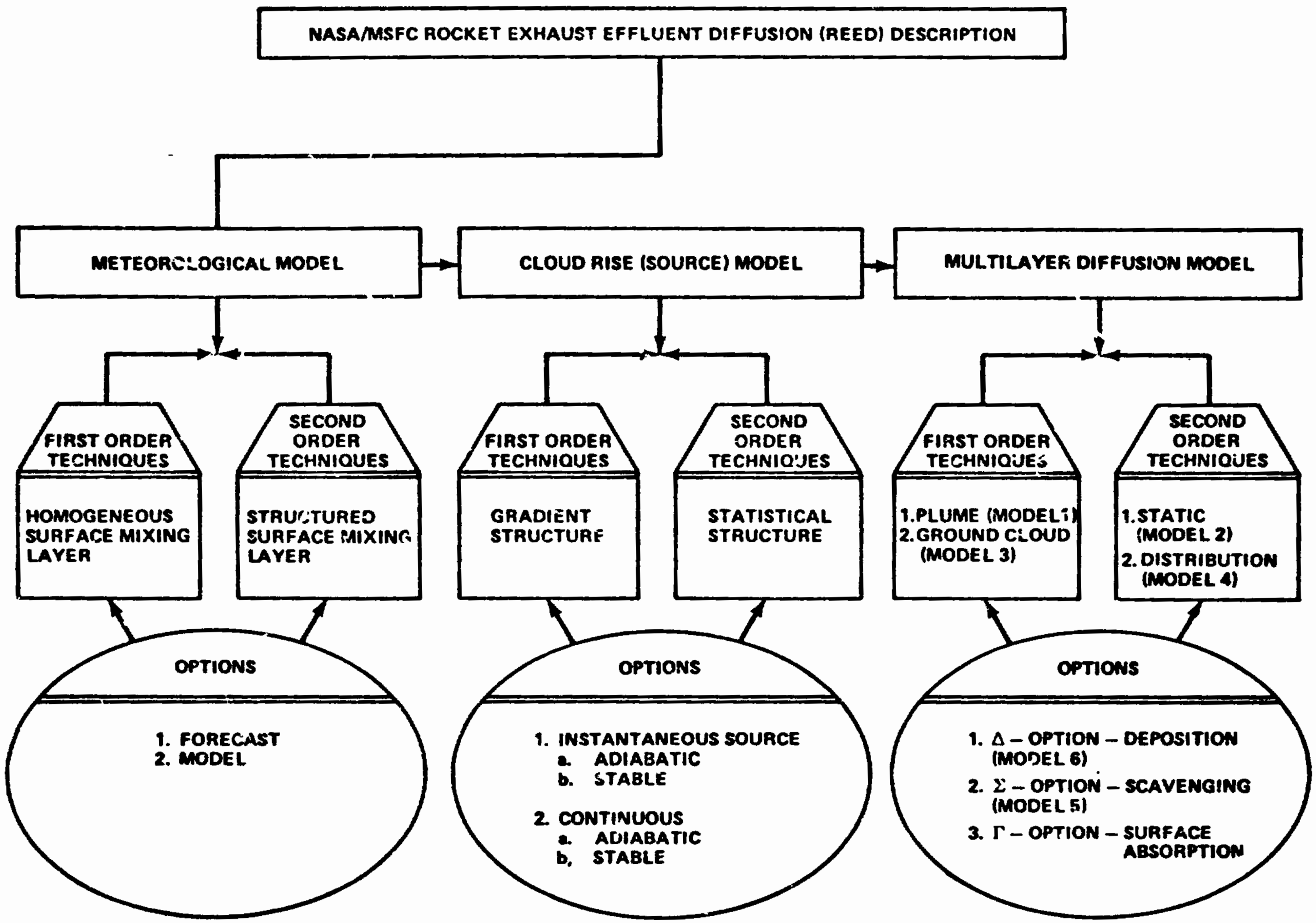

Figure 1.- NASA/MSFC REED Code.

NASA/MSFC EXHAUST EFFLUENT DIFFUSION PREDICTIONS AND MEASUREMENTS FOR STS-1 THROUGH STS-4

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INTRODUCTION

Presented in this paper are the results of the National Aeronautics and Space Administration (NASA)/Space Flight Center (MSFC) air quality predictions made during the first four Space Shuttle launches from John F. Kennedy Space Center (KSC). Space Transportation Systems (STS) 1 through 4 were launched on the following dates:

STS-1 - April 12, 1981
STS-2 - November 12, 1981
STS-3 - March 22, 1982
STS-4 - June 27, 1982

NASA/MSFC has conducted a prediction and measurement program to assess the potential environmental effects from aerospace operations. As a part of a joint program with the Langley Research Center (LaRC), KSC, and Lyndon B. Johnson Space Center (JSC), MSFC developed the NASA/MSFC Rocket Exhaust Effluent Diffusion (REED) Model to measure exhaust effluents. Large-scale solid rocket launches have been monitored since the late 1960's to refine the model and to develop new measurement techniques for use in making environmental analyses of the air quality from the exhaust effluents from the STS launches.

The Space Shuttle exhaust ground cloud results from the exhaust plume from the Space Shuttle Main Engines (SSME's) and the Solid Rocket Boosters (SRB's) initially impinging on the launch complex and flame trench. The initial ground cloud is formed from high-temperature combustion products (exit plane temperatures of approximately 2146°K) and vaporized flame trench water. The exhaust cloud rises to an altitude at which buoyant equilibrium with the ambient atmosphere is established. This occurs at an altitude of 1 km to 2 km in a period of 5 min to 10 min after launch. At this point, the kinematic transport phase commences. At stabilization, the exhaust cloud typically contains approximately 99 percent ambient air entrained during the cloud rise portion of its transport. The major rocket exhaust constituents are hydrogen chloride (HCl), carbon dioxide (CO_2), water vapor (H_2O), and aluminum oxide (Al_2O_3). Figure 1 is a schematic representation of this process. The exhaust cloud rise to stabilization and the turbulent transport are intimately coupled to small-scale meteorological phenomena, rocket exhaust plume chemistry, and turbulent diffusion.

METEOROLOGICAL CONDI[illegible]

Some of the difficulties [illegible] in carrying out launch prediction [illegible] monitoring activities on the transport process is intimately dependent on the abili[illegible] predict time-dependent small and [illegible] scale meteorological conditions.

Real-time atmospheric data and weather forecasts were provided by the Cape Canaveral Air Force Station, Air Weather Service Detachment, located in the Cape Range Control Center. Their data included vertical atmospheric soundings, synoptic weather charts, upper air charts, wind tower data, and other meteorological information. These data were then analyzed in terms of diffusion parameters by a MSFC atmospheric scientist.

ROCKET EXHAUST PREDICTIONS

Exhaust Cloud

The first four launches of the Shuttle produced an exhaust cloud that was very similar in size and concentrations to prelaunch estimations. The first two exhaust clouds (STS-1 and STS-2) went inland, and the next two (STS-3 and STS-4) went out to sea.

The flame deflectors at the launch pad are designed to direct the SRB exhaust plume (which is composed principally of HCl, Al_2O_3, and steam) toward the north and the SSME exhaust plume (which is composed principally of water and steam) toward the south. An apparent chimney effect causes these two exhaust clouds to merge and form a single ground cloud.

Diffusion Predictions

The NASA/MSFC REED code was utilized to make predictions of the transport of exhaust effluents. The objective was to determine the HCl concentration field of the exhaust cloud in the transport layers. The NASA/MSFC REED code includes three separate models to account for the atmospheric conditions and the thermodynamic and kinematic modes of the transport process. The code is outlined in figure 2.

Two sets of diffusion predictions are made for L - O. The first is made based on a meteorological forecast at L - 8.5 hr to support KSC s final deployment of air quality monitoring instrumentation. The centerline peak concentrations, 10-min average concentrations, and dosages for HCl along the ground cloud transit path are made. The HCl isopleths are made for these forecasts also. To correlate the surface measurements with the air quality predictions, the L - O sounding is used in the NASA/MSFC REED code. The L - O HCl centerline concentration dosages and HCl isopleths are made. Figure 3 gives the direction in which the exhaust cloud traveled on each of the launches.

CONCLUSION

The primary effluents from the Shuttle's solid-rocket exhaust are aluminum oxide (Al_2O_3), hydrogen chloride (HCl), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), nitrogen (N_2), and water vapor (H_2O). While only the first four compounds are toxic in significant concentrations, there is always a potential hazard of suffocation from any gas which results in the reduction of the partial pressure of oxygen to a level below 135 mm mercury (Hg) [18 percent by volume at standard temperature and pressure]. Oxygen level reduction does not appear to be a hazard from solid-rocket exhaust due to the large volume of air which is entrained into these exhaust clouds; therefore, this potential hazard can be neglected and attention directed only to the initial four compounds.

The exposure levels for toxic effluents are divided into three categories: (1) public exposure level, (2) emergency public exposure level, and (3) occupational exposure level. The public exposure levels are designed to prevent any detrimental health effects to all classes of human beings (children, men, women, the elderly, those of poor health, etc.) and to all forms of biological life. The emergency level is designed as a limit at which some detrimental effects may occur. The occupational level indicates the maximum allowable concentration of toxic effluents which a man in good health can tolerate; this level could be harmful to some aspects of the ecology. Public health levels for aluminum oxide are not given because the experience with these particulates is so limited that the industrial limits are, at best, very crude estimates.

HCl is an irritant; therefore, the concentration criterion for an interval should not be exceeded. Since HCl is detrimental to plant and animal life and because most launch sites are encompassed by wildlife refuges, the emergency and industrial criteria for HCl are not appropriate to the ecological constraints. Because of the large volume of air entrained in the exhaust cloud, the potential hazard from CO and CO_2 can be neglected.

The potential air quality effects resulting from the first four Shuttle launches have been well below the standard required by the Environmental Protection Agency, [8 ppm peak exposure], as seen in table 1. Field measurements of HCl gas in regions beyond a mile from the launch pad never showed any indication of HCl, except for one or two obviously erroneous readings. The model evidently is extremely conservative with respect to surface concentrations of HCl.

TABLE 1.- AIR QUALITY EFFECTS FROM FOUR SHUTTLE LAUNCHES

Launch	Predicted maximum HCl gas, ppm	Observed far-field maximum HCl gas, ppm
STS-1	2.4	< 0.01
STS-2	0.9	< .01
STS-3	.6	< .01
STS-4	.5	< .01

Details of the REED model predictions for STS-1 through STS-4 are given in references 1 through 4.

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4. Sloan, J. C.; and R. E. Turner: MSFC Exhaust Effluent Diffusion Predictions and Measurements for STS-4. Environmental Applications Branch, Atmospheric Sciences Division, NASA/MSFC, ES 84-4-82, September 1982.

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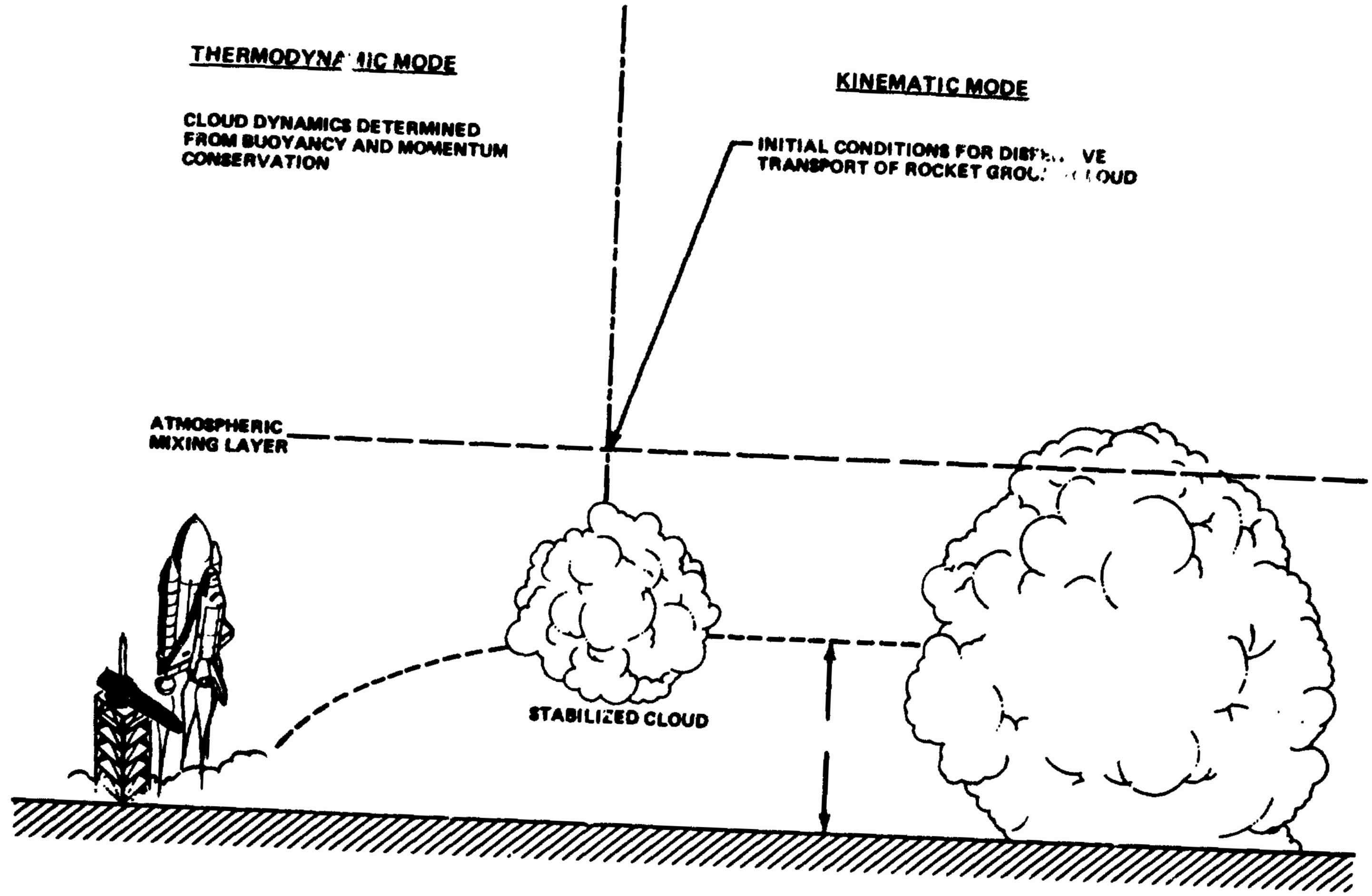

Figure 1.- Schematic of rocket exhaust ground cloud formation and transport.

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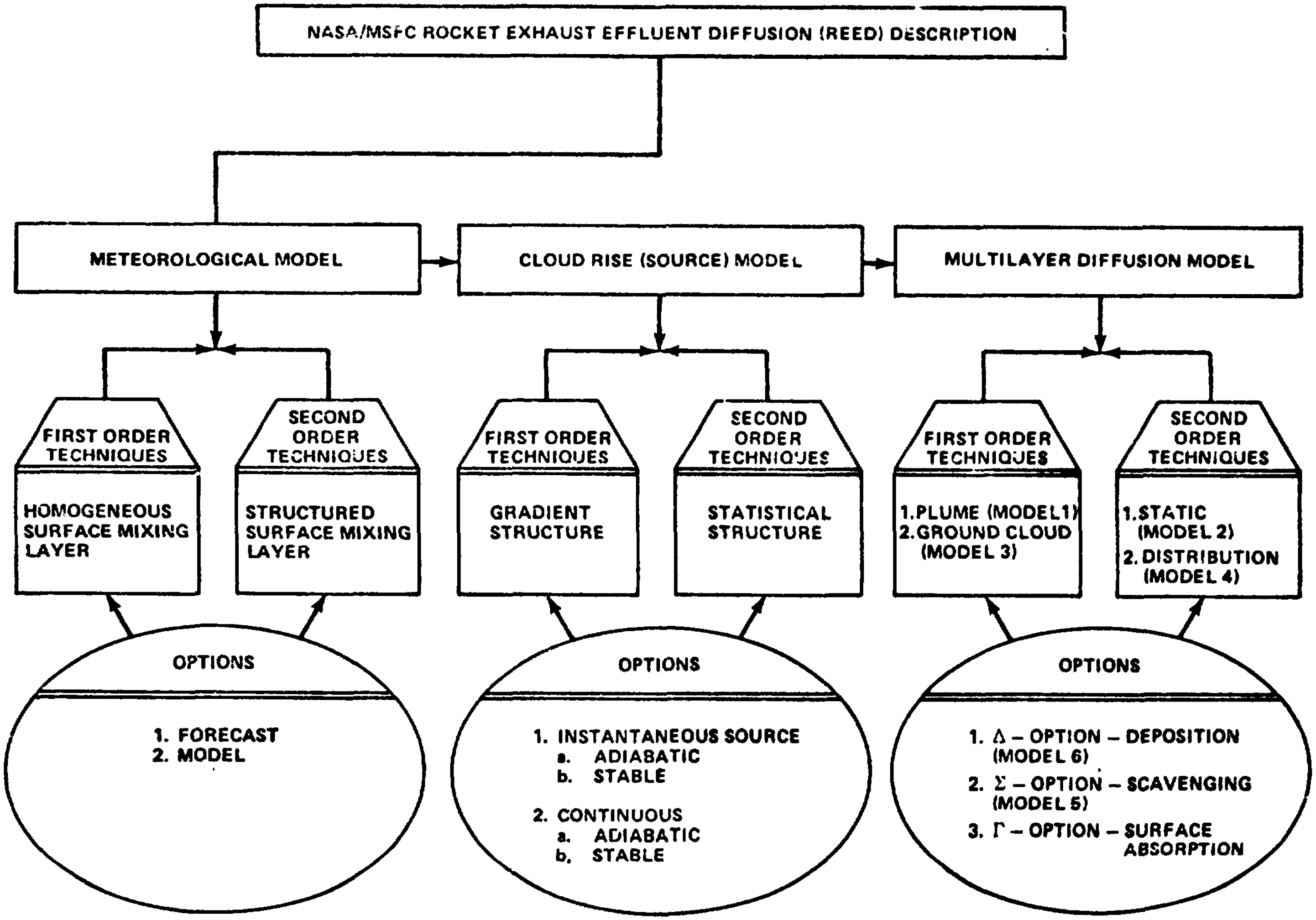

Figure 2.- NASA/MSFC REED code.

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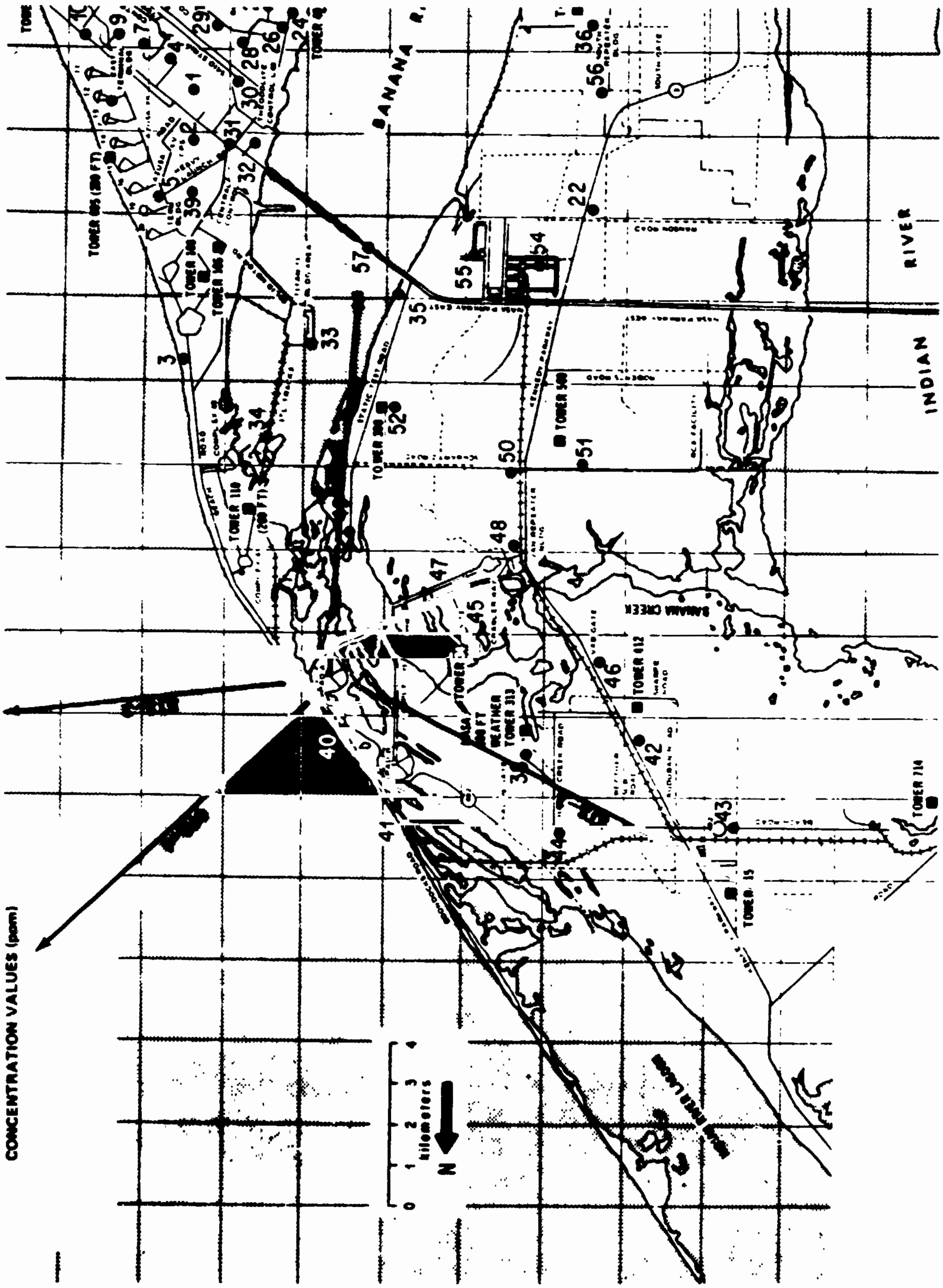

Figure 3.- Exhaust cloud direction.

A COMPARISON OF IN-CLOUD HCL CONCENTRATIONS PREDICTED FROM THE NASA/MSFC MULTILAYER DIFFUSION MODEL TO MEASUREMENTS FOR THE FIRST SPACE SHUTTLE LAUNCH, APRIL 12, 1981[a]

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INTRODUCTION

The objective of this work was to test the National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center (MSFC) Multilayer Diffusion Model (MDM) (refs. 1 and 2), which has been adapted for predictions of surface-level HCl concentrations under the name Rocket Engine Exhaust Diffusion Model (REEDM). However, surface concentrations of HCl are extremely difficult to measure because the direction taken by the exhaust cloud after launch cannot be predicted soon enough to place HCl measurement stations underneath the cloud. Consequently, a limited test of the model was tried using aircraft data for HCl concentration inside the Shuttle exhaust cloud. This approach was previously used to test an earlier version of the MDM or the exhaust clouds produced by launching Titan III C rockets (refs. 3 and 4).

MODIFICATIONS OF THE MDM

In order to use the MDM to give HCl concentrations at levels other than surface level, it was necessary to modify two statements in subroutine SETUP DAT.; i.e., NPTS which identifies the number of levels in the cloud at which concentrations are desired, and ZZL which is the parameter for the height of these levels in meters. With these modifications, the MDM would output HCl concentrations at any level up to the cloud stabilization height.

[a]Abstracted from the Final Technical Report, Contract NAS 9-16162.

Because of the great length and complexity of the MDM, even small modifications can be difficult to accomplish or can cause unexpected problems. This is particularly true if more than one segment of the program is involved. Problems were encountered in changing the constants in the model. For example, even though version 6 constants had been put into the program and the program indicated they had been used, careful checking on the outputs showed the old version 5 constants, in fact, were used. This problem was eventually solved, and the MDM program was run using the most recent constants, the same as those used in the operational REEDM model, denoted as version 7. The constants are listed in table 1. They do not differ substantially from versons 5 and 6 constants, and did not produce significant differences in HCl predictions when run on identical cases.

MDM PREDICTIONS FOR STS-1

The Data

The exhaust cloud from STS-1 was anomalous to the extent that it separated into two distinct clouds, a low-level cloud and a high-level cloud. These two clouds moved in different directions, the lower one in a northeasterly direction and the upper one in a westerly direction. This separation was caused by upper-level inversion and wind shear conditions, as shown in the abbreviated version of the meteorological sounding at launch time given in table 2.

A graph of the temperature and dewpoint temperatures as a function of height from these tables is shown in figure 1. On this same figure, the height predicted by the MDM for stabilization of the launch cloud is given (1187 m). The flights through the fragmented launch cloud A which ranged from 850 m to 900 m, and for cloud B from 1600 m to 1870 m are also given for reference purposes.

The temperature sounding (fig. 1) clearly shows a shallow surface inversion and a moderate upper-level inversion and stable layer extending from 3,256 ft to 7,000 ft. This type of sounding is characteristic of weather regimes for the Cape in which the Bermuda High extends over the Florida Peninsula. Subsidence in the high pressure area produces the inversion and stable layer at upper levels. This stable layer is responsible for suppressing the observed stabilization height for cloud B, but the inversion is not intense enough to suppress the launch cloud to the level predicted by the MDM.

Examination of the wind directions in table 2 indicates a vertical shear of the horizontal wind throughout the mixing layer and across the inversion. This shear helped to fragment the Space Shuttle launch cloud which was observed to stabilize eventually in five segments, each at a different height.

The two main fragments of the Shuttle launch cloud were observed to reach stabilization height at about 8 min after launch. Aircraft sampling of the lower cloud A for HCl gases and aerosols and for particulates began at 8.6 min after launch for cloud A and continued at 2-min-to-5-min intervals until 45 min after launch. The higher cloud B was sampled similarly from 49 min until 2 hr and 8 min after launch. The aircraft measurements have been reported in reference 5.

In-cloud HCl predictions for comparison with the aircraft data were obtained from the MDM using the meteorology from table 2. In-cloud concentrations were computed for four different levels corresponding roughly to the upper and lower limits of aircraft sampling heights for clouds A and B (see fig. 1). Values of maximum centerline HCl at 850 m and 900 m were obtained for the lower cloud and at 1600 m and 1800 m for the upper cloud. The maximum peak HCl predictions for the lower cloud at the 850 m and 900 m levels differed by less than 1 percent, whereas, those for the upper cloud differed by less than 10 percent.

The airborne HCl measurements were made as a function of time in reference to the launch. The MDM predictions, however, are output as a function of distance of the launch cloud from the launch site. In order to make a comparison of these MDM predictions with the HCl measurements, it was necessary to make an assumption relative to the equivalence between the time from launch and distance of the launch cloud from the launch site. The most reasonable assumption would be to consider that the cloud fragments move with a speed equal to the average wind speed of the layer at which the particular cloud stabilized. As shown in table 2, the wind speed decreases from 12 knots at 2,000 ft to 9 knots at the 3,000-ft level. Since cloud A drifted northward at altitudes from 650 m (2,133 ft) up to 950 m (3,117 ft), it would be reasonable to assume that it experienced an average wind speed on the order of 10.5 knots (5.4 m/sec). The second cloud segment was observed to drift westward at altitudes from 1,350 m (4,429 ft) up to 1,880 m (6,168 ft). From data in table 2, the wind speed increases from 8 knots at the 4,000-ft level to 16 knots at the 6,551-ft level making it reasonable to assume an average wind on the order of 12 knots (6.17 m/sec) for cloud B. It is necessary to add to the values output by the MDM the amount of time elapsed from launch to cloud stabilization which was at 1,250 m and 2,500 m downwind from the launch site according to the MDM. By using an average wind speed for the rising launch cloud of 10.5 knots, the time to cloud stabilization for the lower cloud is 5 min 21 sec, and the time for the upper cloud is 7 min 43 sec. This is close to the 8 min to cloud stabilization that was reported to be observed by Sebacher (ref. 5). A shift of the time scale by several minutes in either direction does not significantly alter the general conclusions reached relative to the comparison of observed and predicted HCl concentrations.

Results

The MDM predictions for peak centerline HCl concentrations in the lower cloud A are given in figure 2 by the solid line. The peak values of gaseous HCl are represented by squares, and the peak values of total HCl (gas + aerosol) are represented by crosses. The agreement between the magnitude of the observed and measured values of gaseous HCl is fair considering the uncertainties inherent in both methods of determining it.

The rate of decay of HCl with time is in particularly good agreement for both predicted and measured values. The lower cloud is in a region where the atmosphere is less stable than the region of the upper cloud. This may be determined by looking at the temperature profile in the plot of the meteorological (MET) sounding in figure 1. The rate of decay of HCl concentration as determined by the MDM is largely a function of the standard deviation of the horizontal wind speed (σ) as used in the diffusion calculations. This parameter was obtained from the John F. Kennedy Space Center (KSC) computer which calculates using an objective routine that analyzes the variances in wind direction. The value of $\sigma = 13$, which was used and is relatively large, as parametric studies (ref. 6) have shown. This value of σ would appear to be representative for HCl concentration decay in the region below the upper level inversion.

The magnitude of HCl concentrations predicted by the MDM has been shown to be conservative in other studies which have used it to predict surface concentrations of HCl for Titan launches (refs. 3 and 4). The overprediction of in-cloud HCl would also be expected because of the conservative assumptions which have been built into the MDM. Another factor which tends to cause the predicted HCl values to be larger than the measured values for this particular case is the large amount of HCl that is in the aerosol form. In figure 2, it can be seen that the MDM predicted value is about midway between gaseous and total HCl concentration values. The rate of decay of total HCl closely parallels the rate of decay of the predicted and measured HCl in gaseous form.

In figure 3, the MDM predictions for HCl in cloud B, represented by a solid line, are compared to measurements of gaseous and total HCl concentrations. The MDM predictions in contrast to those for the lower cloud significantly underpredict the gaseous HCl by a factor of about 3. The measurements of gaseous and total HCl also do not display the decay with time predicted by the model. In fact, the gaseous HCl values decay relatively slowly over the 70 min of sampling time, as indicated by the dashed line in figure 3.

The reasons for the lack of agreement are probably related to the fact that the upper cloud has entered a stable environment above the inversion (note fig. 1). In this environment, mixing processes are inhibited while the MDM essentially assumes the same rate decay established by the choice of σ the surface environment. It would have been useful to have HCl concentration measurements of cloud B early in its history to check on the role of the decay rate in this overprediction by the MDM.

Another difference between the lower and upper clouds is that cloud B had a low relative humidity causing the HCl concentration to be almost entirely in the gaseous phase. The measurements of total and gaseous HCl plotted in figure 3 show a great degree of variability perhaps suggestive of the difficulty in making accurate measures under these circumstances. The error range in these measurements was estimated by Sebacher and others (ref. 5), as ± 20 percent with a precision of measurement of 0.5 ppm. The variability of the data could also be related to the difficulty of aircraft sampling when the cloud has become diffuse with the passage of so much time.

One problem with the use of the MDM for making these predictions is certain to cause the HCl values to be underestimated; note the following. The MDM will not compute HCl concentrations above the mixing height which must be chosen subjectively prior to running the program. As shown in figure 1, the height of the surface mixing layer is clearly at the base of the upper-level inversion. In order to have the MDM calculate concentrations above this level, it was necessary to assume the mixing would occur throughout the layer from cloud B to the surface. This assumption is not realistic and causes the concentrations of HCl to be reduced at every level. It is, therefore, quite probable that the underprediction of HCl concentrations in the upper cloud are related to problems inherent in the MDM which prohibit it from more realistic modeling changes encountered in the real atmosphere.

CONCLUSIONS

This work represents a first attempt to compare in-cloud HCl concentration predictions to in-cloud aircraft measurements of HCl for the Space Shuttle launch. The inadequacy of the NASA/MSFC MDM to accurately portray the actual complexities of the diffusion process and particularly to cope with the effect of changing conditions which rocket launch clouds encounter as they drift from the site are well known and have been given consideration in numerous studies. If there is a general conclusion from the work presented here, it is that in spite of the numerous experimental and theoretical difficulties in obtaining the in-cloud HCl concentrations, the agreement is at least within an order of magnitude.

The fragmentation of the Shuttle launch cloud on the April 12, 1981, launch presents a serious difficulty for the MDM at the onset because only simple cloud geometries are assumed. In spite of these difficulties, the decay rate of peak HCl concentrations in the lower cloud are well portrayed by the MDM and are only slightly overpredicted. The overpredictions may be understandable as discussed because of the significant amount of HCl which is in aerosol form due to the high relative humidity of the lower cloud.

The decay of HCl concentrations predicted by the MDM for the upper cloud is much more rapid than observed over the 70-min sampling period. As discussed, this could be related to the use of a standard deviation of the horizontal wind direction (σ) that is appropriate for estimating the diffusion processes in the lower cloud which is in an unstable environment. The upper cloud, however, is in a region of generally high stability which reduces mixing. This could also account for the magnitudes of HCl being underpredicted, particularly since the upper cloud was not sampled until about 50 min had elapsed. In general, it is apparent from this study that the MDM can produce in-cloud HCl values that fall within a reasonable range of measurement.

Comparisons of MDM HCl concentrations with surface HCl measurements show less agreement, since studies indicate it overpredicts by an order of magnitude or more. The presence of a surface inversion layer, as was present for STS-1, would prevent any HCl at all from reaching the surface, and Gaussian diffusion models may be unrealistic at large distance from the cloud center.

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TABLE 1.- MDM PREPROCESSOR PARAMETERS

[Referred to as version 7 constants in this report; they do not differ substantially from version 6 and version 5 constants.]

VPAR No.	Data	Shuttle	Titan	Delta II	Delta IV
1. QC1	Expenditure rate: grams/sec; normal	1.521923 E7	5.437528 E6	8.360685 E5	1.057557 E6
2. QC2	Expenditure rate: grams/sec; one motor on pad burn	6.882968 E6	2.718764 E6	9.09811 E4	1.482923 E5
3. QC3	Expenditure rate: grams/sec; motor explode on pad	3.4141484 E6	1.359382 E6	2.729434 E5	3.70731 E5
4. QT1	Source strength: grams; normal	1.8947941 E9	3.2625168 E8	2.887598 E7	6.70269 E7
5. QT2	Source strength: grams; abnormal	8.56929516 E8	1.6312584 E8	3.14229 E6	9.398616 E6
6. QT3	Source strength: grams; explosion	1.71385903 E9	3.2625168 E8	1.885373 E7	4.699308 E7
7. AA	Rise parameter: $t = aZ^b + c$	0.6522129	0.429580469	0.922156	1.245756
8. BB	Rise parameter: Z = height, m	0.4680846	0.5184223	0.432703	0.4180947
9. CC	Rise parameter: t = time, sec	0.375	5.0	0.54	0.0
10. Heat	N heat output cal/grams	1479.7	2020.1	1766.0	1449.9
11. Heat	M cal/grams	1062.35	1010.55	1000.	1000.
12. Heat	A cal/grams	1000.0	1000.0	690.0	411.18

TABLE 2.- ABBREVIATED RADIOSONDE DATA FOR STS-1

These are data for Cape Canaveral on 1212 Z April 12, 1981, corresponding to the launch of STS-1. Data were provided by Richard Bendura of Langley Research Center (LaRC) but correspond to excerpts from the complete MET data set.

Altitude ft	Wind		Temperature, °C	Dewpoint, °C	Pressure, mbar	Relative humidity, percent
	Direction, degree	Speed, knots				
16	110	4	17.0	15.9	1023.4	93
1,000	136	12	19.1	14.8	988.46	76
2,000	142	12	16.2	13.5	953.98	84
3,000	136	9	14.1	11.7	920.41	86
4,000	099	8	15.1	-0.6	887.90	37
5,000	079	12	15.3	-2.2	856.56	30
6,000	074	15	14.2	-2.7	826.26	31

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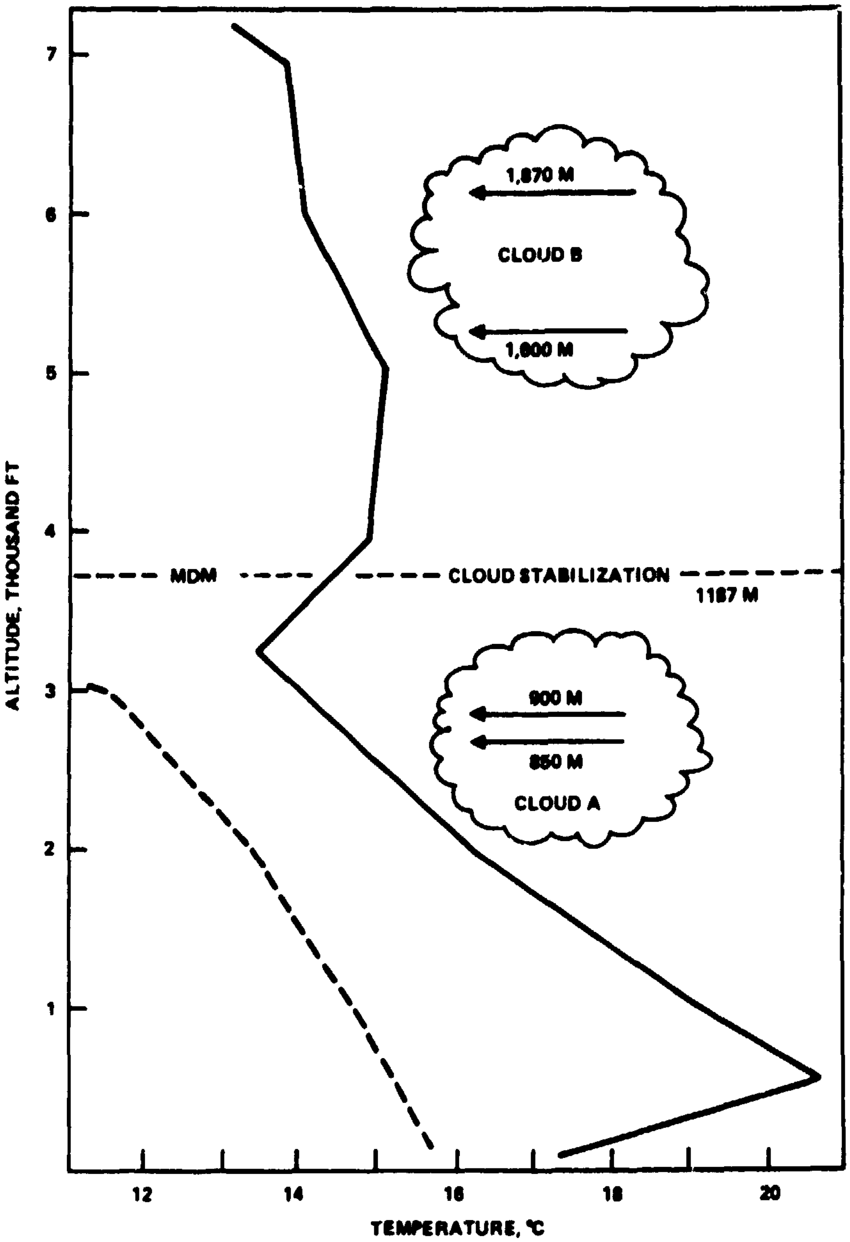

The vertical profiles of temperature (solid line) and dewpoint temperature (dashed line) are from table 2. The stabilization height at 1,187 m was predicted for the Shuttle launch cloud by the cloud rise portion of the MDM. The 850 m and 900 m levels represent the levels used for in-cloud HCl predictions and for aircraft sampling in the lower (Cloud A) portion of the fragmented ground cloud. Aircraft sampling and MDM predictions for the upper fragment (Cloud B) were in the 1,600 m to 1,800 m range.

Figure 1.- Plot of MET data for 1212 Z, April 12, 1981.

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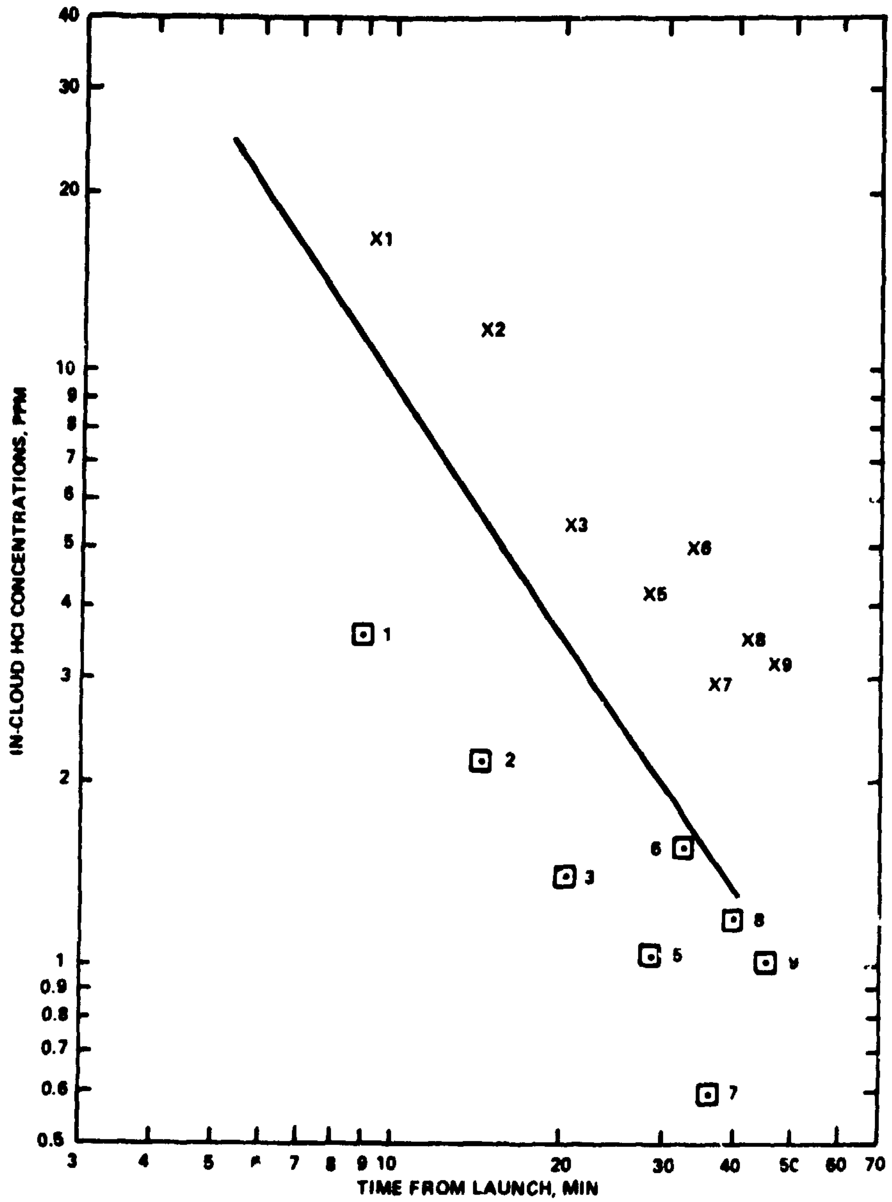

The solid line represents the in-cloud HCl concentrations predicted by the MDM for the 850 m level. The data points marked with an X are for total HCl, including gaseous and aerosol. The data points marked with a square are for the measurements of gaseous HCl only. The numbers by the data points indicate the flight pass number. The data values are for the lower Cloud (A) taken from table 4 in reference 5. The dashed line represents an adjustment of MDM predictions taking into account observed movements of Cloud A given in figure 3.

Figure 2.- Measured and predicted in-cloud HCl concentrations for Cloud A, STS-1.

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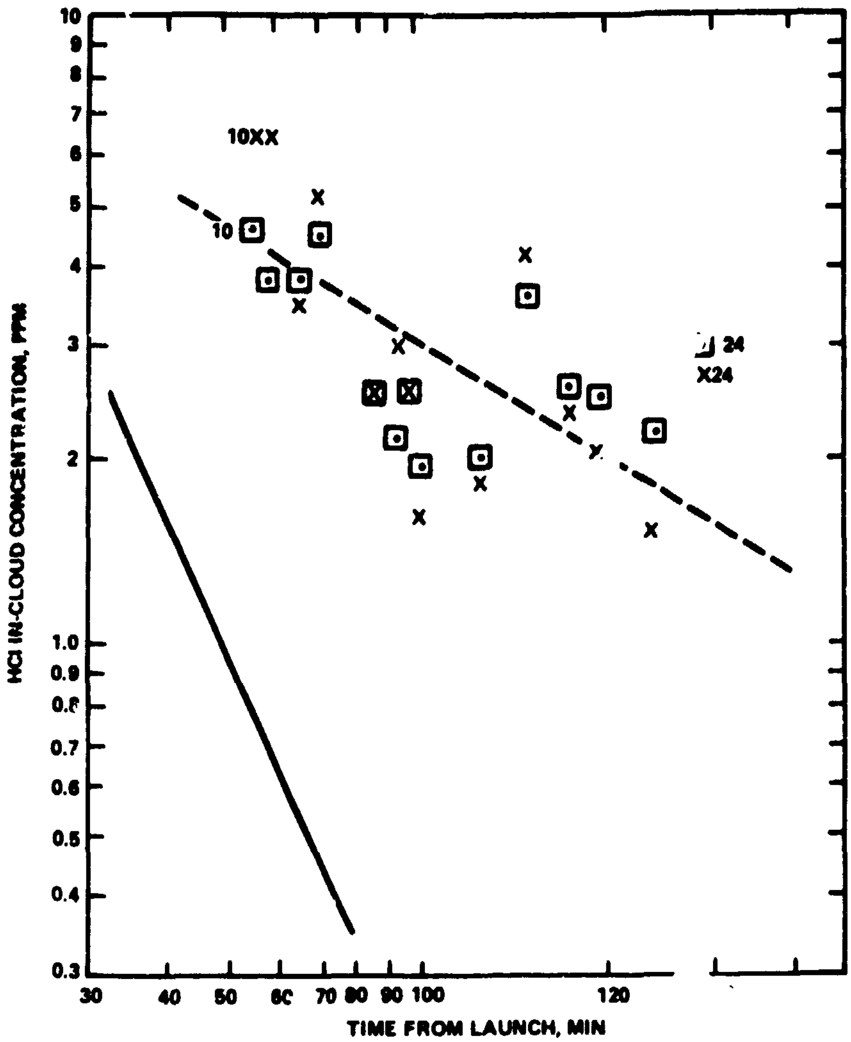

The solid line represents the in-cloud HCl concentrations predicted by the MDM for the 1,600 m or 1,800 m level. The data points marked with an X are for total HCl, including gaseous and aerosol. The data points marked with a square are for the measurements of gaseous HCl only. Some of the data points have corresponding flight pass numbers adjacent to them. The data values are for the upper Cloud (B), taken from table 4 in reference 5.

Figure 3.- Measured and predicted in-cloud HCl concentrations for Cloud B, STS-1.

OBSERVATIONS AND CUMULUS MODELS OF SHUTTLE EXHAUST CLOUDS

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ABSTRACT

Observations taken on the STS-4 launch indicate that the deluge water was blasted out of the flume by the solid rocket boosters (SRB's) and that a wall of water about a decimeter thick was imbedded in the ground exhaust cloud as it passed the perimeter fence. A 1 1/2-dimensional cumulus cloud model gave cloud growth rates that compared favorably with actual cloud growth rates. The model was obtained using atmospheric soundings of temperature, humidity, and wind taken prior to STS-3 and STS-4 launches plus the heat and water vapor impulse produced by the rockets. The effort to investigate the scavenging of exhaust products by cloud and precipitation particles is described in this paper.

INTRODUCTION

This report is divided into three separate parts, each of which pertains to the exhaust cloud from the Space Shuttle. The first section is concerned with observations taken within the cloud on STS-3 and STS-4 and which lead to the conclusion that the deluge water dumped into the flume prior to ignition of the SRB's was blasted out of the flume as a wall of water inside the ground cloud.

The second part of this report provides the results obtained from a fairly simple numerical cloud model which used the heat and water vapor produced by the Space Shuttle rockets as an impulse to the model. The development of the resulting cumulus cloud and subsequent precipitation depended not only on the impulse but also on the ambient conditions; e.g., stability, temperature, and humidity of the atmosphere. Under certain reasonable conditions, the rate of growth of the computer-generated model clouds agreed with that of the observed clouds.

The third part describes some ongoing research concerning deposition of exhaust products from Space Shuttle launches under participating conditions. This research is being conducted by one of the Air Force Geophysics Laboratory (AFGL) scholars; and the scope is limited due to the 1-year length of the research position.

OBSERVATIONS WITHIN THE GROUND CLOUD

In a letter report to the U.S. Air Force (USAF) Space Division dated 31 August 1982[a], it was pointed out that the ground cloud [referred to as the 'flame trench cloud' in a recent article (ref. 1)] contained a wall of water which saturated the PMS particle size measuring equipment, bent the perimeter fence, and broke off two of the three cups on the anemometer. The following calculations indicate the order of magnitude of the mass of water (m) blasted out of the flame trench by the solid rocket boosters (SRB's). The total mass released at the launch pad was:

$$m = \frac{dm}{dt} t$$

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[a]Letter to SD/DEV dated 31 August 1982 from AFGL/LYC entitled Preliminary Report on STS-4 Exhaust Cloud Measurements by Arnold A. Barnes, Jr.

Review of TV tapes for STS-5 launch shows the deluge water began approximately 10 sec prior to the SRB ignition. From a National Aeronautics and Space Administration (NASA) report, the release rate of the deluge water was taken as 17,000 gal/sec

$$m = 17 \times \frac{10^3}{sec} \text{ gal} \times 10 \text{ sec}$$

$$= 1.7 \times 10^5 \text{ gal}$$

$$= 643 \text{ m}^3 = 6.43 \times 10^5 \text{ kg}$$

since

ρ = 1000 kg/m^3 for water and

1 gal of water

$$= 3.785 \times 10^{-3} \text{ m}^3$$

Assuming that one-half of this water was on the SRB side of the deflector and that one-half of that was lost through evaporation or into the holding pond trenches, there remained 160 m^3 of deluge water ejected by the SRB's in the flame trench cloud.

Observations of the pad area after STS-4 indicated that the cloud was about 200 m wide when it passed the perimeter fence. Damage to equipment at the PMS site indicated that the water was over 6 m high but was less than 10 m high, the height of a glass light on a pole inside the perimeter fence. If we assume that this wall of water was 200 m wide and 6 m high, then the 'thickness' would be:

$$T = 160 \text{ m}^3/(200 \text{ m} \times 6 \text{ m}) = 13.3 \text{ cm}$$

One would expect this water to be spread out in the form of gloubles or drops of water over a distance of a few meters. If one assumes that this 13.3-cm-thick wall of water was spread out over thickness of 100 m, then the concentration of water becomes:

$$\frac{13.3 \text{ cm} \times 1 \text{ m} \times 1 \text{ m} \times 1000 \text{ kg/m}^3}{100 \text{ m} \times 1 \text{ m} \times 1 \text{ m}}$$

$$= 13.3 \times 10^2 \text{ g/m}^3$$

The world's record rainfall rate converts to 100 g/m^3, so the deluge water in the cloud was an order of magnitude more concentrated. The PMS probes would be coincident-saturated long before reaching these concentrations.

The condition of the grass and soil under the perimeter fence and around the instrument site indicated that a good amount of water had passed that way from the direction of the pad.

Prior to taking observations in the exhaust cloud, the author was concerned that the exhaust cloud would be hotter and less dense than the ambient air and, hence, would rise above the instruments located 400 m from the center of the pad. Perusal of STS-3 and STS-4 photographs shows that the flame trench cloud remained on the ground as it moved away from the pad and slowed down and came to rest a kilometer or so from the pad. This leading part of the flame trench cloud continued to exist long after the trailing parts had dissipated. It is suggested that this leading part is composed of heated remnants of the water blasted out by the SRB's.

At the John F. Kennedy Space Center (KSC), this leading part of the flame trench cloud ends up on the shore or over the ocean; at Vandenberg Air Force Base (VAFB), such a cloud would be over the land, and its effect on the land will depend on the exhaust products carried in the cloud.

CUMULUS MODEL WITH SPACE SHUTTLE IMPULSE

A revised version of the cumulus cloud model used by Silverman and Glass (ref. 2) was applied to the Space Shuttle exhaust cloud by specifying heat and water vapor impulses. Other inputs were the atmospheric soundings taken prior to the Space Shuttle launches and an initial cloud particle size distribution representative of Florida cumulus clouds.

The time-dependent, one dimensional model (referred to as a 1 1/2-dimensional model) simulates the life cycle of an isolated warm cumulus cloud. The model combines the vertical equation of motion, the equation of mass continuity, the first law of thermodynamics, and the equations of continuity of water, water vapor, and liquid hydrometeors. The dynamic interaction between the cloud and its environment is modeled by: (1) turbulent entrainment representing lateral mixing at the side boundaries of the cloud and (2) dynamic entrainment representing the systematic inflow or outflow of air required to satisfy mass continuity.

Three model runs were made. The first model run used the sounding made at the time of the STS-3 launch and assumed initial impulse radius of 500 m. The second and third runs used radiosonde data, taken during the STS-4 launch, and impulse radii of 300 m and 500 m, respectively.

In the latter two runs, the 500 m impulse radius resulted in rapid growth of the cumulus cloud to unrealistically high altitudes (in excess of 4 km). The 300 m impulse gave cloud growth and subsequent dissipation which closely paralled the growth and dissipation of the cloud as recorded on the photographs of the STS-4 launch. Results from the cumulus model using inputs from STS-3 launch and an assumed 500 m impulse radius appeared reasonable and are shown in figures 1 through 6. Figures 1 through 5 show the change of the drop size spectra at levels from 150 m to 2,625 m. The cloud drops peak around 40 microns and are most concentrated at a height of 2 km at 7 min. No rain shows in these figures, but the computer printouts show the presence of virga which was verified by the photographs.

The cloud liquid water content (fig. 6) shows the cloud rising rapidly to its maximum height in 9 min and then dissipating by 17 min. Note that the maximum liquid water content occurs at 7 minutes at a height of 2 km on this diagram also.

Dissipation of the cloud started shortly after 9 min and was completed shortly after 17 min. Strong downward vertical velocities hastened the dissipation. These model results are similar to those seen on the STS-3 photographs provided by NASA.

DEPOSITION OF EXHAUST PRODUCTS

Large amounts of water (in excess of 300,000 gal) are used for cooling and sound suppression during Space Shuttle launches. A large fraction of this water is vaporized by the exhaust heat, and some of this vaporized water recondenses as cloud particles, and (if the ambient conditions are favorable) these clouds may produce rain. Through many different microphysical processes, the exhaust products (primarily HCl gas and Al_2O_3 particles) may become attached to a cloud and precipitation droplets and then fall out of the cloud with the raindrops and deposit on the ground.

Specifically, the purpose of this 1 man-year study is to construct a mathematical model to investigate the fate of airborne contaminates associated with the Space Shuttle exhaust clouds. The model will incorporate the physical processes of diffusive attachment, impact collection, accretion, phoretic, and electrical influences, as well as the size spectra of contaminates, precipitation, and cloud droplets.

This study will go beyond the present diffusion models by including microphysical properties and by considering the roles of precipitation and cloud dynamics. As one of the AFGL scholars, Dr. Yean Lee will be performing this study. Dr. Lee's previous research in cloud and precipitation scavenging (refs. 3 and 4) is being brought to bear on this 1-year effort which started in September 1982.

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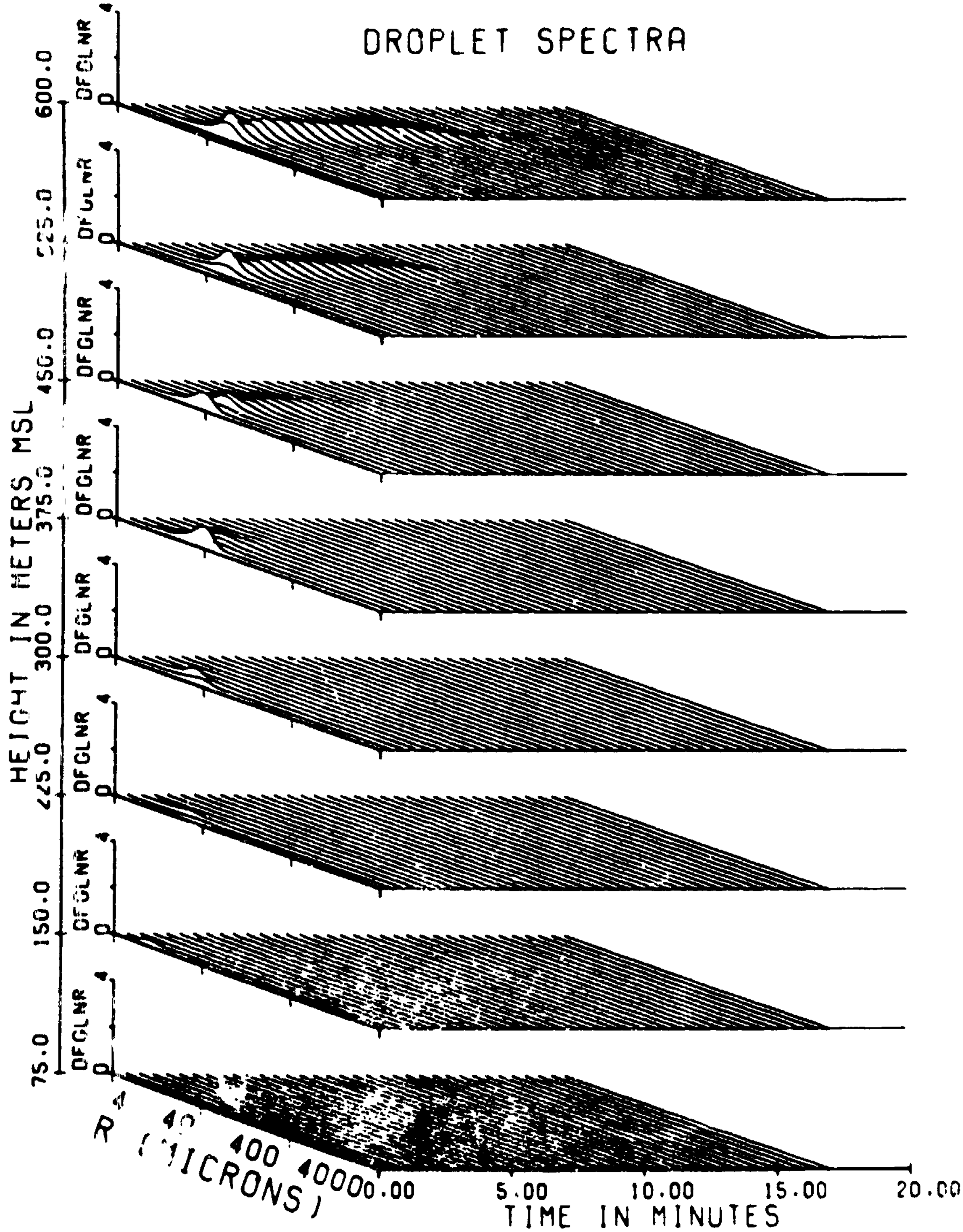

Figure 1.- Drop size distribution from 75 m to 600 m in the STS-3 ground cloud from the AFGL 1 1/2 D model using a 500 m heat and moisture impulse.

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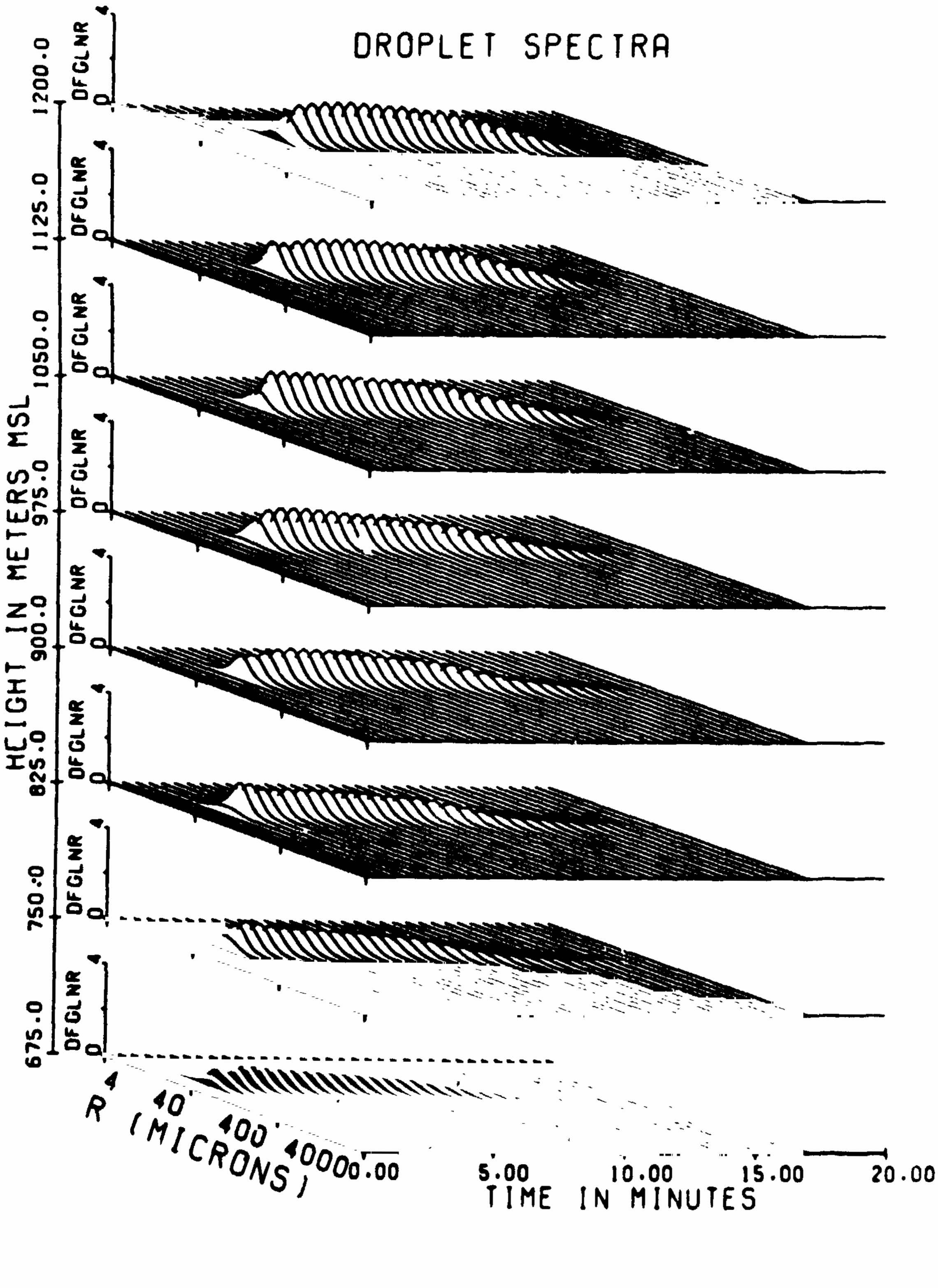

Figure 2.- Drop size distributions from 675 m to 1,200 m in the STS-3 ground cloud from the AFGL 1 1/2 D model using a 500 m heat and moisture impulse.

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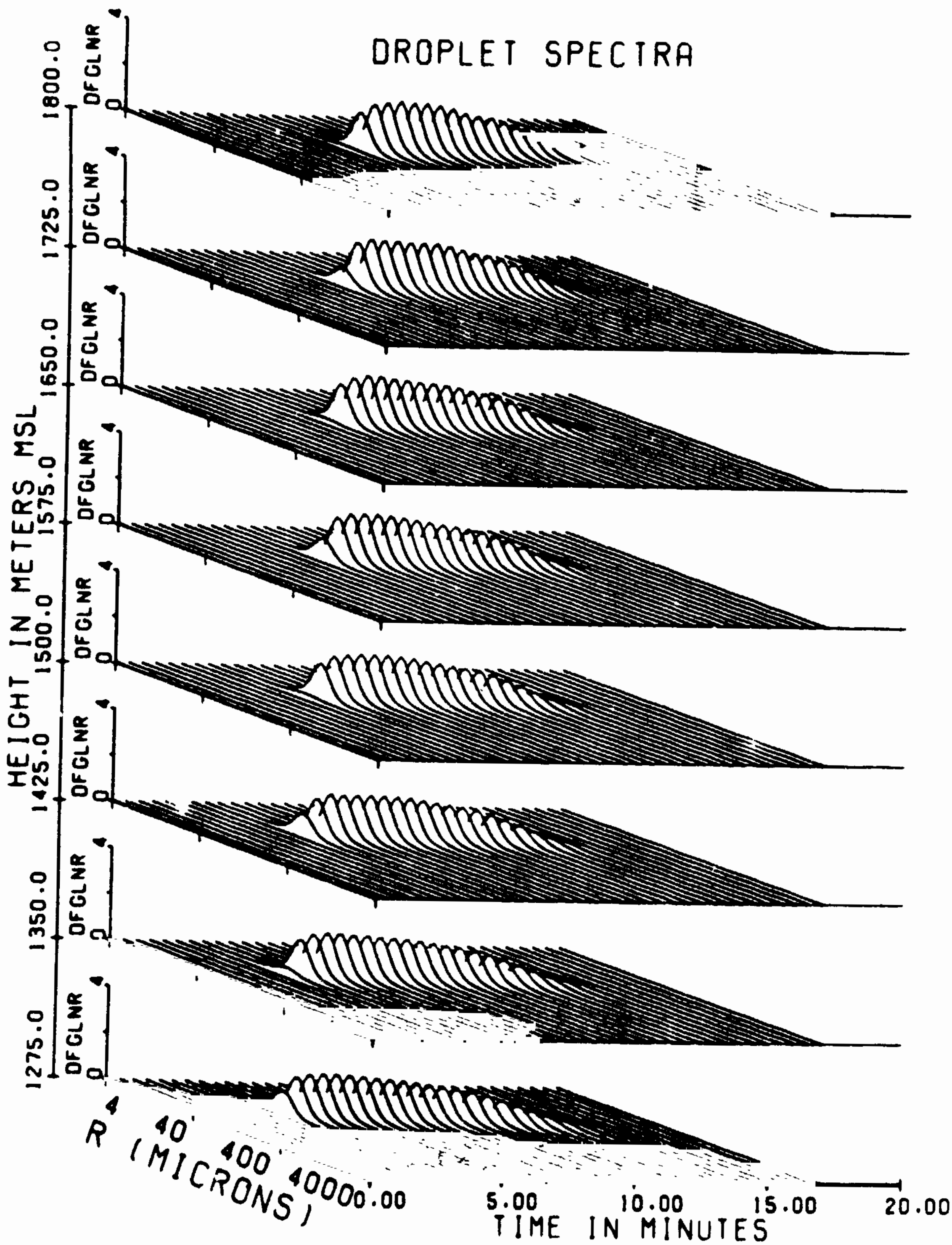

Figure 3.- Drop size distributions from 1,275 m to 1,800 m in the STS-3 ground cloud from the AFGL 1 1/2 D model using a 500 m heat and moisture impulse.

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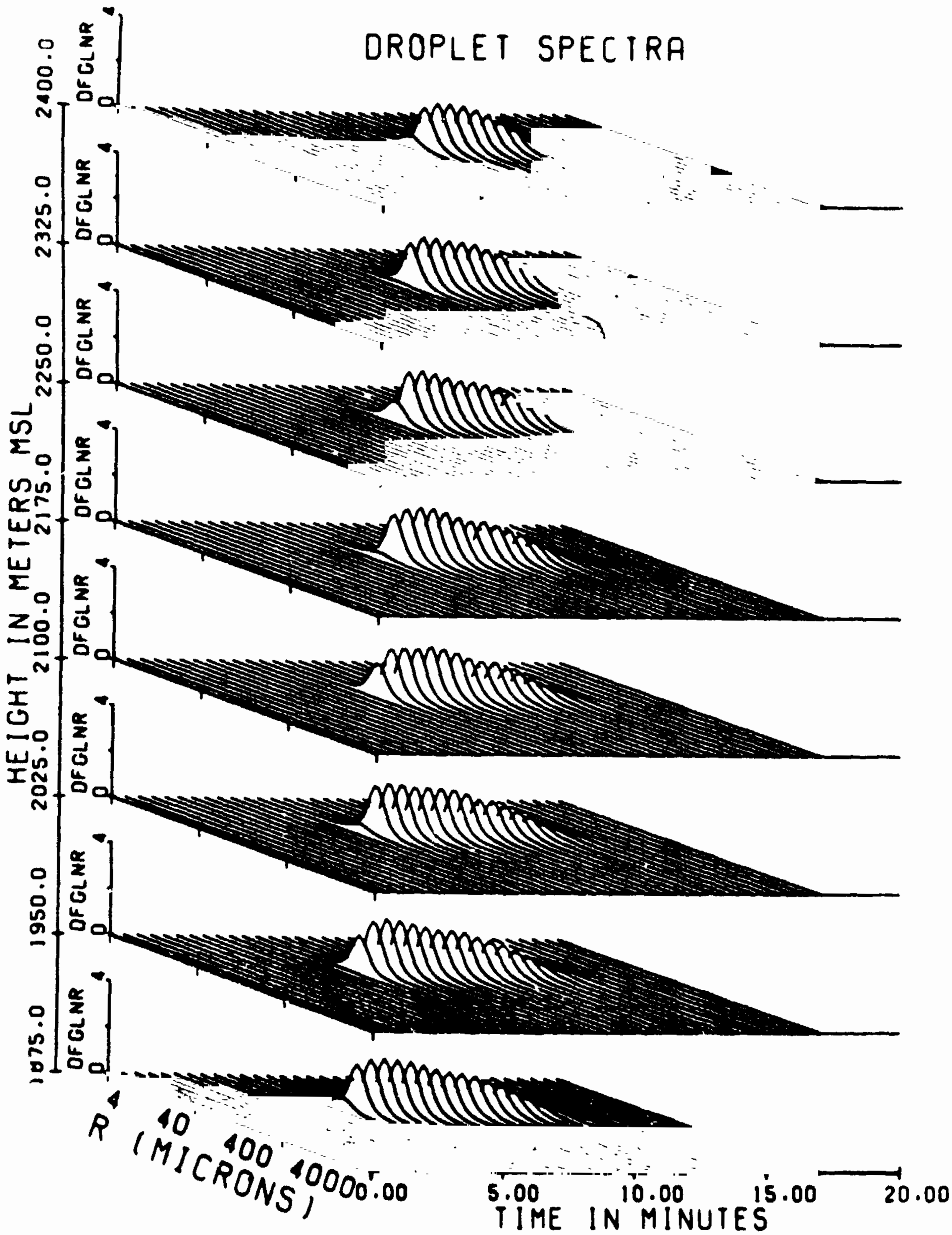

Figure 4.- Drop size distributions from 1,875 m to 2,400 m in the STS-3 ground cloud from the AFGL 1 1/2 D model using a 500 m heat and moisture impulse.

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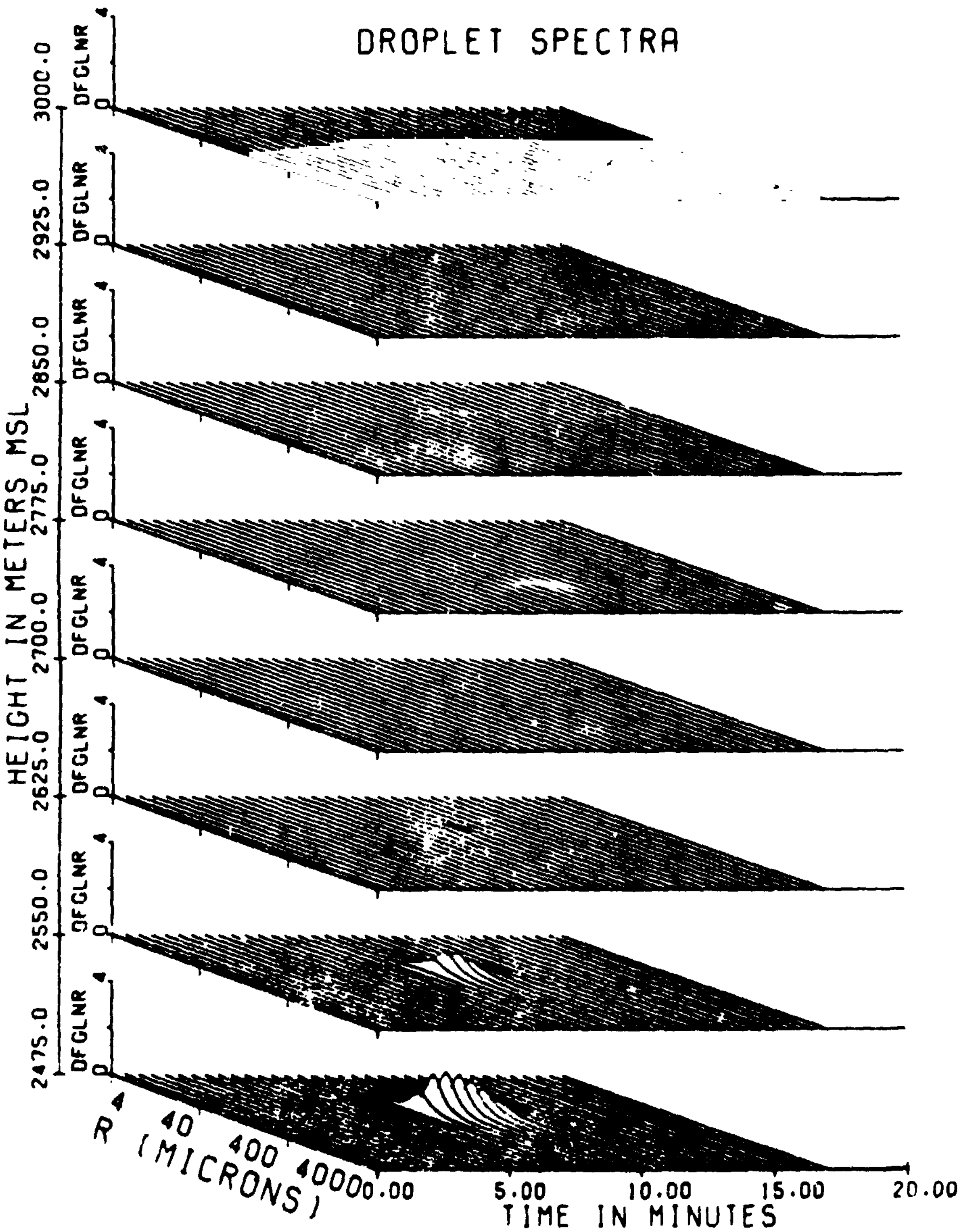

Figure 5.- Drop size distributions from 2,475 m to 3,000 m in the STS-3 ground cloud from the AFGL 1 1/2 D model using a 500 m heat and moisture impulse.

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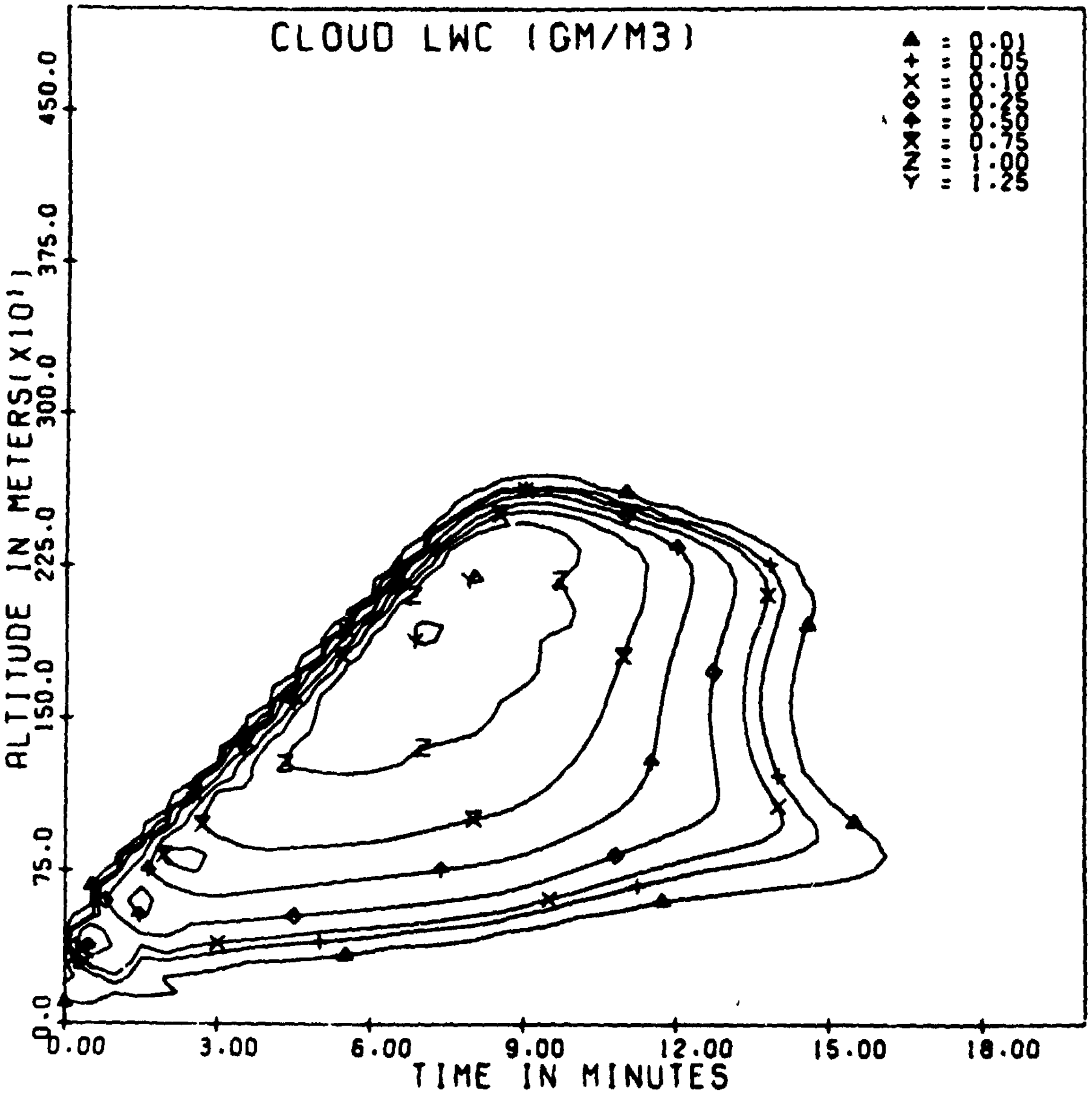

Figure 6.- Vertical profile of liquid water content versus time from the AFGL 1 1/2 D model for the STS-3 ground cloud using a 500 m heat and moisture impulse.

AN APPLICATION OF MODEL TESTING FOR THE STUDY OF ROCKET EXHAUST CLOUD PROPERTIES[a]

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INTRODUCTION

In this paper, the application of the 6.4-percent Shuttle Model Test Facility at the Marshall Space Flight Center (MSFC) is discussed as it relates to the study of the Space Shuttle exhaust cloud properties. Primary emphasis is on properties related to the production of the 'deposition' which has occurred with each launch. The deposition is typically submillimeter-sized drops composed of an acidic liquid and alumina solids. It is deposited primarily within 1,000 m of the pad, but a portion is carried to moderate distances by the ambient winds. With the relatively brisk winds during the STS-2 launch (8 to 12 m/s below 3,000 m), very light traces were detected as far as 22 km from the launch pad.

The first application of the 6.4-percent Shuttle Model was in conjunction with a field study at the John F. Kennedy Space Center (KSC) during the launches of STS-2, STS-3, and STS-4. (See the companion paper by Keller and Anderson in these proceedings.) The objective of this study was to determine the production mechanism for the deposition. Follow-on studies with the model are continuing to investigate ways to alleviate problems associated with the deposition by adding neutralizer to the deluge/sound suppression water system.

[a]Presented at the Ninth Conference on Aerospace and Aeronautical Meteorology, Omaha, Nebraska, June 6-9, 1983.

FACILITY DESCRIPTION

The 6.4 percent Shuttle Model Test Facility is a test stand for static firing solid and/or liquid rocket motors in a configuration where the motors, launch pad, and deluge water system are all scaled down from the actual (planned) system. The solid rocket motors (SRM) used are from Tomahawk missiles which use the same fuel as the Shuttle SRM's, but their output is $(0.064)^2$ times less. Internal temperatures and pressures within the motors are comparable. Mass flow rates in the deluge/sound suppression water system are also scaled by this factor. Flow velocities are scaled one-to-one; pressures are not scaled. Linear dimensions of the launch mount are scaled down by 0.064. The facility is utilized for acoustic and initial overpressure suppression testing. Initial overpressure is the pressure wave generated by SRM ignition. Both the KSC and Vandenberg Air Force Base launch configuration can be modeled. The data discussed here were obtained from measurements made as add-ons during a series of overpressure tests with the facility in the Vandenberg [Western Test Range (WTR)] configuration.

OBSERVATIONS

The first observations of model firings to study acidic deposition production were made in late May and early June 1982, during a series of screening tests for the WTR overpressure problem. Only the north flame trench of the WTR configuration was modeled in this series; and only one Tomahawk, modeling one Shuttle SRB, was fired per test. The liquid engines were not fired. The objective was exploratory to determine the applicability of the model to the acid deposition problem.

Tests were conducted on May 17, 20, 24, and June 4, 1982. The May 17 test modeled the full sound suppression/deluge water flow rate baselined for the WTR. Subsequent tests used a fraction of that amount. For the overpressure tests, the deluge water flow rate and cross-sectional area of the flame duct are primary quantities to be modeled; whereas, for this study, the total quantity of water in the duct, preignition flow included, is the important quantity. Thus, while the tests were nominally 100, 50, 25, and 50 percent of baseline (flow rate), they were only 45, 21, 18, and 22 percent of baseline in terms of total water quantity (scaled). The fractions are small because the preignition flow is only allowed to run for a fraction of a second to keep the cross-sectional area of the duct in scale. At full scale, the preignition flow runs for about 15 sec.

Following the practice used at Cape Canaveral (KSC) to study the STS-2 and STS-3 launches, an array of copper plates and pH papers were deployed at 15 to 20 sites; the cloud development and dissipation were recorded by infrared (IR) sensitive video (2 angles) and timed 35 mm still photography; observations of temperature, relative humidity, and winds were made.

The most significant observation from this test series is the fact that acidic fallout, essentially identical to that observed from the Shuttle launches, occurred with each test even though the exhaust clouds dissipated very rapidly. Dissipation times varied from 1 min to 3 1/2 min, with a faint pale of smoke lasting until perhaps 5 min. There have been too few tests to be certain what parameters control the cloud lifetime, probably humidity and the vertical atmospheric temperature structure dominate with the deluge water flow rate being a possible contributor. Observations of recent tests, all with the WTR baseline flow rate, show that the lifetime varies by a factor greater than 2 because of differing atmospheric conditions. In any case, the cloud lifetimes are all very short compared to the times required to develop precipitation-sized particles in any natural system.

The pH papers deployed during this test series indicated the pH of the deposition to be in the 0 to 0.5 range, the lowest range on the papers. This acidity was roughly confirmed by the reaction spots on the copper plates. However, it is possible that the deposition was slightly more acidic, out of the range of the pH papers. The acidity of the deposition at KSC, measured with pH papers, copper plates, pH meters, and titration, was similar. Recent 6.4-percent scale model test firings using WTR baseline deluge water flow rates have allowed collection of liquid samples for titration. These samples were 2 N HCl solutions.

Drop sizes in deposition from the model tests are generally slightly smaller than for an actual launch, as one would expect due to the weaker updrafts; but large drops were found near the stand. The deposition collected near the test stand and at KSC near the pad perimeter is approximately 70 percent liquid and 30-percent solid alumina particles by volume.

PRODUCTION MECHANISM

From condensational growth theory, the drop radial growth rate, dr/dt, is inversely proportional to the drop radius. Thus, very small drops grow very quickly by condensation, easily forming visible clouds of typically 10-μm diameter drops; but additional growth becomes progressively slower. A simple condensation process would require about 1,000 sec to grow a 100-μm diameter drop, given a steady 1-percent supersaturation. Thus, even when times of 10 min to 20 min are available, as in natural clouds, other mechanisms contribute to produce drops as large as 100 μm. Since the exhaust clouds from the model tests dissipate within 1 min to 3 1/2 min, this mechanism is clearly not fast enough.

In the Shuttle cloud, a rapid quenching process occurs as the hot exhaust mixes with the ambient air. This may produce a transient high supersaturation in some cases, which would produce large quantities of small drops, not a few large ones, because of the inverse relationship between growth rate and radius. This has been verified in numerous experimental situations, for example, supersonic nozzels, and it is especially true here because of the large numbers of aluminum oxide particles which provide nuclei for condensation.

Condensational growth accompanied by coagulation is a process which is more difficult to exclude as the controlling mechanism in the acidic deposition production. The fact that millimeter-size drops from the Shuttle exhaust cloud typically contain 10^4 aluminum oxide particles per drop shows that a scavenging/coagulation process is clearly occurring. Since the theory for this process is nonlinear and requires numerical methods for a complete solution, we illustrate the case with a simple, linearized upper limit calculation on the fastest of the coagulation mechanisms, precipitation scavenging. In this process a few large drops, in excess of 40- μm diameter, pass through a cloud of small drops. The relative motion can be caused by either the slower response to turbulent air motions of the larger drops or to their greater terminal fall speeds.

When a large drop passes through a population of small particles, the number of particles collected can be expressed as the product of the area of intersection, an efficiency factor, the path length, and the number concentration of small particles. The efficiency factor, E_i, accounts for the influence of hydrodynamic forces which tend to carry the small particles around the large one and wake interactions. The numerical value is a function of relative particle size. The effeciency is small for coagulation of particles, less than 5- μm radius. For an upper limit calculation, we assume that the efficiency is given by $0.1\,B_i$ where B_i is the small drop radius expressed in microns. It is also assumed that the collector drop moves with a velocity with respect to the small drop field of $V_i = kA$ where k is a proportionality constant and A is the collector drop radius. With $k = 0.83$ cm μm^{-1} s^{-1}, V_i just exceeds measured terminal fall speeds of drops as large as 800- μm diameter. Using these simplifications, equation 1 has been derived which gives the minimum time required to grow a drop from radius A_o to radius A_f.

$$T = \frac{3}{\pi k \varepsilon_i N_i \Sigma_i B_i^3} \left[\ln\left\{ \frac{A_f + \bar{B}}{A_o + \bar{B}} \right\} + \frac{\bar{B}}{A_f + \bar{B}} - \frac{\bar{B}}{A_o + \bar{B}} \right] \quad (1)$$

Here we have assumed that the cross section of the volume swept out by the collector drop is $\pi(A+\bar{B})^2$ where B is a large, 'typical' value of B_i, chosen to provide an upper limit of the collection rate. This expression is easily evaluated if the number, concentration N_i, for each wet particle radius, B_i, is known. Unfortunately, this is not the case for the Shuttle exhaust cloud. Two attempts at making this measurement failed due to the extremely hostile environment near the vehicle at lift-off, and no data have been found in earlier studies on the wet particle sizes in the first 2 min of the cloud's life. Therefore, we must resort to a construct distribution for evaluating the minimum coagulation time.

To obtain an estimate of the small particle concentration, we begin with the fact that the two solid rocket boosters (SRB's) exhaust 2.3×10^7 g of Al_2O_3 in the first 8 sec. Photographic analysis shows that the SRB portion of the cloud occupies at least 1.4×10^6 m^3 at L + 8sec, so the density of Al_2O_3 must be about 17 g m^{-3}. Beginning with this fact, two construct distributions were formed by using appropriate dry particle distributions (refs. 1 and 2) and assuming additional growth by condensation so as to maintain the observed solid-to-liquid ratio in the final product. The distributions are exhibited in table 1 along with the resulting values for the minimum time to grow drops of 200-μm diameter (the mode value from the STS-3 aircraft measurements) and 300-μm diameter (the mass mean). Even though the distributions differ considerably, they both yield minimum times of order 1 min or 2 min percent to form marginally large drops. Since the 6.4-percent model tests show that large drops (~1-mm diameter near the test stand) are formed when 1 min or 2 min are the maximum time available, it appears very unlikely that coagulation is the controlling mechanism in the production of the acidic fallout. Rather, the large drops are being produced by another mechanism - directly by the interaction of the exhaust and the deluge water spray - and then modified by rapid scavenging of wet acidic aluminum oxide particles. Visualized in this way, equation 1 shows that the acidic fallout can form in a few seconds.

CURRENT STUDIES

Based on the conclusion that the major fraction of the liquid in the deposition is coming directly from the deluge water without intervening phase changes, the possibility arises that the acid in the deposition can be neutralized by addition of a base to the deluge water. Current work with the 6.4-percent model is directed toward verification and implementation of this hypothesis. First emphasis is placed on water and HCl balance determinations which are necessary to define the production mechanism in greater detail. The objective is to provide a basis for selecting the neutralizing material and concentrations.

The HCl-balance investigation is emphasizing the role of temperature in determining the concentration of HCl in the deposition. Solubility of HCl in water is greater at lower temperatures. Preliminary analysis indicates that the temperature is probably the primary factor in limiting the quantity of HCl taken up by the water. Both duct temperature, which is determined by the quantity of deluge water used, and ambient air temperature probably play a role. In the WTR configuration where the large quantities of water used should lead to highly efficient scrubbing, the total quantity of HCl available may also be a limiting factor.

CONCLUSIONS

The 6.4-percent Test Model Facility has proven to be an effective tool for studying rocket exhaust cloud properties. As the cloud lifetime data and analysis presented here indicate, it has provided the most conclusive evidence for the atomization mechanism of deposition production, although this conclusion is also supported by other evidence from the field and aircraft studies of actual Shuttle launches.

The advantages and disadvantages of the Shuttle Model Test Facility are typical of any research involving scale models. The model is much easier to instrument and modify than the full-scale system. Access to the area is typically within 5 min after a model firing, 3 hr after a Shuttle launch, and the instrumentation is concentrated in a much smaller area. Of course, the model can be fired much more frequently than the Shuttle. The primary problem in working with the model is scaling. Not all parameters scale the same way, so not all can be scaled at the same time. Cloud lifetime is a good example. In the preceding analysis, the fact that the model cloud lasts for only a minute or two was used to advantage, but this complicates analysis of the neutralization problem. Because deposition drops may spend 20 times as long in the exhaust cloud at a real launch, their pH and the final HCl balance compared to that of the model, may be considerably different. The problem must be approached by trend analysis. In certain cases, for example, study of the ice nucleating ability of the exhaust products, scaling is not a problem because the major parameters are one-to-one with full scale.

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2. Smith, S. D.: Space Shuttle Solid Rocket Motor Sea Level Exhaust Plume Predictions. Report on Contract NAS 8-33719, Lockheed Missiles and Space Company, Inc., Huntsville, Ala., January 1981.

TABLE 1.- CONSTRUCT PARTICLE DISTRIBUTIONS

A. CASE 1[a]

Index	Dry radius, μm	Wet radius, μm	Number/cm^3
1	3.15	7.2	3,170
2	4.70	7.6	1,910
3	5.90	8.2	966
4	6.95	9.0	591
5	8.15	9.9	366
6	9.70	11.3	109

[a]Total particle concentration: 7,120 cm^{-3}; B: 10 μm; Initial large-drop radius: 20 μm; minimum time to reach mode diameter (200 μm): 45 sec; minimum time to reach mass mean diameter (300 μm): 57 sec.

B. Case 2[b]

Index	Dry radius, μm	Wet radius, μm	Number/cm^3
1	1.13	3.3	62,100
2	3.00	4.3	10,800
3	5.00	5.9	1,460
4	7.00	7.7	483
5	9.00	9.6	201
6	10.88	11.4	89

[b]Total particle concentration: 75,100 cm^{-3}; B: 10 μm; Initial large drop radius: 20 μm; minimum time to reach mode diameter (200 μm): 70 sec; minimum time to reach mass mean diameter (300 μm): 95 sec.

THE 6.4-PERCENT SCALE MODEL OF THE SPACE SHUTTLE

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SD/WE
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INTRODUCTION

A 6.4-percent scale model of the Space Shuttle was developed at the Marshall Space Flight Center (MSFC) to test acoustics and overpressures. It is a static model that is bolted to a test stand (see fig. 1). This 6.4-percent scale model was used in a series of environmental tests conducted at MSFC in May 1982. Different flame trench configurations installed beneath the model were tested. Tomahawk missiles were fired to simulate the solid rocket booster (SRB), and the Space Shuttle Main Engines (SSME) were simulated by firing a hydrogen and oxygen mixture that is piped through the Orbiter model. The model was scaled to 6.4 percent so as to scale the mass flow of the Tomahawk missile against that of an SRB.

In this series of tests, a single Tomahawk missile was statically fired into a Vandenberg Air Force Base (VAFB) Space Launch Complex (SLC)-6 flame trench configuration. The missile was mounted directly over the SRB hole on the pad. The purpose of the tests was to study the effect of deluge water on the acoustics and overpressures. The tests started at the scale of the full water flow designed for SLC-6. The flow was then decreased by one-half on each subsequent firing. The SSME's were not fired. To make the environmental tests, technical personnel 'piggy-backed' on these acoustic and overpressure tests. A network of copper plates, pH paper, and polyethylene film were set up. In addition, each firing was videotaped from two different directions (see fig. 2).

As this was the first time the 6.4-percent scale model had been used for environmental tests, technical personnel were not sure what to expect. Observing how closely the exhaust cloud from the Tomahawk simulated that of an SRB in regards to the deposition and to HCl concerns was a major goal.

FIRST FIRING OF SCALE MODEL

The first firing of the model was at 1830 hours on 17 May. The test team was surprised that the exhaust cloud dissipated very rapidly. It was a very dry, powdery appearing cloud that stabilized at about 10 m to 15 m and dissipated over the pad. Only three of the copper plates were hit (see fig. 2). These were the plates directly in line with the flame trench exit. The pH paper and these plates were completely wetted and were of no use.

Since the polyethylene film used to collect water samples for laboratory analysis did not receive any hits, we collected water samples from the pad itself. One site was near the mouth of the flame trench and did not show an acidic reading. Another sample was taken at about 30 m from the mouth of the trench and had a pH less than 0.5. The pH was the only valid information obtained from these water samples.

Temperature, relative humidity, and wind readings were made at the time of the firing. The temperature was 90°F and the relative humidity was about 70 percent.

thermodynamics of the cloud resulting in the very low stabilization height. The temperature readings taken inside the trench by the acoustic and overpressure test group (see fig. 3) seem to confirm this finding.

2. The deluge water was turned on just before the missile was fired and settled in the flame trench. When the missile was ignited, the force of the exhaust blew this water out of the trench and onto the pad. This would account for the water near the exit to the flame trench having no pH indication.

3. This firing indicated that the deluge water plays an important role in the acidic deposition. With this increase in deluge water [about twice that used at John F. Kennedy Space Center (KSC)], the exhaust cloud characteristics are drastically altered.

SECOND FIRING OF SCALE MODEL

The second firing of the 6.4-percent scale model on May 20, 1982, also used only one Tomahawk missile and no main engine burn. The amount of deluge water was cut in half. This time the exhaust cloud behaved much like the actual SRB exhaust cloud. Dr. Jeff Anderson and Dr. Vern Keller again set out the copper plates, pH paper, and polyethylene film.

The exhaust cloud from the second firing stabilized higher; did not have the dry, powdery appearance; and there was acidic deposition from this cloud out to 150 m. The atmospheric conditions were essentially the same as the first test except the relative humidity was about 90 percent.

THIRD FIRING OF SCALE MODEL

The third firing of the model on May 24, 1982, was similar to the second firing, except the amount of deluge water added was again decreased by one-half. (It should be noted here that because of time lags, the deluge water is turned on early. This means that, in reality, the third firing had about 40 percent of the SLC-6 designed water flow.)

This exhaust cloud had much more buoyancy than the previous two. However, the deposition was less than on the second firing. A check of the flame trench temperatures revealed that the cloud was much hotter than the first cloud (see fig. 4).

CONCLUSIONS

From this completed series of tests, the following conclusions were noted:

1. The amount of deluge water added during ignition is very important in the production of acidic deposition. At VAFB (SLC-6), approximately twice the KSC (Pad LC-39A) deluge water flow rate will be used. If the model is representative, then one would expect the VAFB Space Shuttle exhaust cloud to be much dryer. There will be much more acidic water thrown out in the immediate pad area. (This could be a problem with HCl revolatilization delaying entry to the pad area after a launch.) But the cloud should stabilize much lower than the KSC Space Shuttle exhaust cloud. (Note: the 6.4-percent scale model is a static firing. We do not know what effect the column cloud will have as the Space Shuttle lifts off the pad.)

2. The acidic deposition is caused by the deluge water being atomized, carried aloft, and then redeposited.

3. With the current VAFB designed flow rate, there will be more acidic water that must be washed down and collected after launch. There will also be the danger of an acidic fog forming during the summer fog season with this large amount of acidic water on the ground.

More tests using the 6.4-percent scale model are planned. The acoustic and overpressure group will conduct another series of tests in January 1983. Again, only one Tomahawk missile and the SLC-6 pad configuration will be used. Plans are to repeat tests that were made in May; however, this time a tracer dye will be added to the deluge water that will isolate the deluge water from the atmosphere. The dye (uranine) also decomposes at high temperatures. This will prevent it from showing up on the copper plates if the water is vaporized by a high heat source and then recondenses.

The tracer dye can only be used on the 6.4-percent scale model. There is a possibility that if used during an actual launch, it could stain the Orbiter or affect the thermal tiles and change their characteristics.

Dr. Jeff Anderson and Dr. Vern Keller are also checking the feasibility of conducting a test to try to neutralize the exhaust cloud. This is still in the study phase, and we are looking for ideas. We have been asked: why use the 6.4-percent scale model? Why not just make measurements during an actual launch? There are a number of benefits from using this model, and some are listed below.

1. The cost to the environmental technical group is very low. By "piggybacking" on other tests, we eliminate the need for a large budget.
2. Some tests can only be done on the scale model, the tracer test mentioned above is one.

3. The cloud characteristics of the model are similar to that of an SRB. The deposition is not to scale, and we cannot study the "chimney effect" caused by lift-off; but, the behavior of the cloud and the production mechanisms do not change much.

4. The test conditions are controlled which allow for fast, easy access to the pad and equipment.

5. A number of tests can be conducted over a short period of time.

6. In the past, only one Tomahawk missile was fired which eliminated the SSME as a water source. In the future, a "full-up" firing is planned which will utilize two Tomahawk missiles and the SSME. On this test, the model will be fired, raised above the pad configuration, and fired again. This procedure will be repeated several times. It should give a fair representation of the STS lifting off the launch pad.

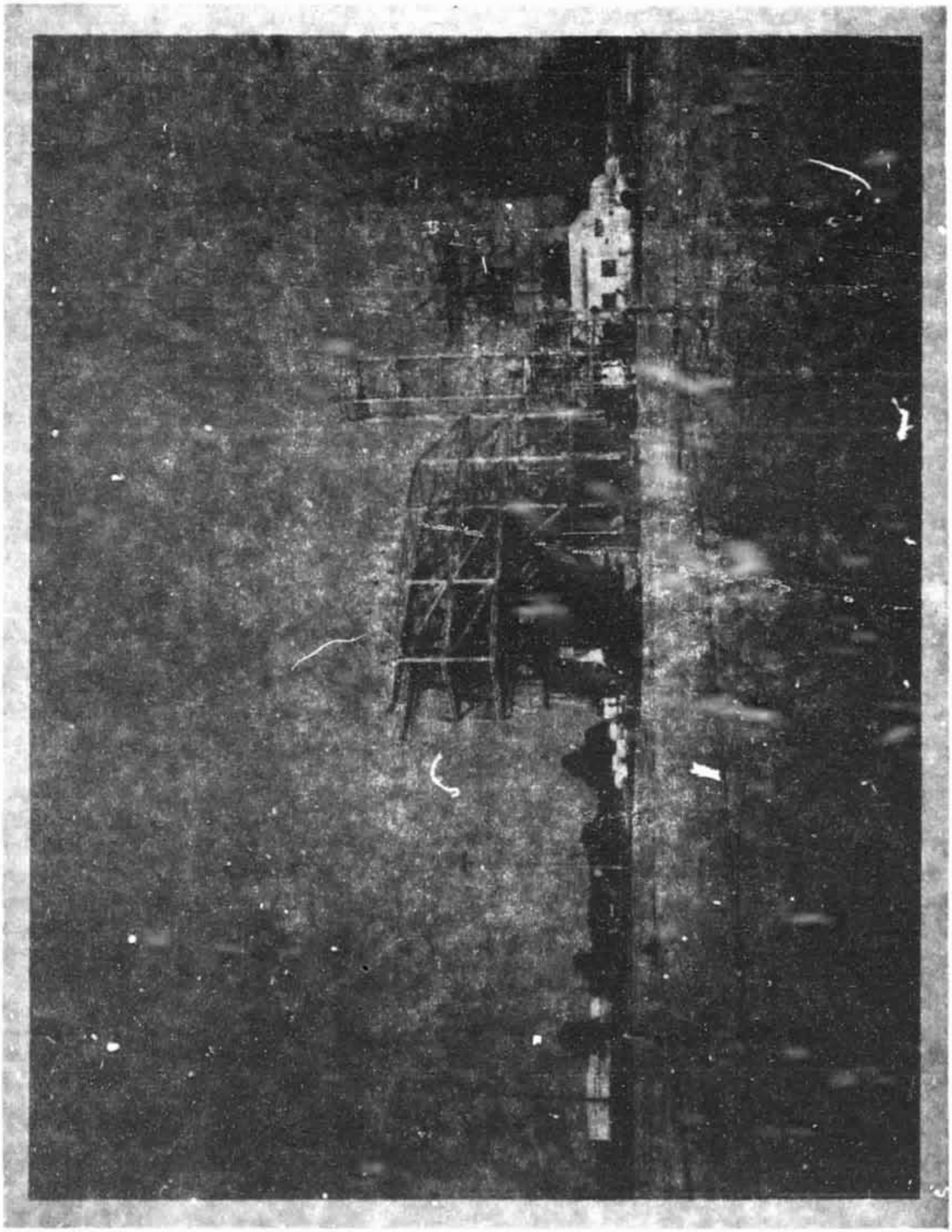

Figure 1.- MSFC Test Facility 116 (6.4-percent scaled model of Space Shuttle).

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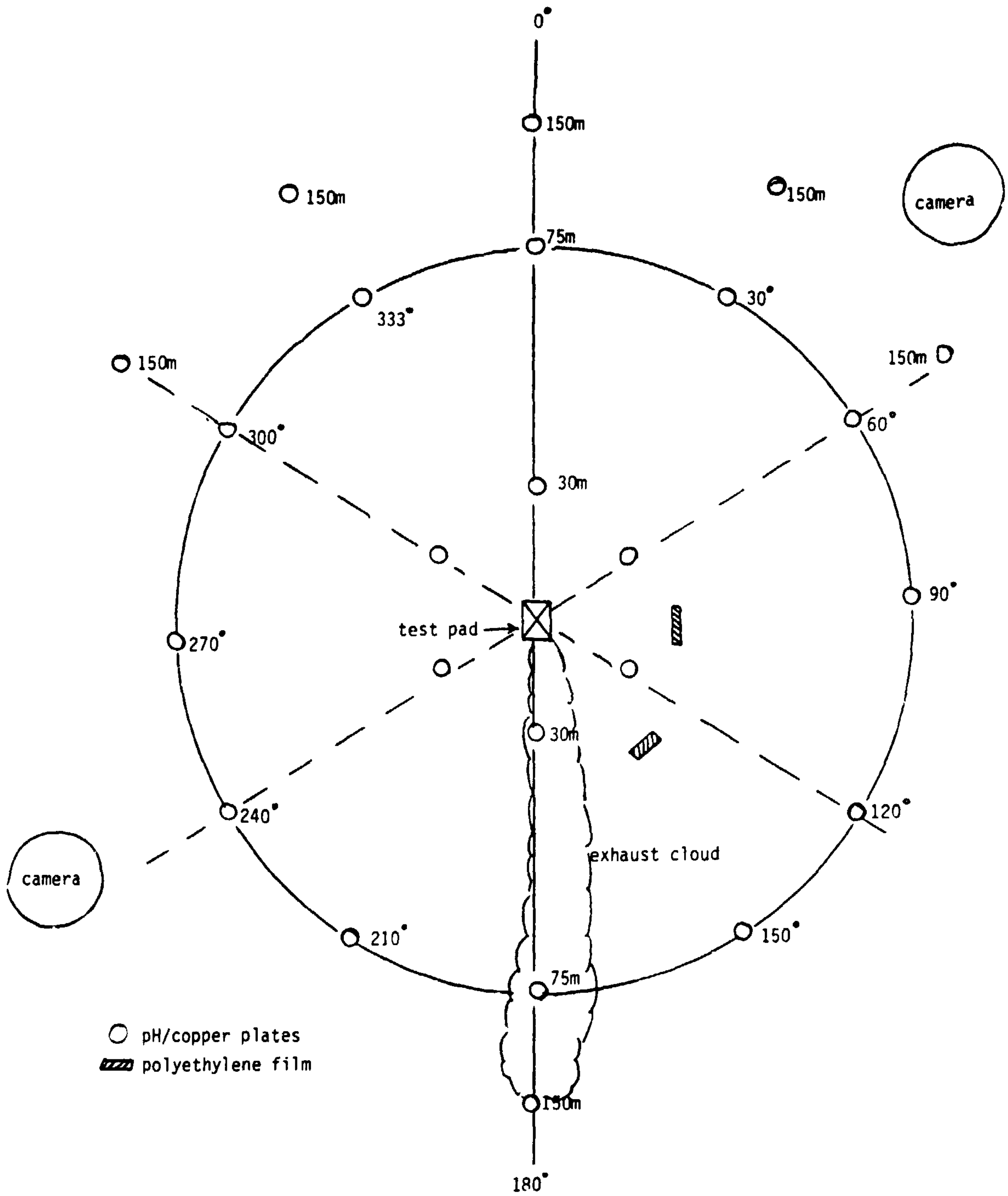

Figure 2.- Monitoring network of the test firings of the Tomahawk missile at VAFB.

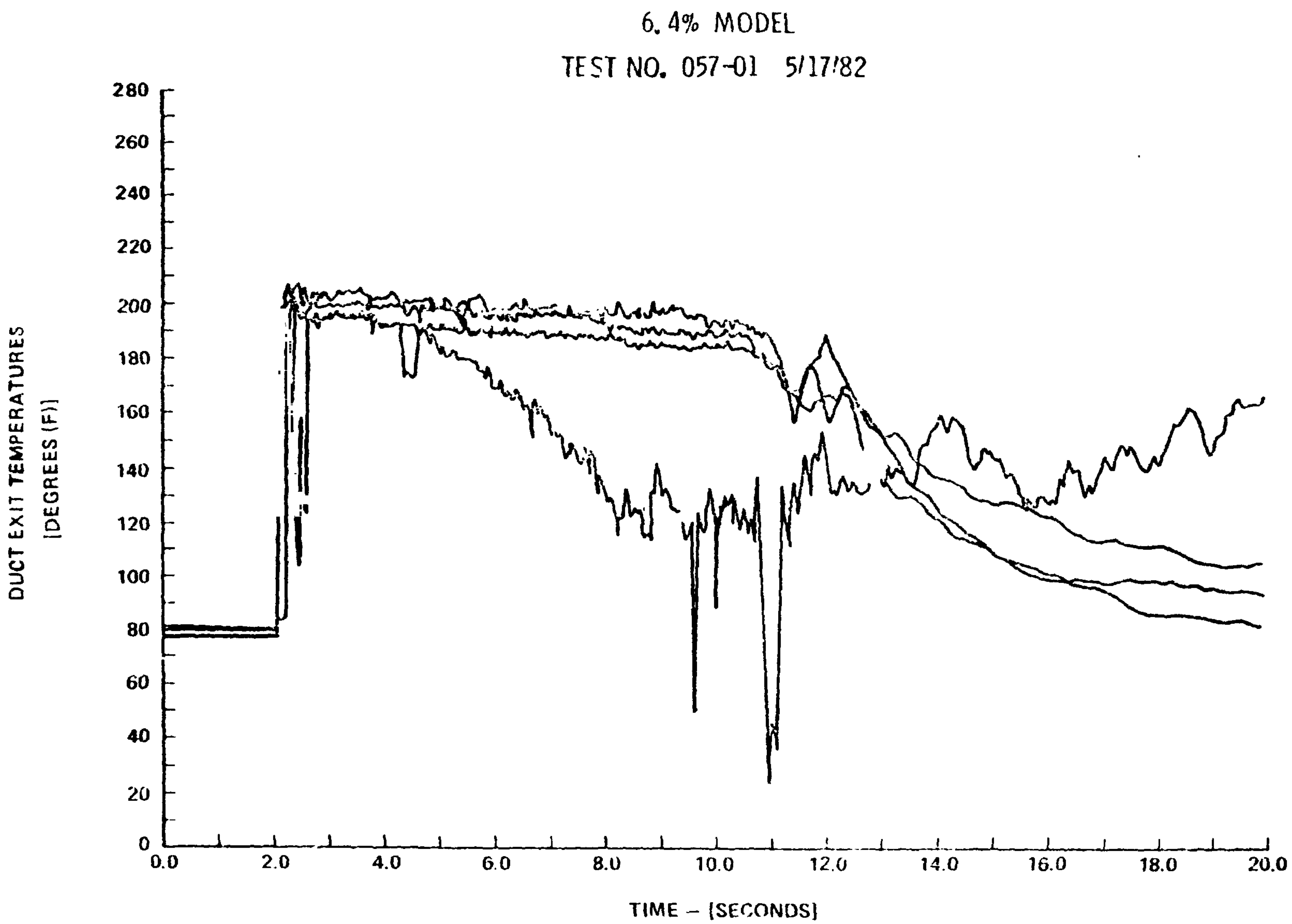

Figure 3.- Temperature readings taken inside the trench on May 17, 1982.

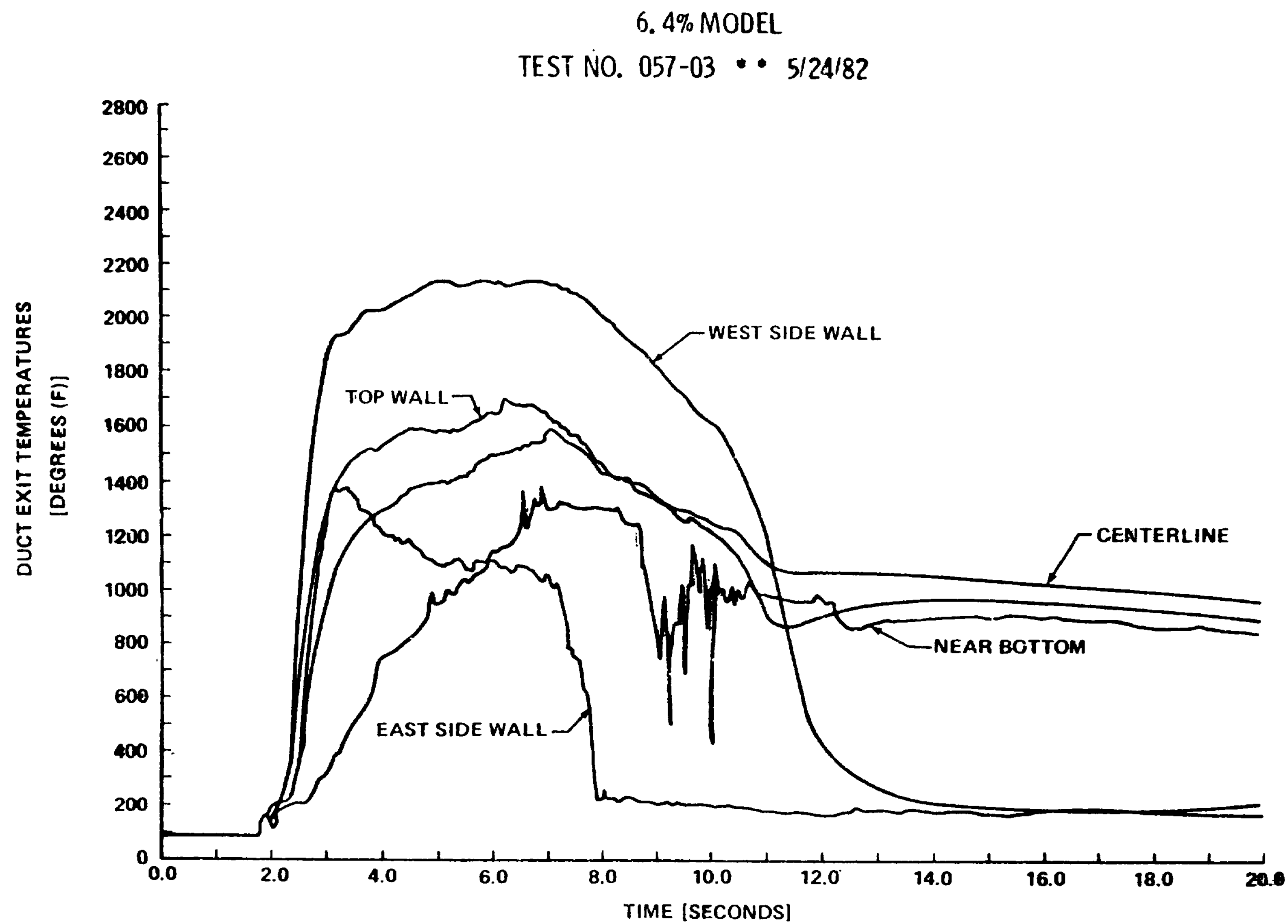

Figure 4.- Temperature readings taken inside the trench on May 24, 1982.

USAF SPACE SHUTTLE DISPERSION MODELING WORKSHOP

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INTRODUCTION

A workshop was held at the U.S. Air Force (USAF) Occupational and Environmental Health Laboratory (OEHL), Brooks Air Force Base, San Antonio, Texas, from 30 November to 2 December 1982. The purpose was to evaluate the need for atmospheric dispersion models and to recommend actions for model implementation prior to Space Transportation System (STS) launches from Vandenberg Air Force Base (VAFB), California. This paper is a shortened version of the author's original report (ref. 1).

BACKGROUND

Missiles with solid rocket boosters (SRB's) emit large quantities of hydrogen chloride (HCl) into the atmosphere. The fate of this HCl is not well understood and is the subject of on-going measurement and modeling efforts. STS launches are of greater interest than previous missile launches because two and one-half times more HCl is emitted from STS launches than from Titan III launches (ref. 2) and 300,000 gal of deluge water enhance the near- and far-field acid deposition potential (fig. 1). Measurements from STS-5 suggest some of the aqueous HCl may 'revolatilize' for hours after a launch and form gaseous HCl concentrations of potential health concern for workers near the launch pad (ref. 3).

Far-field HCl effects can be produced from acid washout, acid rainout, or gaseous HCl concentrations. Acid washout occurs when rain from an overhead convective cloud scavenges HCl from the rocket exhaust ground cloud. In a heavy rain, one model predicts nearly all of the HCl in the ground cloud (roughly 30 tons) could be deposited within 18 miles of the launch site (ref. 4). Spontaneous acid rainout, in the absence of a convective cloud, has been observed after all five STS launches to date but is poorly handled by existing models. Gaseous HCl air parcels which diffuse to ground level have not been observed nor are generally predicted to occur in high enough concentrations downwind to be of health or environmental concern.

A Heated Exhaust Toxic Area Forecast (HETAF) dispersion model has been used successfully at VAFB for many years (ref. 5). However, due to simplifying assumptions, it is very conservative and predicts more stringent evacuation and/or launch-hold conditions than are believed necessary. The National Aeronautics and Space Administration (NASA) Rocket Exhaust Effluent Dispersion (REED) model is more refined (ref. 6) and has qualitatively done well in launches STS-1 through STS-5. However, it does not have an acid rain prediction capability, account for VAFB terrain, or have dispersion coefficients representative of VAFB. While the need for dispersion model improvements for VAFB launches has been generally perceived for some time, a consensus position among involved USAF offices does not exist. What is clear is that little time remains to make such model improvements prior to the first STS launch at VAFB (fig. 2).

WORKSHOP OBJECTIVES/ ATTENDANCE

The purpose of the USAF Space Shuttle Dispersion Modeling Workshop

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was to get consensus recommendations from government meteorologists, scientists, and environmental engineers who were closely associated with recent efforts. Participating organizations and attendees are presented in figure 3. Recommendations will facilitate planning and budgeting for environmental modeling efforts during STS activation and operations at VAFB. Workshop objectives were:

1. To define requirements and expectations for models.

2. To review current STS model studies.

3. To recommend model improvements for VAFB.

Each of these three objectives will be described in the following sections.

MODEL REQUIREMENTS

For this workshop objective, about one-half day was devoted to define when and why dispersion models are required for Space Shuttle operations; results are shown in figure 4.

Environmental measurements and models are so interrelated that the same or similar requirements list can be used to prioritize future efforts of both measurements and models. Motivations to use models beyond measurements are for future predictions and extrapolation of measurements at John F. Kennedy Space Center (KSC) to specific launch configurations and atmospheric conditions at VAFB. The term "model," therefore, applies to parametric techniques with near-field empirical measurements as well as downwind dispersion modeling.

Models are required during launch periods, T - 24 hours up to T - 0, for actions involving launch risk assessments or area restrictions (fig. 4). Model applications prior to launch are required for planning for facility design, securing personnel protective equipment, or for regulatory review. While much of this planning has already been done for VAFB, modifications may have to be made if suggested by on-going KSC measurements and model applications. Model studies are also required after launches. Assessments of whether damage claims are legitimate are likely to be needed. A scientific understanding of model and measurement results is essential to establish the degree of confidence which should be placed on operational model predictions made during future launches.

The priorities for model uses shown in figure 4 represent a consensus derived from individual submissions of all attendees. The fact that no model use received a low priority indicates that a multi-faceted-modeling program is required rather than one focused on a few key problems. Operational models to be used during launch periods were given a high priority. More sophisticated models used prior and after launches were given a medium priority, but they are also essential for understanding and improving the operational model results.

REVIEW OF STS MODELS

The second workshop objective was to review recent efforts aimed at developing an acceptable model for STS launches. This review included presentations listed in figure 5, with model descriptions in reference 1. The discussions after the presentations were used to formulate recommendations which follow:

1. Use the NASA Operational Model

   The first recommendation is to use the NASA REED model for operational predictions during STS launches at

VAFB. It is a big improvement over the HETAF model currently used. Source emissions, plume rise equations, a nonuniform vertical dispersion, multiple layers of the stabilized ground cloud, and dry deposition in addition to gaseous HCl predictions are all handled more precisely with the REED model.

Additional testing and improvements of the REED model are needed (fig. 6). While the model has qualitatively performed well, observations at STS-1 through STS-5 launches have not been scientifically compared to model predictions. Plume rise equation results should be compared to photographs and videotapes. Wet deposition in the form of acid rain has been observed in every STS launch, yet the model was never designed to make such predictions. Near-field deposition must be considered. Aircraft and ground measurements need to be compared to model results.

Adaptation of the REED model to VAFB conditions will be received before it can be considered operational. Specific diffusion coefficients to be used to input meteorological data have to be determined. The rugged terrain at VAFB must be addressed, either with simple correction factors or with estimates of errors which result from neglecting terrain. The impact of special conditions such as fog, local inversions, and shore wind effects on personnel and the environment should be modeled.

Additional model applications in the form of a preliminary risk assessment are recommended. Model runs with reasonable 'worst case' meteorological conditions from recommendation 3 may allow a deemphasis of issues such as far-field gaseous HCl concentrations if such issues can be shown to be insignificant.

2. Use Sophisticated Models

Models of greater sophistication are recommended to improve or eventually to replace the REED operational model (fig. 7). A one- or perhaps three-dimensional convective model should be combined with empirical measurements to predict near-field deposition and plume rise. Results are important for the revolatilization of gaseous HCl concerns which have recently been indicated.

Numerical models have fewer inherent simplifying assumptions than Gaussion models and promise improved accuracy in complex wind fields such as at VAFB. Even though computer difficulties and meteorological data limitations may not allow use of numerical models for during-launch operational applications, these complex models are useful for prior- and after-launch applications. Numerical models, which are currently available, should be used to help determine the diffusion coefficients and evaluate the simpler operational models. They should be applied with reasonable 'worst case' meteorological conditions for risk assessments which are more precise than possible with simpler models.

Advanced numerical models promise greater predictive accuracy than techniques currently used. Advances in computers and remote meteorological sensing equipment may eventually make these complex techniques practical. Improvements in forecasting as well as model accuracy are benefits which should be sought in future research efforts.

3. Collect Additional Data for Models

Since all of the models considered are heavily dependent on empirical parameters, accurate collection of measurement data is critical to model performance. Much of these data are valuable alone and independent from models. Six data collection task areas are recommended (fig. 8) and described in sequence.

Engineering calculations and observations are needed for initial model inputs. A surprise finding of the December 1982 conference at KSC is that a mass balance of HCl and water is not known to exist. The original assumption that all HCl exists as a gas in the downwind ground cloud is clearly not correct. However, neither the HCl nor the water deposited around the launch pad have been quantified. Calculations of HCl removal mechanisms (even preliminary ones) such as atomization, nucleation, condensation, wet deposition, and rainout should be produced and circulated for critical peer review.

Particle size distributions as a function of time, distance, and meteorological parameters are important to model the acid aerosol/rain phenomenon. Ground measurement efforts should be improved and integrated with aircraft measurements.

A meteorological data set of reasonable "worst case" conditions needs to be assembled from existing VAFB data (fig. 8). This set is to be used as input data for risk assessments using both operational and available numerical models. Both types of model applications can then be used to identify shortcomings in the current data so that needed improvements in the meteorological system at VAFB can be incorporated in a cost-effective manner.

Downwind measurements are important for model performance evaluations to establish confidence or improve dispersion models. Aircraft, remote sensing, and ground measurements are all recommended because each method has both advantages and disadvantages. Aircraft measurements produce the most quantitative data as a function of distance but only at cloud heights. Remote sensing of wind fields and atmospheric concentrations offers great promise but is limited in range and requires further development and testing. Ground monitoring is best for damage evaluations, especially for acid rainout.

Events such as the 6.4-percent scale model tests at NASA-Marshall Space Flight Center or Titan III launches at VAFB can be treated as targets of opportunity to measure parameters for direct use or for model input. The scale model tests should continue to be used to test measurement techniques and to study the effect of deluge water spray quantities on plume buoyancy and acid rainout. Measurements at Titan III launches should be initiated for personnel training and preliminary model evaluations prior to the first STS launch.

4. Form a Steering Committee

Due to the limited time to get an acceptable model for the first STS launch at VAFB which is scheduled for October 1985, a steering committee is recommended to review and take appropriate action on all recommended modeling efforts (fig. 9). This committee should meet biannually to ensure ample progress on all efforts. After a review of progress in each task, action should be taken to redirect efforts if needed. An important function of this group would be to identify "data gaps" where empirical measurements are needed for model inputs.

SUMMARY

All workshop objectives have been met. Models are required for many reasons as presented in figure 4. Recommendations are summarized in figure 10.

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1. Naugle, Dennis F.; and G. Douglas Swoboda: Recommendations for Space Shuttle Launch Dispersion Modeling. USAF OEHL Report on the workshop held at Brooks Air Force Base, San Antonio, Texas, 30 November to 2 December, 1982.

2. Pellett, Gerald L.; and W. L. Staton: Application of a Gaussion Multilayer Diffusion Model to Characterize Dispersion of Vertical HCl Column Density in Rocket Exhaust Clouds. NASA Technical Paper No. 1956, December 1981.

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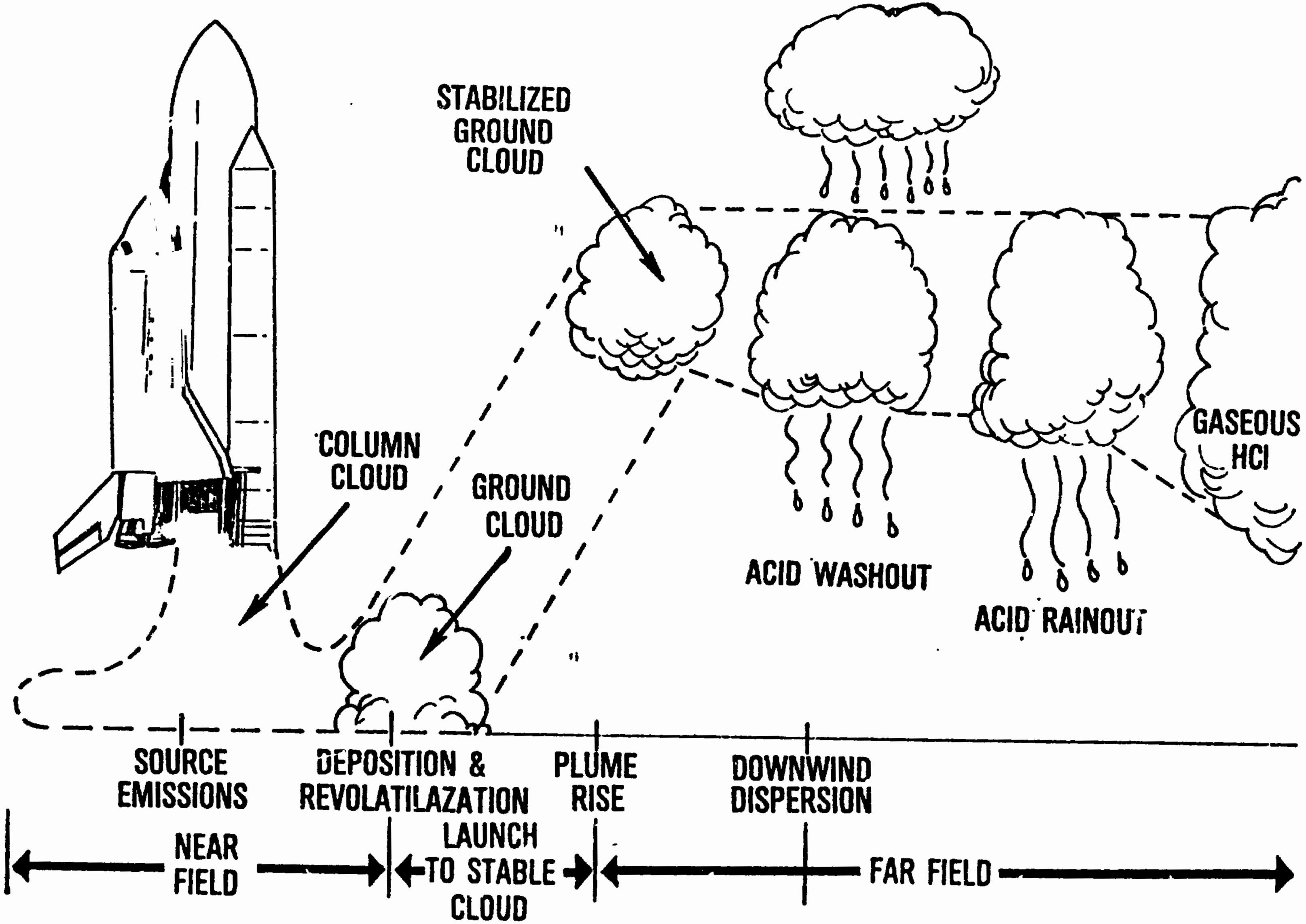

Figure 1.- Near- and far-field acid deposition potential during and after STS launches.

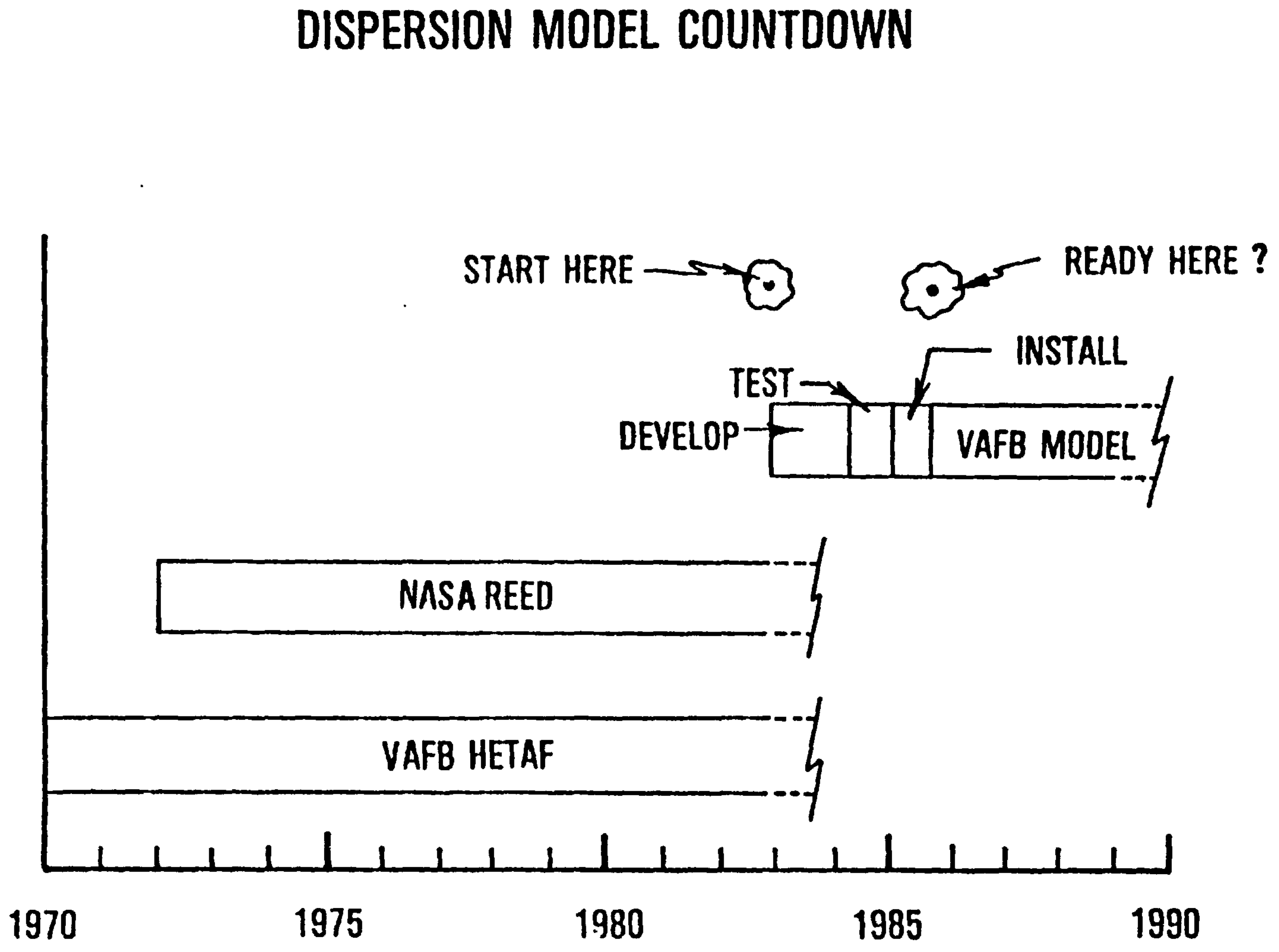

Figure 2.- Dispersion model schedule.

SHUTTLE MODELLING WORKSHOP ATTENDEES

(BRIEFING TO GROUP ONLY)

	ORGANIZATION	NAME OF ATTENDEE
1	SD/DEV	LT. COL. WOOTEN
2	SD/SGX	MAJ. REED
3	SD/WE	CAPT. COMPTON
4	SD/YVA	LT. COL. SCHNEIDER
5	SD/YVAS	CAPT. EPPERSON
6	AEROSPACE	DR. BYWATER
7	WSMC/SEY	MR. DARGITZ
8	WSMC/WE	CAPT. ROLLER
9	ESMC/DET 11 (2 WS)	MR. SLOAN
10	AFGL/LYT	MR. KUNKEL
11	NASA/MSFC	DR. KELLER
12	OEHL/ECA	LT. COL. NAUGLE
13	OEHL/ECA	CAPT. SWOBODA
14	AFESC/RDV	LT. COL. RYAN

Figure 3.- Workshop participating organizations and attendees.

MODEL REQUIREMENTS

WHEN ?	PRIORITY: HIGH	MED	LOW	WHY ?
• DURING LAUNCH				• ACTION
				(A) LAUNCH RISK ASSESSMENT
				PERSONNEL PROTECTION
	X			NEAR FIELD
	X			FAR FIELD
				ENVIRONMENTAL PROTECTION
		X		NEAR FIELD (EQUIPMENT)
	X			FAR FIELD (BIOLOGICAL)
	X			(B) AREA RESTRICTIONS
• PRIOR TO LAUNCH				• PLANNING
				(A) LAUNCH RISK ASSESSMENT
				PERSONNEL PROTECTION
	X			NEAR FIELD
	X			FAR FIELD
				ENVIRONMENTAL PROTECTION
		X		NEAR FIELD (EQUIPMENT)
		X		FAR FIELD (BIOLOGICAL)
		X		(B) REGULATORY REVIEW
• AFTER LAUNCH				• ASSESSMENTS
		X		(A) DAMAGE CLAIMS
				(B) SCIENTIFIC UNDERSTANDING
		X		ENV IMPACT ASSESSMENT
		X		MODEL IMPROVEMENTS

Figure 4.- Model requirements for actions involving launch-risk assessments or area restrictions.

REVIEW STS MODELS

• ALTERNATIVES	
- HETAF, IMPS, MADAM	CAPT. ROLLER, WSMC
- NASA REED	CAPT. SWOBODA, OEHL
- DIFFUS	MR. DARGITZ, WSMC
- DEPOSITION THEORY	DR. KELLER, NASA-MSFC
- AVAILABLE NUMERICAL	DR. BYWATER, AEROSPACE
- ADVANCED NUMERICAL	MR. KUNKEL, AFGL
• CONSIDERATIONS	
- STS-1 TO STS-5 MODEL RESULTS	MR. SLOAN, ESMC
- STS 6.4-PERCENT SCALE TEST FIRINGS	CAPT. COMPTON, SD
- MODEL EVALUATION THEORY	LT. COL. NAUGLE, OEHL

Figure 5.- Workshop presentations reviewed to develop an acceptable model for STS launches.

RECOMMENDATION (1)

- USE NASA OPERATIONAL MODEL
  - INCORPORATE STS-1 TO STS-5 OBSERVATIONS
    + PLUME RISE
    + WET DEPOSITION
    + AIR AND GROUND MEASUREMENTS
  - ADAPT TO VAFB
    + LOCAL DIFFUSION COEFFICIENTS
    + TERRAIN
    + DEPOSITION IN FOG, INVERSIONS, SHORE EFFECTS
  - PERFORM RISK ASSESSMENT
    + REASONABLE 'WORST CASE' CONDITIONS

Figure 6.- First recommendation of workshop on model development.

RECOMMENDATION (2)

- USE SOPHISTICATED MODELS TO IMPROVE (OR REPLACE) OPERATIONAL MODEL
  - 1D OR 3D CONVECTIVE MODEL FOR NEAR-FIELD DEPOSITION AND PLUME RISE
  - APPLY AVAILABLE NUMERICAL MODELS
    - + EVALUATE OPERATIONAL MODEL
    - + DETERMINE DIFFUSION COEFFICIENTS
    - + PERFORM RISK ASSESSMENT
  - DEVELOP ADVANCED NUMERICAL MODELS
    - + START WITH BOUNDARY LAYER MODELS
    - + IMPROVE FORECASTING POTENTIAL

Figure 7.- Second recommendation of workshop on model development.

RECOMMENDATION (3)

- COLLECT ADDITIONAL DATA FOR MODELS
  - ENGINEERING CALCULATIONS AND OBSERVATIONS
  - PARTICLE SIZE DISTRIBUTION
  - 'WORST CASE' CONDITIONS FOR RISK ASSESSMENTS
  - IMPROVE METEOROLOGICAL DATA AT VAFB
  - MEASUREMENTS FOR MODEL EVALUATION
  - STS SIMULATION STUDIES

Figure 8.- Third recommendation of workshop on model development.

RECOMMENDATION (4)

- FORM A 'STEERING COMMITTEE'
  - BIANNUAL MEETINGS
  - REVIEW MODELING EFFORTS
  - ACTION ON ALTERNATIVES
  - IDENTIFY 'DATA GAPS'

Figure 9.- Fourth recommendation of workshop on model development.

VAFB MODEL RECOMMENDATIONS

1. USE NASA <u>OPERATIONAL</u> MODEL
   - WITH IMPROVEMENTS
2. USE <u>SOPHISTICATED</u> MODELS
   - TO IMPROVE OR REPLACE <u>OPERATIONAL</u> MODEL
3. COLLECT ADDITIONAL DATA FOR MODELS
4. FORM A 'STEERING COMMITTEE' FOR MODELING EFFORTS

Figure 10.- Summary of workshop recommendations.

ROCKET EXHAUST DIFFUSION MODEL EVALUATION AT THE AIR FORCE WESTERN SPACE AND MISSILES CENTER

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With the advent of the first missile launch from Vandenberg Air Force Base (VAFB) in 1958, there has been an ongoing concern for the potential of personnel being exposed to harmful levels of toxic rocket propellant vapors. Toxic propellant vapors are produced from planned and unplanned releases of certain rocket propellants and from the combustion of solid-propellant rocket motors. The solid-rocket motors of the Space Shuttle vehicle produce approximately 54 tons of hydrogen chloride (HCl) gas in the stabilized exhaust ground cloud that forms during the first minute of launch.

Prior to STS-1, the Western Space and Missile Center Safety Division (WSMC/SE) assigned a task to their Flight Safety Analyses Contractor, the J. H. Wiggins Company (JHW), to evaluate computerized diffusion models that predict the transport and deposition of HCl products from exhaust clouds produced by the Space Shuttle. At that time it was the consensus of both the U.S. Air Force (USAF) and NASA agencies that gaseous HCl presented the main environmental and safety concern associated with Shuttle-launch operations and exhaust ground cloud fallout. Specifically, the JHW was tasked to tabulate the predictions of three diffusion models operated against 48 selected sets of meteorological rawinsonde soundings listed in both the USAF and NASA Space Transportation System Environmental Impact Statements. The models are the Heated Exhaust Toxic Area Forecast (HETAF), a simple Gaussian model operationally used by WSMC; the NASA Rocket Engine Exhaust Diffusion Model (REEDM), a Gaussian model operationally used by NASA; and DIFFUS, a Lagrangian numerical model acquired by WSMC for evaluation. The DIFFUS model has the capability to simulate the effects of terrain on boundary-layer air motion. The JHW was tasked to operate DIFFUS in both a terrain and nonterrain mode, and all three models were operated for both the nominal launch and the catastrophic case scenarios (both solid-rocket motors burn on the launch pad in a conflagration). Available and reliable gaseous HCl ground measurements made at VAFB during Titan III launches were also compared to HETAF, REEDM, and DIFFUS predictions, using meteorological data measured at launch. After completion of the model computations, the contractor was directed to assess the frequencies with which the models predict concentrations in excess of toxic concentration criteria beyond the Toxic Limit Line (TLL), which coincides with the boundary line of the southern half of VAFB.

The task has not yet been completed because of other higher priority tasks assigned to the contractor and also because of a lack of computer availability and core size because of range-support operations. Results, as of January 1983, are given below:

1. The HETAF predicted no violations of the maximum HCl concentration criterion (8 ppm) beyond the TLL for nominal launches and two violations of the maximum HCl concentration criterion (14 ppm) for the catastrophic case.

2. The REEDM predicted no TLL violations for either case.

3. The DIFFUS model has exhibited some problems and has not yet been run against all of the 45 soundings. The problems involve abnormal wind velocity computations, unwieldy cell-size selection that causes DIFFUS, in some instances, to require an excessive amount of computer memory and numerical instability (not uncommon to this type of modeling technique).

Based on a series of runs on some of the 45 soundings, DIFFUS has shown an apparent terrain effect on maximum concentration predictions that is unaffected by the above-mentioned difficulties. Table 1 below illustrates various ratios of concentrations with the terrain modeled to concentrations without terrain modeling.

TABLE 1.- CONCENTRATION WITH TERRAIN MODELED TO CONCENTRATION WITHOUT TERRAIN MODELING

Item	Nominal Launch, TLL		Castrophic Launch, TLL	
	In-side	Out-side	In-side	Out-side
Instantaneous median ratio	4.1	5.5	2.3	3.5
10-minute average median ratio	4.0	4.5	2.5	3.7

The following conclusions and recommendations have been made (January 1983).

1. The DIFFUS model needs several modifications before its predictions can be considered accurate within an order of magnitude. Its wind field subroutine, or an equivalent algorithm, should be investigated to determine the course of abnormal wind velocities. The subroutine, the modeling technique, and/or input data may require modification to overcome or minimize this condition. If execution time and/or computer memory requirements cannot be reduced, other techniques, such as a table lookup of results from similar wind field profiles, could be pursued as a satisfactory alternative.

2. The REEDM also has limitations. Conceptually, as a Gaussian model, it cannot account for downwind changes in wind speed and direction as evidenced on South VAFB from the constant-level balloon flights and meteorological towers. It has no capability, in it's current form, to account for terrain effects. The model assumes that in a catastrophic launch scenario, the solid propellant burns for 1,027 sec, yet the REEDM User's Manual recommends the exhaust cloud to be assumed spherical. Over the 1,027-sec period, with a 12-knot wind speed (common at VAFB) over the depth of the exhaust cloud, the cloud would extend over 3 n. mi. and could hardly be considered spherical. The assumption of a spherical shape versus an elongated, elliptical shape could affect centerline maximum instantaneous concentration predictions and centerline maximum dosage predictions.

3. The HETAF model, in its simplicity, is the most conservative model. It is two-dimensional; there is no calculation of dispersion in the vertical plane. The HETAF is not time-dependent; i.e., it does not calculate the time required for a maximum concentration to occur at some point downwind. It only predicts in-

cloud concentrations and does not consider terrain. Predictions are conservative, in that the model operator assumes the in-cloud concentrations will equal the ground-level concentrations. No consideration is made of diffusion in the vertical plane.

4. Neither DIFFUS nor the HETAF model calculated the hot, buoyant rise of the exhaust cloud to an equilibrium-stabilized altitude. In operating these two models, the altitude of the stabilized exhaust cloud computed by the REEDM was used. The REEDM begins calculating transport and diffusion after the exhaust cloud stabilizes. None of the models address effluent fallout before stabilization is reached. Because fallout has been photographed immediately after T-0, during Shuttle launches, it should be simulated in a model.

5. None of the model studies can predict the deposition or acidity of HCl aqueous aerosols. Since deposition of acidic material has been observed and/or measured and has caused some minor chemical skin irritations to several personnel within the ground track of the exhaust cloud during the majority of Shuttle launches, this phenomenon of acidic effluent deposition should also be modeled and predictable.

6. The 48 rawinsonde soundings are not statistically representative of the VAFB Space Shuttle launch site. Rather, they were released at the airfield on North VAFB. Because there were apparently no series of soundings from the launch site available, the next best source of upper air measurement were those from the airfield. More detailed climatology should be collected in the immediate vicinity of the Shuttle launch site to adequately understand the dynamic effects of the boundary-layer meteorological elements (wind speed/direction, vertical temperature profiles,relative humidity, atmospheric stability, etc.) upon the transport and dispersion of the exhaust cloud. This would facilitate a risk assessment of HCl exposure by identifying the worst case meteorological conditions (those conditions most conducive to minimum dispersive and turbulent processes and maximum deposition of acidic material and transport distance).

7. None of these diffusion models can predict, before launch, what the meteorological conditions will be in the vicinity of the launch pad at the time of launch. Such predictions are, of necessity, subjective and can only be made by a meteorologist. If subjective forecast launch conditions are put in the appropriate formats for input into the REEDM and DIFFUS models, then those models will predict the downrange HCl concentrations and translate the predicted verticle profile of wind velocities into a transport direction of the stabilized exhaust cloud. Accurate prelaunch prediction of the exhaust cloud transport direction is especially important to the WSMC/SE. WSMC/SE has the responsibility of protecting or evacuating onbase personnel and offbase, nongovernmental civilians from all hazards associated with Space Shuttle launches. An inaccurate prediction of exhaust cloud transport direction (e.g., off by ± 20 to 30 degrees) 3 hours before liftoff could result either in unknowingly hazarding people who are beyond the TLL and thought to be in a safe area or in unnecessarily deploying security personnel to evacuate areas mistakenly thought to be at risk from toxic exhaust deposition.

GROUND CLOUD MICROPHYSICAL TERRAIN EFFECTS

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INTRODUCTION

Originally, this discussion was to be in two sections: Ground Cloud Microphysics and Terrain Effects as they apply to the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC) Rocket Exhaust Effluent Diffusion Model (REEDM). Dr. Vern Keller and Dr. Jeff Anderson of MSFC are working on the ground cloud microphysical processes; therefore, only terrain effects[a] are considered herein. Discussion of terrain effects in this paper refers to the impact which the terrain around the Space Launch Complex (SLC-6) at Vandenberg Air Force Base (VAFB) has on the diffusion of the Space Shuttle exhaust cloud.

BACKGROUND

In 1973, a joint program for rocket exhaust prediction and launch monitoring was initiated by NASA for all Titan launches from the John F. Kennedy Space Center (KSC). This program revealed the need for the development of a real-time dispersion prediction capability. As a result, the REEDM computer code was developed. It has since been used to assess the environmental impact of Space Shuttle operations and to support actual Space Shuttle launches.

During a Space Shuttle launch, the burning of the solid rocket boosters (SRB's) during the first few seconds prior to and immediately following vehicle lift-off results in the formation of a large cloud of hot, buoyant exhaust products near ground level which subsequently rises and entrains ambient air until the temperature and density of the cloud reach an approximate equilibrium with ambient conditions. By convention, this cloud is referred to as the ground cloud. The SRB's also leave an exhaust trail from normal launches which extends throughout the depth of the troposphere and beyond. The NASA MSFC/REEDM code is designed to calculate peak concentration, dosage, and deposition from this ground cloud.

Figure 1 is a schematic diagram illustrating the major components of the REEDM computer code. Notice that there is no terrain algorithm in this computer program. This code was used at VAFB for the Space Shuttle Environmental Impact Statement (EIS).

STUDY OF TERRAIN EFFECTS AT VAFB

To provide estimates of gaseous constituent contributions occurring from periodic launches, meteorological data from VAFB [taken at 0400 Pacific standard time (PST), when the atmosphere is generally most stable] on 48 days in 1974 were used. In every case, the maximum ground level concentration was predicted to occur within 10 km of the launch pad (with no terrain consideration). A schematic of the transport direction at cloud stabilization height is given in figure 2. The actual ground cloud data predicted for the 48 cases are contained in the VAFB Space Shuttle EIS.

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[a]The only study of terrain effects on the use of the MSFC REEDM was done in conjunction with the Vandenberg Air Force Base (VAFB) Space Shuttle Environmental Impact Statement (EIS)].

To further study these 48 cases, four of the cases which had on-shore flow were run through the White Sands Missile Range terrain model, using VAFB terrain data. The validity of these four runs has been questioned, but they do show that if the cloud stabilizes above the height of the terrain, the cloud will transport with the wind field. Previous launches of the Space Shuttle indicate that the cloud stabilizes between 1300 m and 1600 m. The hignest point around SLC-6 is Mt. Tranquillon at an elevation of 2,150 feet (655 m). If the ground cloud from a SLC-6 Space Shuttle launch stabilizes as it does at KSC, then terrain will have little effect on the transport direction. With this in mind, what are the chances of the cloud being transported over land?

Figure 3 shows the general air flow in the VAFB vicinity. As can be seen, there is little diurnal or seasonal change in the direction of the wind around South Vandenberg. The prevailing direction is from the northwest. Wind direction closer to SLC-6 is reflected in table 1 where the most frequent wind direction for the Santa Maria and Point Arguello areas are given. Again, the indication is that the wind is predominately trom the northeast. To go one step further, USAFETAC Report 7069 shows the wind at the 300-ft level of Tower 301 (at SLC-6) to be from the north-northwest through north-northeast from 78 percent of the time at 1100 PST to 89 percent at 0000 PST on an annual basis.

Figure 4 shows a wind rise from Tower 301 for the 12-ft level. Again, the indication is that the wind is from the north-northwest through north-northeast 76 percent of the time. Looking through past records, it appears there is onshore flow (south-southwest through west) from 10 to 25 percent of the time, depending on the season. This all correlates very well with the NASA/MSFC REEDM transport direction given in figure 2.

What does all this mean? Well, overall it means that terrain will only be a factor on the output of the NASA/MSFC REEDM about 16 percent of the time (usually to the souteast). In summary, the following statements are evident.

1. Better than 80 percent of the time the cloud will transport to the south or southeast and over water.

2. On previous STS launches, the ground cloud stabilized above 1,000 m (above the highest terrain at VAFB). The 48 cases ran through the White Sands Missile Range terrain model using VAFB meteorology varying the stabilization height from 729 m to 1,484 m.

3. If the ground cloud stabilizes above the terrain, the direction will be determined by the wind field.

4. In the 48 cases ran without terrain data, the maximum concentration was within 10 km of the launch pad and either over water or on VAFB.

All of the above implies that terrain will only affect the diffusion of the ground cloud. The direction will be dependent on the wind field. It is in this context that inversions and orographics need to be considered.

Figure 5 shows four types of temperature profiles that are common at Point Arguello. Profiles B and C are characteristic of subsidence inversion associated with the Pacific subtropical anticyclone. The data for 0400 PST for 1960-1963 suggest that inversion below 300 m occurs about 10 percent of the time during the summer, but at 1600 PST, inversion occurs about 30 percent of the time during the summer. In their position paper on the potential of inadvertent weather modification of the Vandenberg area resulting from the Space Shuttle SRB exhaust clouds, L. Bosart et al. found that most low level inversions occur with favorable winds (north-northwest through south-southwest). This implies that most clouds, if trapped within the inversion, would go out over water. But, what if they do not go out over the water? In that situation, the terrain would act as a dam, holding the cloud against the windward side of the mountains. The cloud would most likely slide off to the southeast. It would be difficult for it to move to the northwest then to the northeast. Using this reasoning, one concludes that the effect of terrain with a strong low inversion would be beneficial (with the exception that the cloud wall would remain in the pad area much longer, causing corrosion, erosion, and exposure problems).

In the event the ground cloud made it through the inversion or there was no inversion and the cloud was transported over land, the effect of orographics would come into play. Without going into detail, the effect would be more turbulent mixing or diffusion of the cloud. This was found to be true in the Iron Mountain Study done at VAFB years ago. From this, one can conclude that since the MSFC/REEDM model predicts the maximum concentration within 10 km of the pad without terrain and terrain increases the diffusion rate, then the model will be conservative (over-predict) at VAFB. Thus, the maximum concentration should be even closer to the pad area.

CONCLUSIONS

Conclusions[b] follow:

1. Terrain at SLC-6 will be beneficial in keeping the deposition away from populated areas.

2. Eighty percent of the time the cloud will go to the south or southeast and ove water.

During the first week in December 1982, a diffusion modeling workshop was held at the Occupational and Environmental Health Laboratory (OEHL) at Brooks Air Force Base, San Antonio, Texas. The outcome of this workshop was to recommend that the NASA/MSFC REEDM be adapted for use at VAFB. Two major recommendations were:

1. Add a terrain subroutine to the model to handle the VAFB terrain.

2. Improve the cloud rise portion of the model so it will show the deposition during the time between leaving the exhaust and stabilization.

I fully support these recommendations; however, I also recommend that the NASA/MSFC REEDM be brought to VAFB now and using the model 'as is', making modifications as necessary. I believe very little modification (other than the cloud rise modification) is needed.

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[b]Author states the conclusions are his and many people disagree.

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TABLE 1.- MOST FREQUENT WINDS ALOFT[a]

[From U.S. Weather Bureau and California State Dept. of Health, 1962.]

Local standard time (PST)	Height	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
		Average wind speed (knots) for most frequent wind direction cases												
0400 (4 A.M.)	5,000 ft	N/20	N/21	N/22	N/19	N/19	N/14	N/12	SE/9	N/14	N/17	N/18	N/18	N/17
	4,000 ft	N/17	N/19	N/18	NE/17	N/16	N/14	NE/12	NE/10	N/12	N/16	N/15	N/18	N/15
	3,000 ft	N/15	N/16	N/16	NE/18	NE/15	N/14	NE/12	NE/10	NE/12	N/13	N/13	N/15	N-NE/14
	2,000 ft	NE/14	N/14	N/14	N/16	N/14	N/11	N/9	N/10	N/9	NE/14	N/11	NE/15	N/13
	1,000 ft	NE/11	NE/10	N/13	NW/13	NW/13	N/7	NW/7	NW/7	N/7	N/10	NE/9	NE/9	N/10
	Surface	E/6	E/5	NW/9	NW/8	NW/9	NW/6	NW/6	NW/5	NW/6	E/6	E/6	E/6	NW-E/7
1600 (4 P.M.)	5,000 ft	N/20	N/1[illegible]	N/17	N/16	N/17	NE/12	NE/9	NE/9	NE/11	N/14	N/15	N/17	N-NE/15
	4,000 ft	N/16	NW/15	N/15	NW/14	N/14	NW/11	NW/10	NW/10	NW/11	N/13	N/14	N/14	N-NW/13
	3,000 ft	N/13	NW/14	N/14	NW/14	NW/16	NW/13	NW/11	NW/11	NW/11	NW/12	N/14	N/11	N-NW/13
	2,000 ft	N/13	NW/15	NW/17	NW/17	NW/19	NW/14	NW/12	NW/11	NW/12	NW/14	NW/12	NW/12	NW/14
	1,000 ft	NW/12	NW/14	NW/18	NW/16	NW/17	NW/13	NW/10	NW/11	NW/12	NW/14	NW/13	NW/11	NW/13
	Surface	NW/11	NW/12	NW/14	NW/15	NW/14	NW/13	NW/10	NW/10	NW/11	NW/12	NW/11	NW/9	NW/12

[a]Period: 1957-1962 in Santa Maria and Point Arguello areas.

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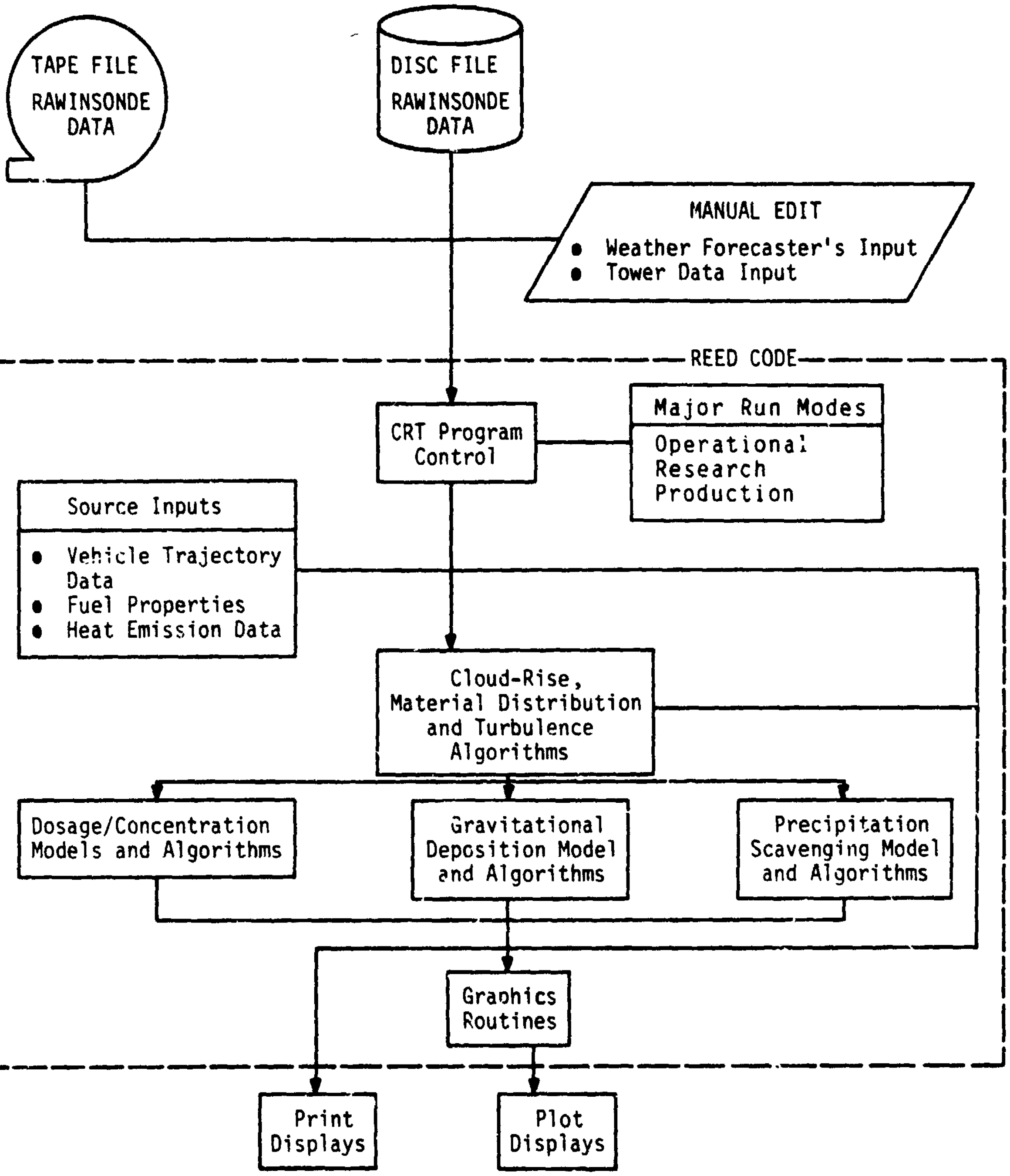
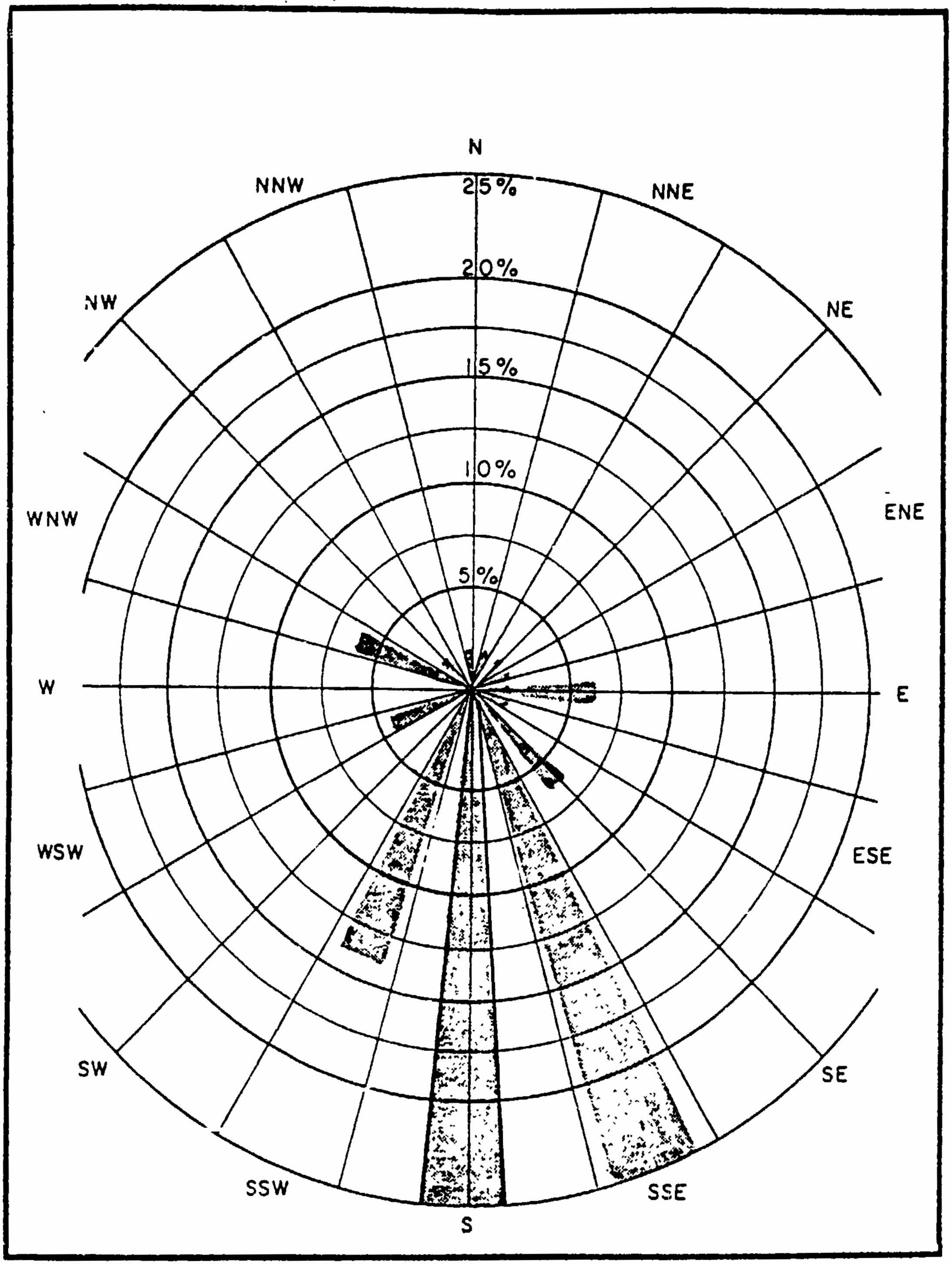


Figure 1.- Schematic diagram illustrating major components of the REED structure.



Reference: NASA/MSFC, 1976.

Figure 2.- Transport direction at cloud stabilization height expresed in percent occurrence for 48 selected meteorological cases at Vandenberg AFB for 1974.

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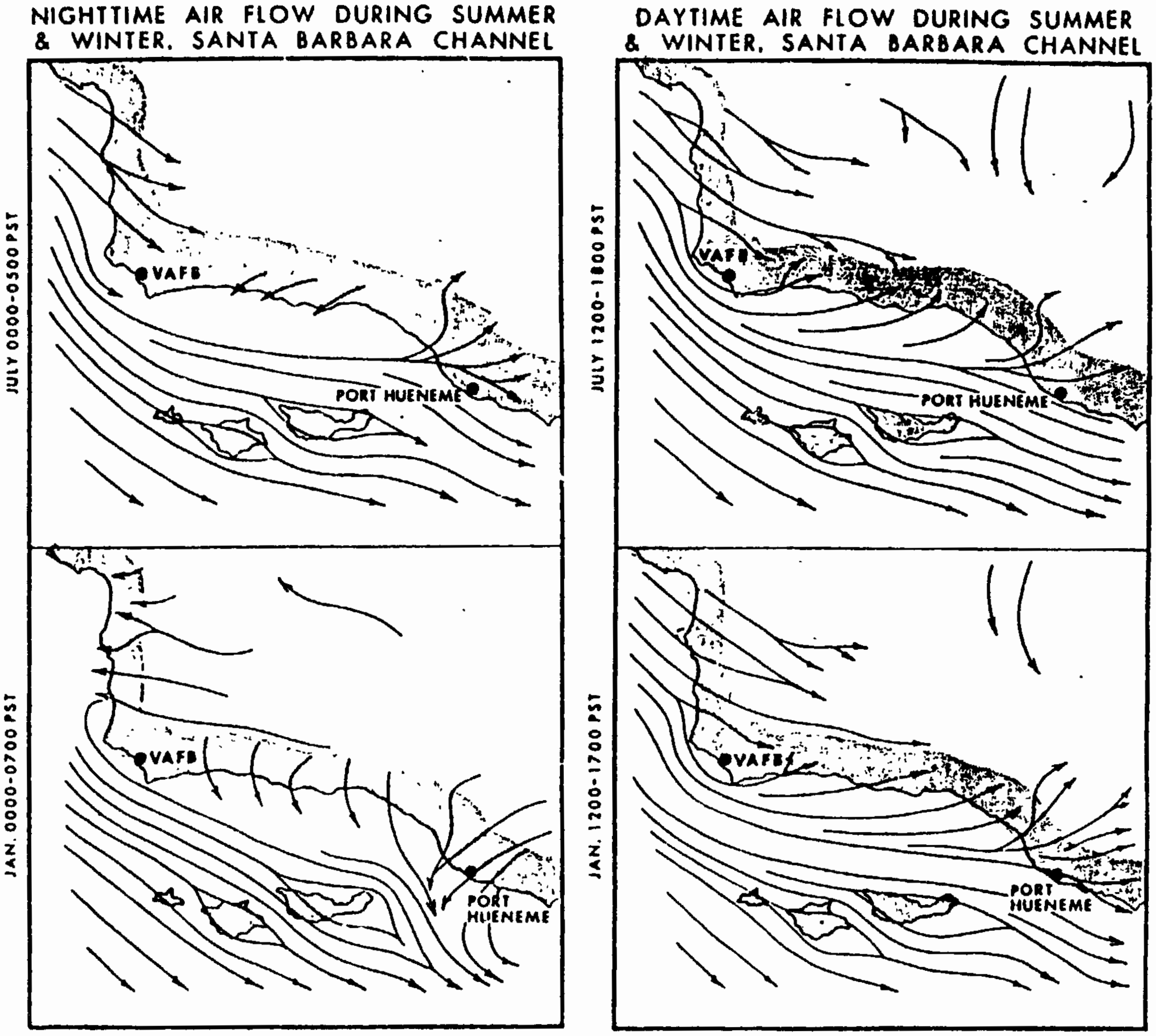
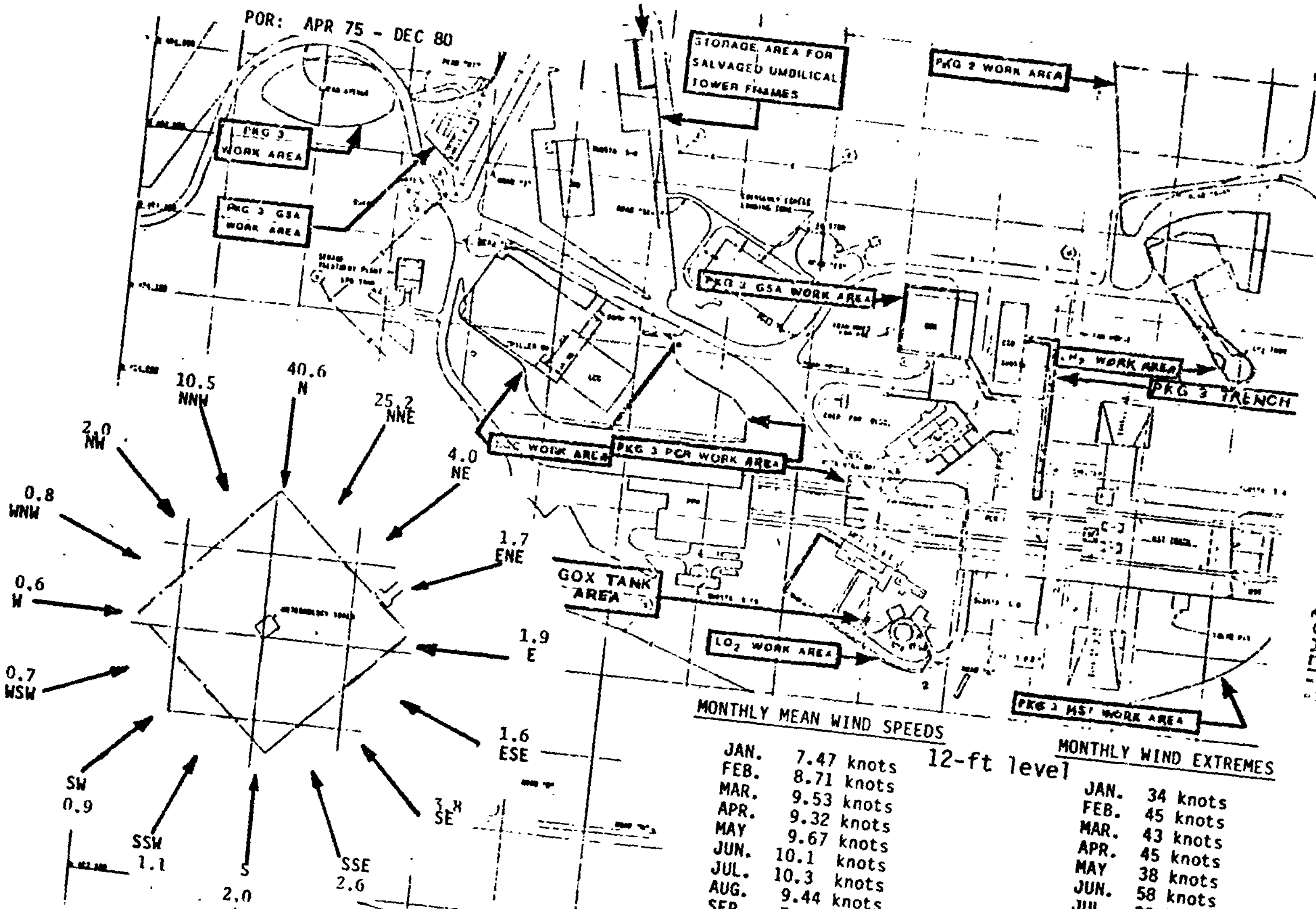


Reference: DeMarrais, Holzworth, and Hosler, 1965.

Figure 3.- Diurnal and seasonal air flow in the project vicinity.



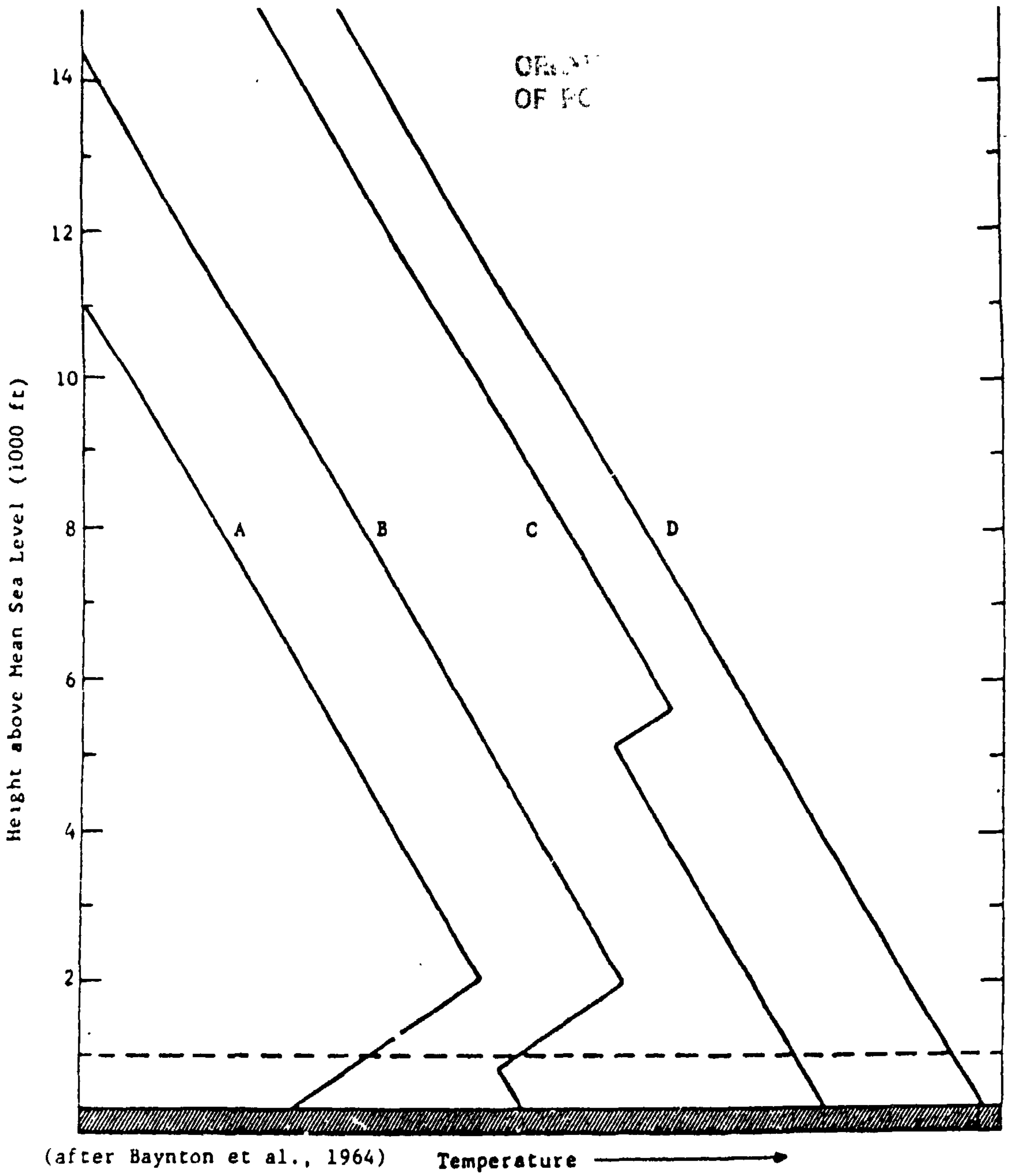
MONTHLY MEAN WIND SPEEDS

JAN.	7.47 knots
FEB.	8.71 knots
MAR.	9.53 knots
APR.	9.32 knots
MAY	9.67 knots
JUN.	10.1 knots
JUL.	10.3 knots
AUG.	9.44 knots
SEP.	7.43 knots
OCT.	8.70 knots
NOV.	8.51 knots
DEC.	8.65 knots

MONTHLY WIND EXTREMES

JAN.	34 knots
FEB.	45 knots
MAR.	43 knots
APR.	45 knots
MAY	38 knots
JUN.	58 knots
JUL.	30 knots
AUG.	46 knots
SEP.	38 knots
OCT.	47 knots
NOV.	40 knots
DEC.	47 knots

Figure 4.- Vandenberg Air Force Base SLC-6 wind rise - 12-ft level.



Legend:

A = surface inversion

B = inversion aloft, base below 1,000 ft

C = inversion base above 1,000 ft

D = no inversion

Figure 5. Types of lapse rate at Point Arguello.

SONIC BOOM

- SONIC BOOMS FROM LAUNCH AND LANDING OF THE SPACE SHUTTLE
  Garcia
- SHUTTLE-FOCUSED SONIC BOOM: THE NEED FOR DIRECT EVIDENCE
  Wooten

SONIC BOOMS FROM THE LAUNCH AND LANDING OF THE SPACE SHUTTLE

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INTRODUCTION

Sonic booms are produced during both the launch and landing of the Space Shuttle. The boom from reentry of the Orbiter, just before landing at John F. Kennedy Space Center (KSC), is heard over a part of the Florida peninsula. However, the boom produced during the launch of the Shuttle from KSC can only be heard in the Atlantic Ocean, 40 mi or more from shore. As a consequence, NASA's interest in the sonic boom is confined to the landing boom because it is the only NASA operation which might affect the public.

The U.S. Air Force (USAF) plans to launch the Shuttle from Vandenberg Air Force Base (VAFB), California. At this location, the launch boom may impact (for some launch azimuths only) the Channel Islands off the California coast. Consequently, the USAF's interest in sonic booms is centered on the launch boom.

The landing boom was addressed in the 1978 Environmental Impact Statement for the Space Shuttle Program (ref. 1), where the peak overpressure was predicted to be 2.1 lb/ft^2. The environmental effect of a sonic boom of this magnitude is not significant, producing only mild startled effects in some people and no structural damage to buildings beyond the possible triggering of loose plaster falls and the like. However, the overpressure predictions were extrapolated from small-scale wind tunnel tests, and it was stated in the Environmental Impact Statement that the predictions would be verified during the design, development, test, and engineering (DDT&E) phase of the Space Shuttle program. For this reason, a series of sonic boom overpressure measurements were made during landing of the Orbiter at Edwards Air Force Base, California. An additional measurement will be made in Florida for the first landing at KSC. Plans are to continue a small-scale monitoring effort in Florida for a period of time following full activation of the KSC landing site.

As mentioned previously, launch booms may impact land areas for launches from VAFB. The launch boom can become very strong in a narrow zone, a few hundred feet wide by several miles long, due to focussing. When the Space Shuttle pitches over on its way into orbit, the curved path causes sonic booms from different parts of the trajectory to arrive at the same point on the surface, all at the same time. The resultant boom is the summation of all these booms and, theoretically, could have a very large amplitude. The magnitude of the focussed boom can be predicted by approximate theories, but the validity of these predictions has not been tested. As a result, the USAF sponsored the measurements of the launch boom in the Atlantic Ocean off KSC during the STS-5 launch. Further tests are also planned for future launches.

DATA ACQUISITION SYSTEM

Up to ten microphone-tape recorder systems were deployed in the sonic boom footprint area of Shuttle landings. Each of these systems consisted of four condenser microphones, a seven-channel FM-FM tape recorder, a satellite time code receiver, and a gasoline generator to furnish power supply for operation at remote sites. The equipment was housed in rented vans or trailers which were parked at the measurement site. Communications with mission operations control was by temporary telephone hookups, in most cases. Redundant microphones were used to record the acoustic signal at several different gain levels to ensure that the boom was recorded at an optimum gain level on at least one channel. The microphones were calibrated before and after the measurement using standard pistonphone techniques. The Photocon 404 condenser microphones provided a frequency response flat to ±2 dB at 10 kHz and down -5 dB at 0.01 Hz. For Space Shuttle launch measurements, the same measurement systems were used, installed in 60- to 70-ft boats.

SONIC BOOMS FROM ORBITER REENTRY

Reentry of the Orbiter was monitored for STS-1, STS-2, and STS-4, STS-3 was not monitored because the Orbiter landed at White Sands, N.M., rather than at Edwards Air Force Base, California.

Results for STS-1 have been analyzed and published in reference 2. The locations of the STS-1 stations are shown in figure 1. Measurement sites were spread along the ground track from the landing site almost to the California coast. The measured and predicted sonic boom overpressures are shown in table 1. The predictions were made using postflight trajectory and meteorological data. The mean difference between the observed and predicted values was 10.9 percent; the standard deviation was 16.1 percent; therefore, data from stations 9 and 10 appear anomalous, with differences about twice the standard deviation. If these two values are set aside, the mean difference falls to 5.5 percent, and the standard deviation falls to 12.1 percent. Local meteorological conditions and flight maneuvers near the termination of the flight might be responsible for the difference observed at stations 9 and 10.

Figure 2 is a map showing the location of the measurement sites for STS-2. The sites were placed around the predicted location of maximum overpressure. Results are shown in table 2. Measured overpressures in table 2 may be compared with predictions made using preflight trajectory and meteorological data. On average, the predicted values were about 10 percent higher than the measured values (opposite to the STS-1 results).

Figure 3 is a map showing the location of measurement sites for STS-4. The sites were selected in order to measure the region near lateral cutoff of the sonic boom footprint. Results are shown in table 2. The predicted values in this table were calculated using preflight trajectory and meteorological data. The measurements clearly show lateral cutoff located about station 3. Predictions made by using the postflight trajectory and meteorological data are expected to resolve the difference between measured and predicted values.

SONIC BOOMS FROM SHUTTLE LAUNCH

The STS-5 flight measurement plan called for deployment of nine ships positioned along the predicted sonic boom focal zone, from a point under the ground track southwards to the region of lateral cutoff of the sonic boom. The planned arrangement of ships is shown in figure 4. Unfortunately, the sea state at the time of STS-5 launch was so high that only one ship could be deployed. The sonic boom signature recorded by microphones aboard this ship which was located at a point about 38.7 n.mi. east of

Cape Canaveral, Florida, is shown in figure 5. The signature shows three distinct peaks, typical of sonic booms measured near the focal zone, which generally displays multiple peaks. The maximum overpressure was 3.66 lb/ft^2, and the predicted value made by using preliminary trajectory data was 3.10 lb/ft^2. A more detailed analysis of the STS-5 launch data is given in reference 3.

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3. Garcia, F.; J. H. Jones; and H. R. Henderson: Preliminary Sonic Boom Correlation of Predicted and Measured Levels for STS-5 Launch. NASA Technical Memorandum No. 58253, April 1983.

TABLE 1.- STS-1 ENTRY SONIC BOOM OVERPRESSURES

Station	ΔP measured, (lb/ft^2)	ΔP predicted[a], lb/ft^2
0	0.72	0.80
1	1.22	1.00
2	0.92	1.10
3	1.15	1.10
4	1.55	1.30
5	1.61	1.60
6	2.38	2.00
7	1.93	2.00
8	1.79	1.80
9	2.19	1.60
10	1.86	1.40

[a]Based on postflight analysis.

TABLE 2.- ENTRY SONIC BOOM OVERPRESSURES

Station	ΔP measured, lb/ft^2	ΔP predicted[a], lb/ft^2
STS-2		
1	1.44	2.0
2	2.28	2.1
3	1.74	2.1
4	2.16	2.1
STS-4		
1	0.94	1.22
2	.88	1.01
3	.28	0.74
4	.06	.62

[a]Based on preflight predictions.

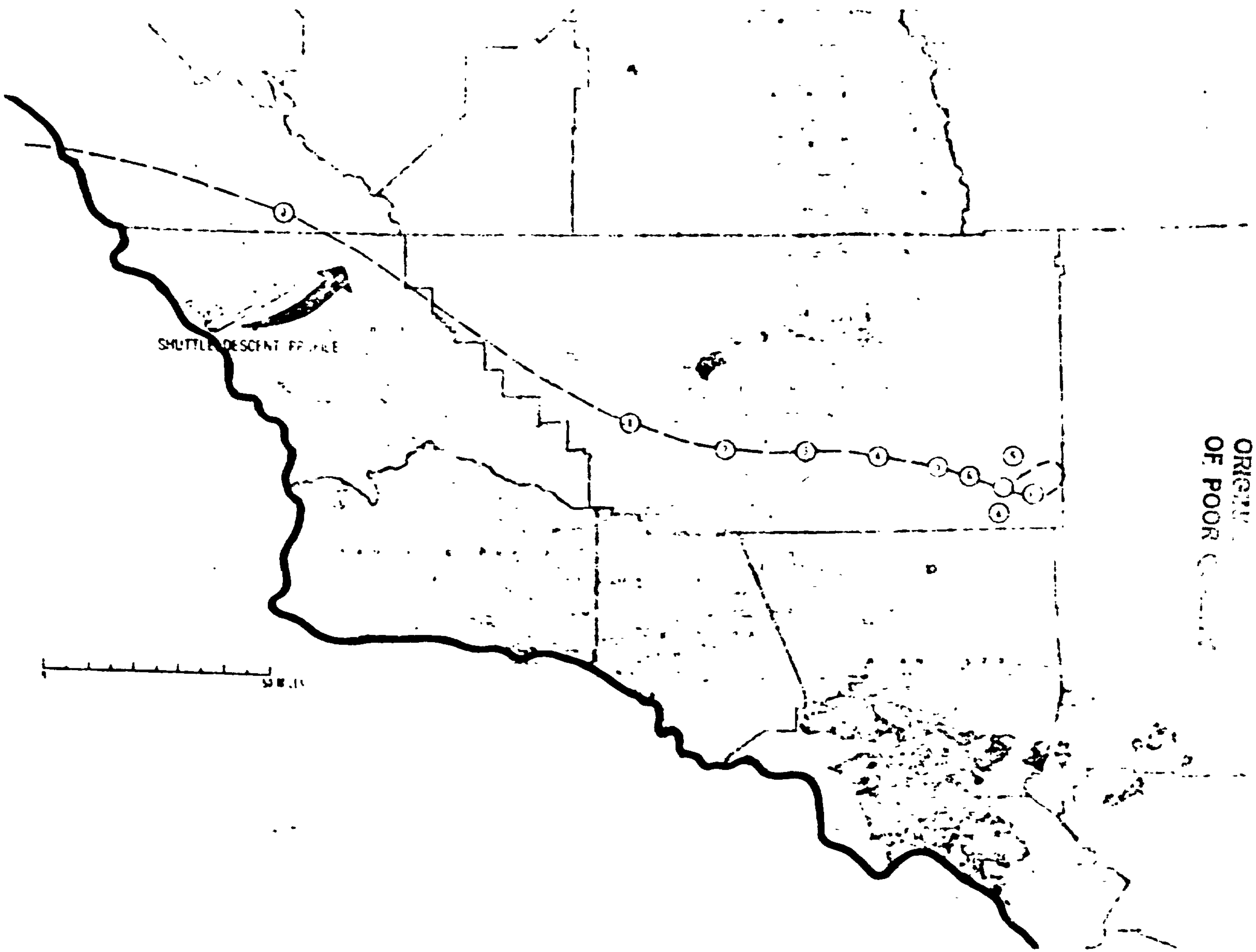

Figure 1.- STS-1 reentry track and measurement stations.

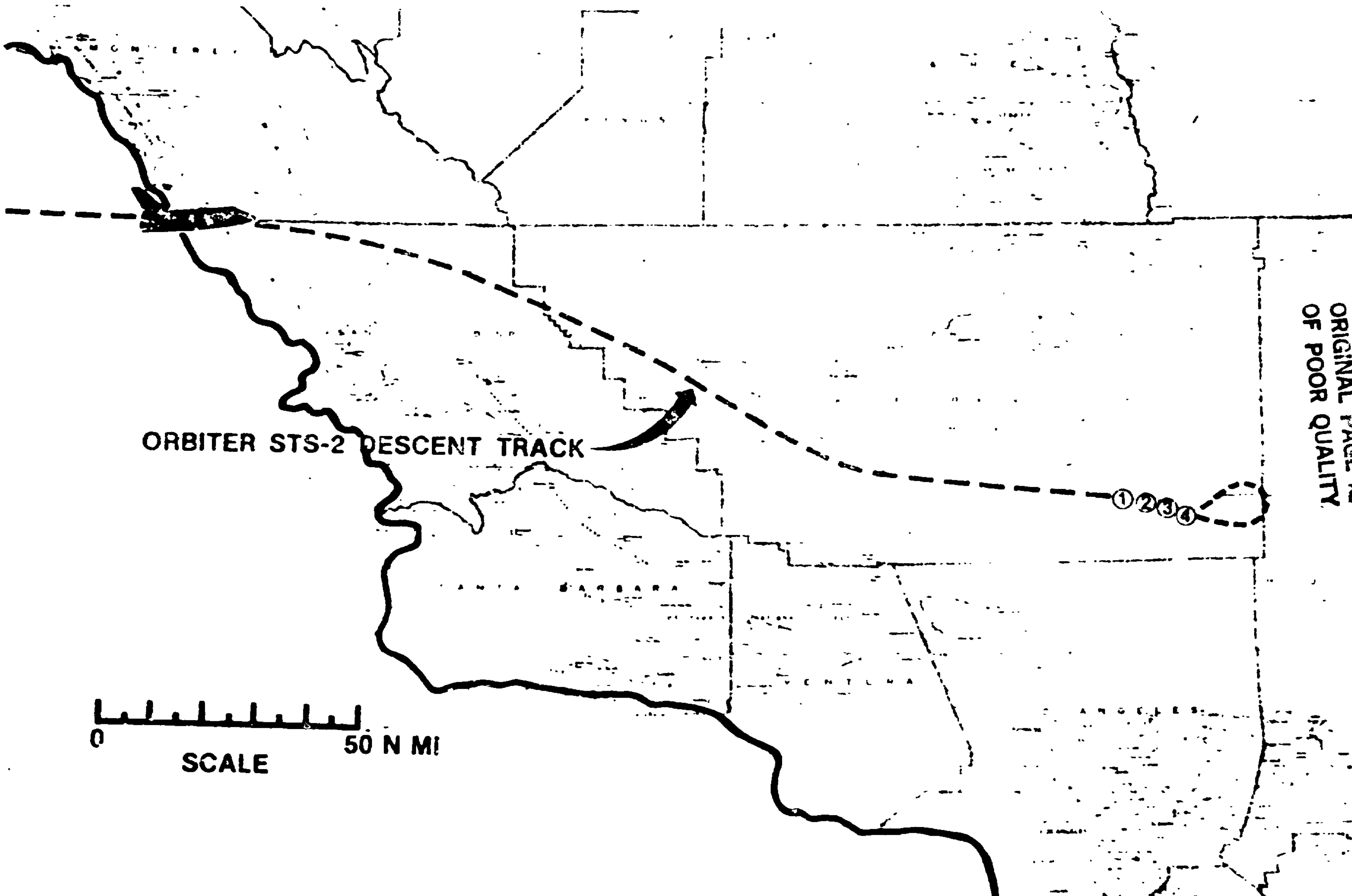

Figure 2.- Areas of four sonic boom measuring sites located under and laterally to the STS-2 reentry track into Edwards Air Force Base, California.

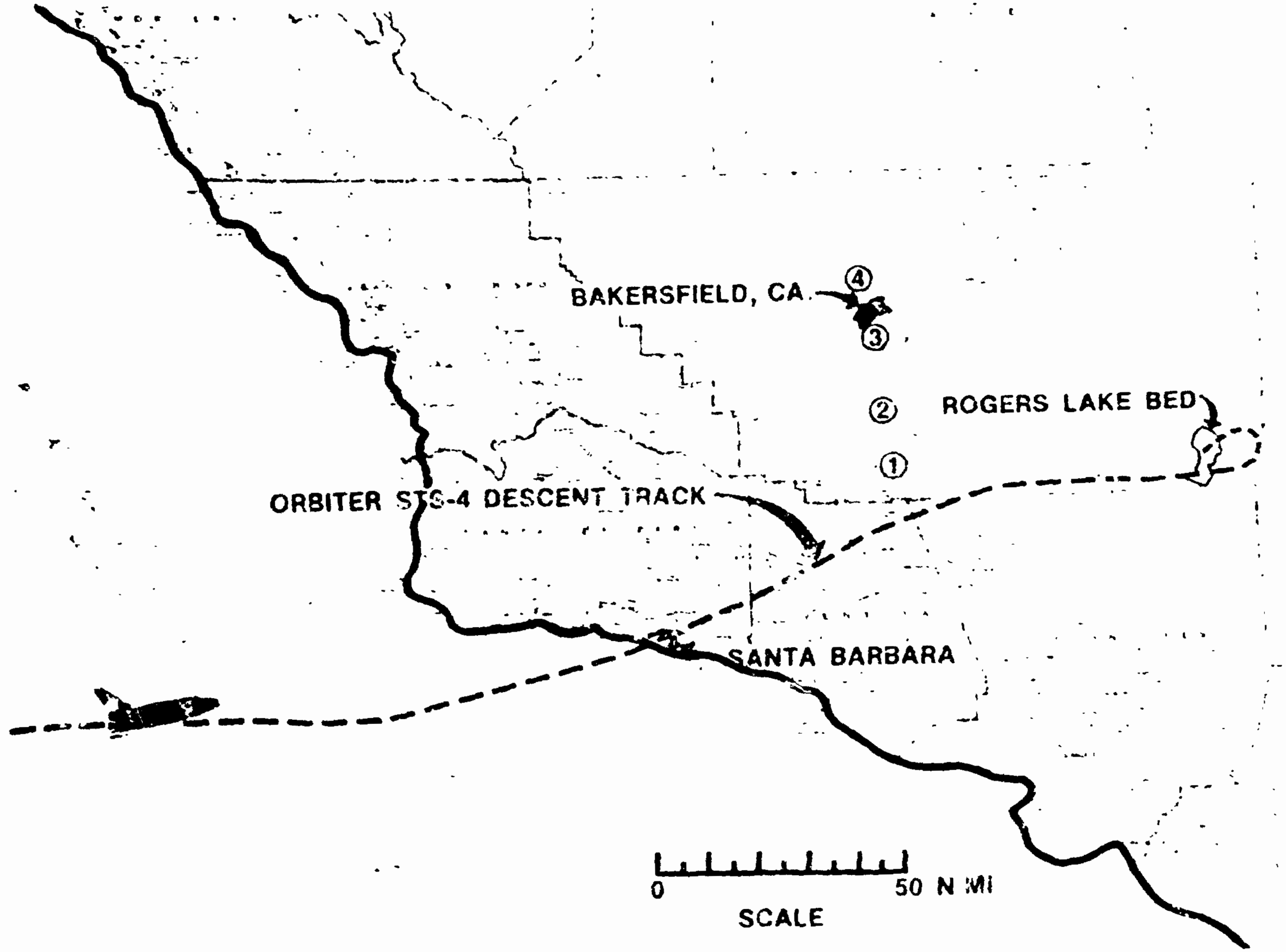

Figure 3.- Location of the four lateral sonic boom ground mea[illegible]ing sites in the Bakersfield area for the STS-4 reentry into Edwards Air Forc[illegible] [illegible]ase, California.

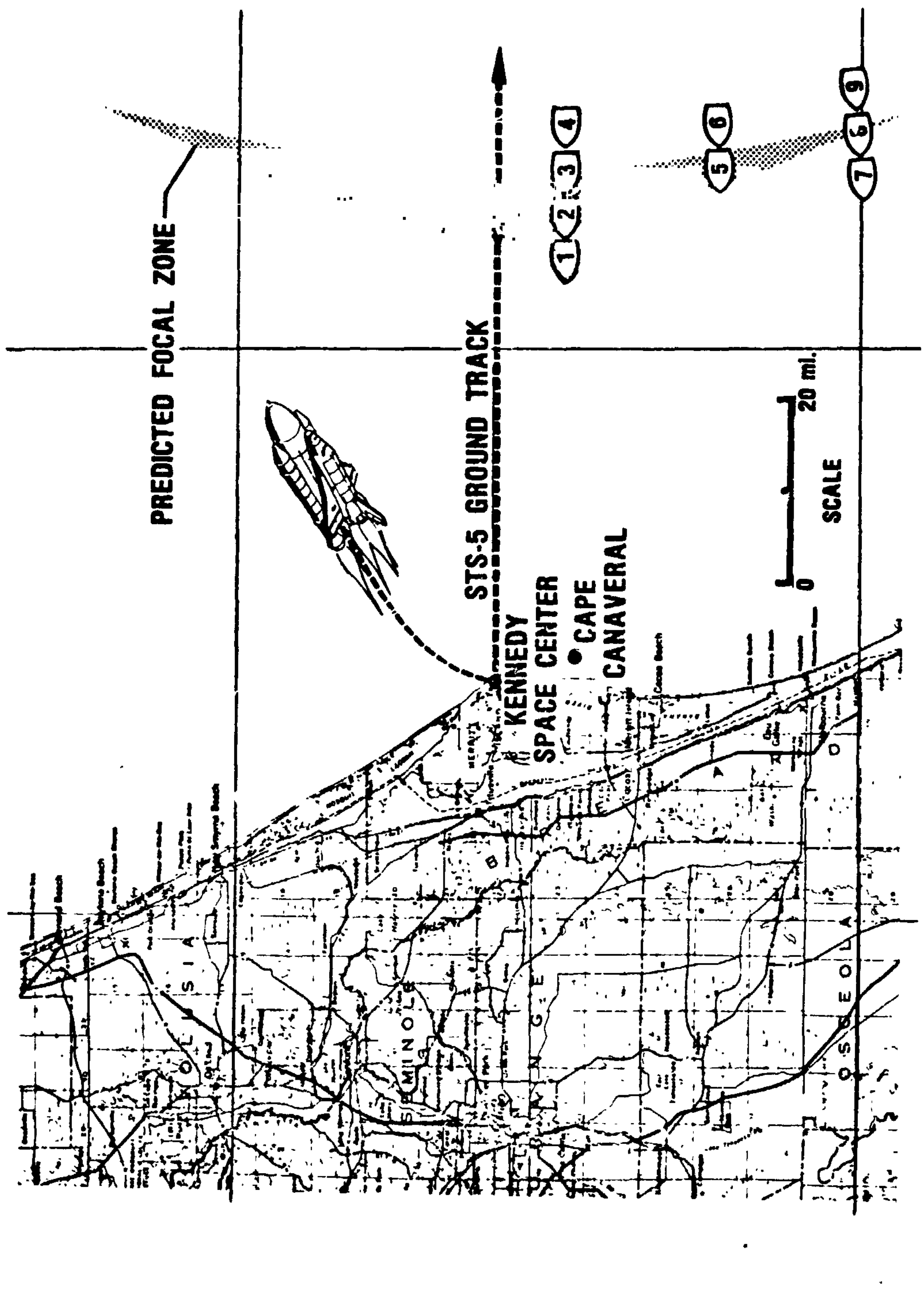

Figure 4.- Measurement station locations.

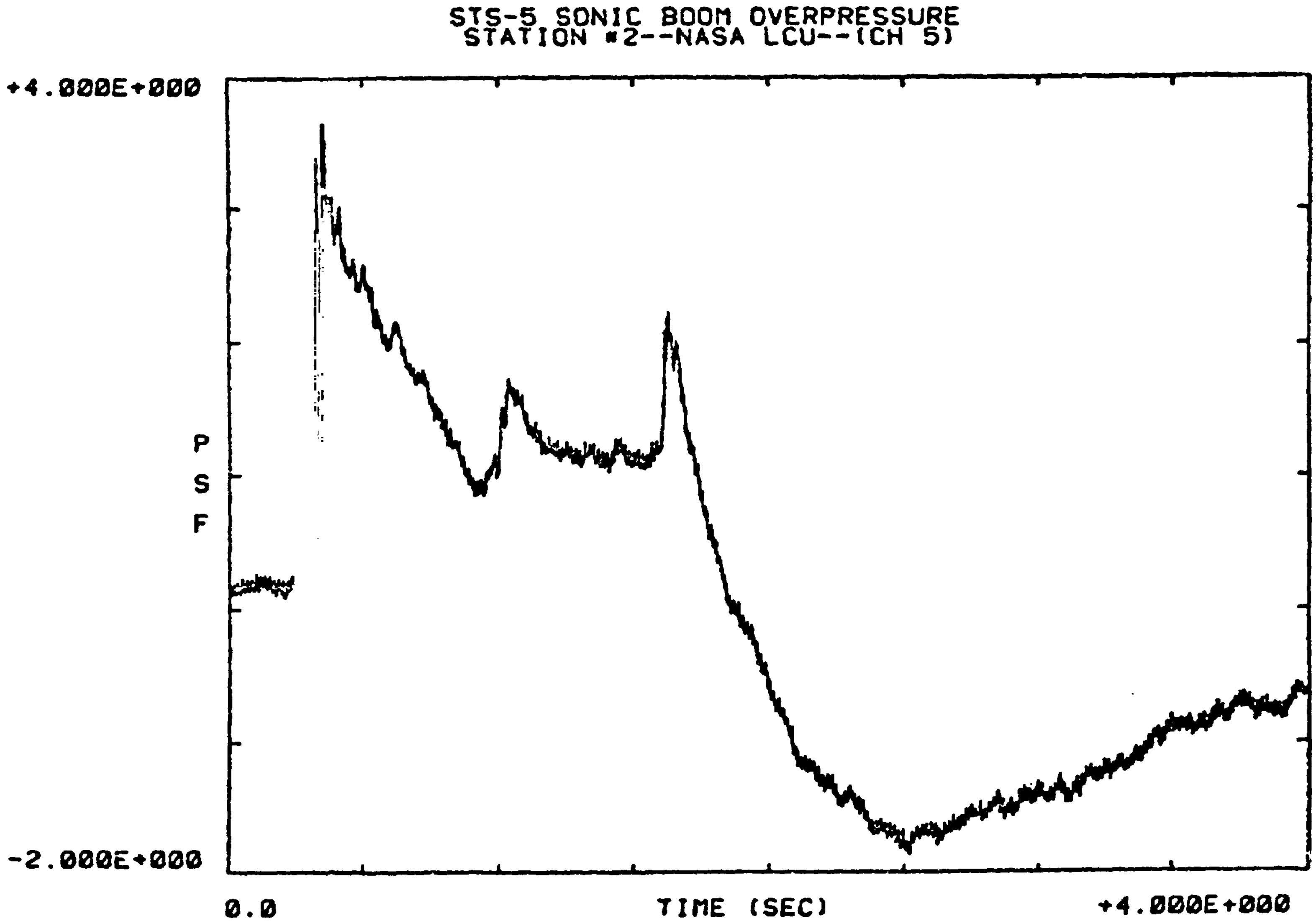

Figure 5.- Sonic boom signature of STS-5 launch recorded aboard a ship deployed about 38.7 n.mi. east of Cape Canaveral, Florida.

SHUTTLE-FOCUSED SONIC BOOM: THE NEED FOR DIRECT EVIDENCE

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INTRODUCTION

Space Shuttle launches from Vandenberg Air Force Base (VAFB), California, at or near the 150° launch azimuth, are likely to produce a 30-psf-focused sonic boom over the Northern Channel Islands (fig. 1). More specifically, the greatest impact of the boom will be on San Miguel Island. The Northern Channel Islands are considered a unique national resource. In addition to being a National Park and Wildlife Sanctuary, they harbor a unique assemblage of plants, animals, and cultural resources. The scientific community and regulatory agencies have an overwhelming 'sensitivity' to environmental perturbations likely to affect these resources.

REGULATORY PROCESS AND APPLICATIONS OF SCIENTIFIC DATA

Scientific judgement and analyses regarding the potential impact of sonic booms from Space Shuttle launches and landings over the Channel Islands are subject to regulatory review. Based on this review, agencies may grant a permit or make a determination as to whether this part of the Space Shuttle operation is in compliance with the 'protective intent' of federal and state statutes. Their rulings in the environmental review process could affect the outcome of the Department of Defence (DOD) proposal for launching the Space Shuttle from VAFB.

The U.S. Air Force (USAF) Shuttle Environmental Impact Statement developed under the National Environmental Policy Act (NEPA) provided a forum for the review and comment on the sonic boom problem by the public and regulatory agencies (ref. 1). A number of regulatory agencies under independent state and federal legislation required further review.

In considering the first regulatory requirement, the Endangered Species Act of 1974 and the Section 7 consultation requirement under the Act, the U.S. Department of the Interior (USDI) had to make a determination as to whether Shuttle launches and landings would jeopardize the continued existence of the Brown Pelican (Pelecanus occidentalis), an endangered species (ref. 2). The primary nesting site for the Brown Pelican is on Anacapa Island, northern-most island of the Channel Islands.

Our approach to answering the endangered species question, as well as those on other species, was to ask a number of biological questions that could be researched and applied to the Channel Islands ecosystems. The questions that were addressed are included in a report by Cooper and Jehl (ref. 3) in their assessment of the problem. In the Section 7 process, the USDI identified a number of research questions to be answered as a condition for making their determination (ref. 2). For all cases, indirect evidence had to be applied for potential effects on the species. The endangered Brown Pelican could not be used as an experimental animal because of its endangered status and a Space Shuttle sonic boom could not be closely simulated under field or laboratory conditions.

Application of indirect experimental evidence to the sonic boom biological effects problem can best be demonstrated by the following results. The potential for nesting Brown Pelicans to be adversely affected by sonic boom exposure was investigated in a simulation study by the Schreibers (ref. 4) exposing Brandt's Cormorants (Phalacrocorax pelagicus) to carbide cannon explosions. Birds became alert but did not take flight or behave in any way that would suggest nesting disruptions if exposed to a sonic boom. The data suggest that similar nesting Brown Pelicans might behave in a similar fashion to a sonic boom. In hatchability studies, Cogger and Zegarra (ref. 5) drew comparative conclusions using indirect evidence that hatchability in pelican eggs would not be affected by sonic booms based on results seen in domestic fowl eggs exposed to carbide explosions of 157 dB.

The USDI, drawing on the indirect evidence described above, made a determination that Space Shuttle launches and landings from Vandenberg would not jeopardize the continued existing of the Brown Pelican (ref. 2). While a weighting factor was not indicated in their determination, parametric studies (table 1) by Wiggins (ref. 6) indicating that sonic boom focusing was unlikely to occur over Anacapa Island from Vandenberg launches may have contributed significantly in their determination. It is important to note that the USDI, in this case, was only interested in the endangered species, not the ecosystem as a whole.

On the other hand, the scientific community has expressed concerns about the total ecosystem, especially the potential effects of focusing sonic booms on marine mammals. These concerns were that a focused sonic boom event is likely to cause stampeding in marine mammals resulting in high pup mortality during the pupping seasons.

Baseline environmental studies on San Miguel Island by Bowles and Stewart (ref. 7) showed some interesting occurrences of marine mammal stampeding in the natural environment. Using time-lapse photography and automatic noise monitoring equipment at San Miguel, marine mammals were shown to stampede (at least 50 percent of the animals rushing into the water) over a hundred times per year due to a variety of stimuli. Such responses could be associated with aircraft sonic booms, fixed wing aircraft, power boats, or natural environmental sources such as changes in ambient temperature. The stampede-triggering response was also noticed to occur without a detectable acoustic stimulus. No obvious mortality was associated with this activity.

More precise experimental studies were conducted by Stewart (ref. 8) on populations of northern elephant seals (Mirounga angustirostris) and California sea lions (Zalophus californianus) on San Nicolas Island to see if stampeding could be caused by a simulated sonic boom and what conditions might result. California sea lions were exposed to carbide cannon explosions during various stages of pupping activity. Although stampeding behavior did occur, no mortality or permanent mother-pup bond disruption was observed after exposing several populations. Elephant seals were generally unresponsive. This indirect evidence along with observations in the natural environment suggest that stampeding caused by the Space Shutt[illegible]ocusing boom may not result in extens[illegible] mortality due to trampling or disruption of mother-pup association.

The applications of scientific data regarding the potential effects of sonic booms on the Channel Islands have undergone its most thorough review by the California Coastal Commission. Under the Coastal Zone Management Act, the Coastal Commission made a 'finding of consistency' with the state's Coastal Zone Management Program for the Shuttle project. A major issue in their deliberation was the effects of focusing sonic booms and whether launches over San Miguel Island should be restricted to avoid sensitive breeding periods for marine mammals (table 2). The Coastal Commission and the USAF agreed (ref. 9) that the sensitive breeding period would be defined as 'May through July' with special consideration for launch windows between peak pupping activities in March and April. This restriction applies to the first launch over San Miguel Island unless vital national security requirements preclude an alternative date or flight trajectory to avoid launching over San Miguel. This restriction for subsequent flights would not apply if monitoring data and review by the scientific community show that such restrictions are not warranted. The Executive Director of the Coastal Commission will coordinate the review of the results of the initial launch for all state resource agencies. These restrictions were placed and agreed to because there is lack of 'direct evidence' regarding the potential effects. The scientific community would not rule out the potential for unacceptable impacts based only on 'indirect evidence.'

SONIC BOOM MEASUREMENTS PROGRAM

Ascent and descent sonic boom measurements during initial Space Shuttle flights will allow the National Aeronautics and Space Administration (NASA) and the USAF to verify sonic boom model predictions. These predictions, now being used, are a part of the 'indirect evidence' problem of potential focusing sonic boom effects over the Channel Islands. Conclusions regarding biological effects (ref. 10), especially physiological and anatomical, are largely based on the focused boom not exceeding 30 psf and generating mostly low frequency energy. Verification of these models will add to the credibility of predictions or a revision of impact predictions. The USAF and NASA will conduct ascent sonic boom measurement programs for at least two launches from the John F. Kennedy Space Center (KSC).

VERIFICATION OF THE CHANNEL ISLANDS IMPACTS

The USAF could be well into the operation of the Space Shuttle program at VAFB before there is 'direct evidence' of the impacts of Shuttle launches over the islands. Only a small fraction of the launches are expected to cause focusing over San Miguel Island. Also, the intense focal region (1,000 ft wide) may not occur on a region of the island (San Miguel) occupied with the species of concern (figs. 1 and 2). Depending on the launch schedule, such a flight may also occur during the time of year when observational data will contribute very little to understanding the effects of the focusing boom on sensitive breeding activities. Again, the scientific community may not have available the 'direct evidence' it requires to rule out unacceptable impacts.

Population information on the marine mammal species will be gathered and evaluated prior to the first launch over San Miguel to ensure that the effects on the population can be determined. Scientists (ref. 11) predict that major changes in marine mammal populations may occur as they expand on the islands in the 1980's. Such changes may correspond in time to an increase of Space Shuttle sonic booms over the islands from launches and landings at Vandenberg but be associated with other ecological and environmental conditions outside of Space Shuttle influences. Animal activities resulting from a focused sonic boom will be recorded as well as the sonic boom characteristics impinging on San Miguel Island. The results of these evaluations will be submitted for review and comments from the regulatory agencies. Future restriction considerations regarding launches over San Miguel Island must await that evaluation of the "direct evidence."

CONCLUSIONS

Studies conducted so far indicate that the potential for adverse impact on the Channel Islands from focused sonic booms is low. The infrequent number of potential exposures because of a few launches rule out cumulative impacts. Only direct evidence will conclusively answer the sonic boom questions. It is unlikely that the evidence will be available until late in the operational life of the Space Shuttle program at VAFB.

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10. Chappel, Mark A.: Possible Effects of Space Shuttle Sonic Booms on Marine Mammals. Chapter 7, TR 80-1, Center for Marine Studies, San Diego State University, California, December 1980.

11. Cooper, Charles F.: The Perils of Success: Implications of Increasing Marine Mammal Populations in the Southern California Right. Ocean Study Symposium, Nov. 1982.

TABLE 1.- SUMMARY OF SONIC BOOM OCCURRENCE PROBABILITIES[a]

[Ninety-percent confidence limits are shown in parentheses; probabilities are based on sample sizes of 106.]

Region	Launch azimuth		
	150°	180°	193°
	Focal region		
Channel Islands	0.96 (0.92-0.99)	0.09 (0.05- .15)	0.00 (0.00-0.03)
San Miguel	.81 (.72- .86)	.06 (.02- .11)	.00 (.00- .03)
Santa Rosa	.15 (.10- .22)	.06 (.02- .11)	.00 (.00- .03)
Santa Cruz	.08 (.04- .13)	.00 (.00- .03)	.00 (.00- .03)
Anacapa	.00 (.00- .03)	.00 (.00- .03)	.00 (.00- .03)
	Sonic boom footprint		
Channel Islands	1.00 (0.96-1.00)	0.09 (0.05-0.15)	0.00 (0.00-0.03)
San Miguel	0.86 (.79-0.91)	.06 (.02- .11)	.00 (.00- .03)
Santa Rosa	1.00 (.96-1.00)	.08 (.04- .14)	.00 (.00- .03)
Santa Cruz	1.00 (.96-1.00)	.00 (.00- .03)	.00 (.00- .03)
Anacapa	0.98 (.94-1.00)	.00 (.00- .03)	.00 (.00- .03)

[a]Source: Haber, 1981 (ref. 6)

TABLE 2.- PUPPING SEASON FOR MARINE MAMMALS

Marine mammal	Pupping season date
California sea lion	May 20 - August 1
Steller sea lion	May 20 - August 1
Northern elephant seal	December 20 - February 20
Harbor seal	February 26 - May 1
Northern fur seal	May 20 - August 1

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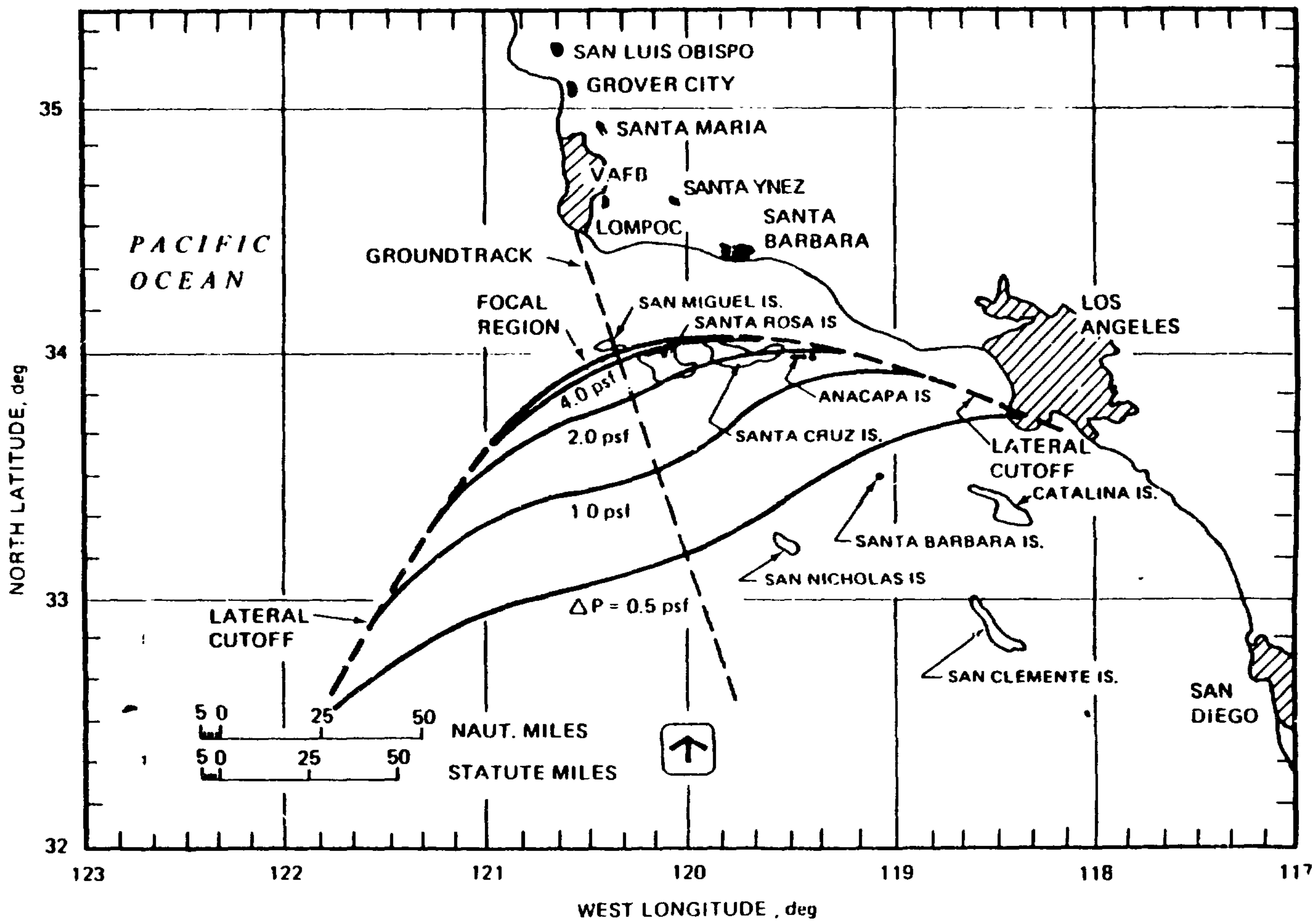

Figure 1.- Predicted sea level footprint of sonic boom overpressures resulting from VAFB Shuttle launches from SLC-6 for a 150° azimuth.

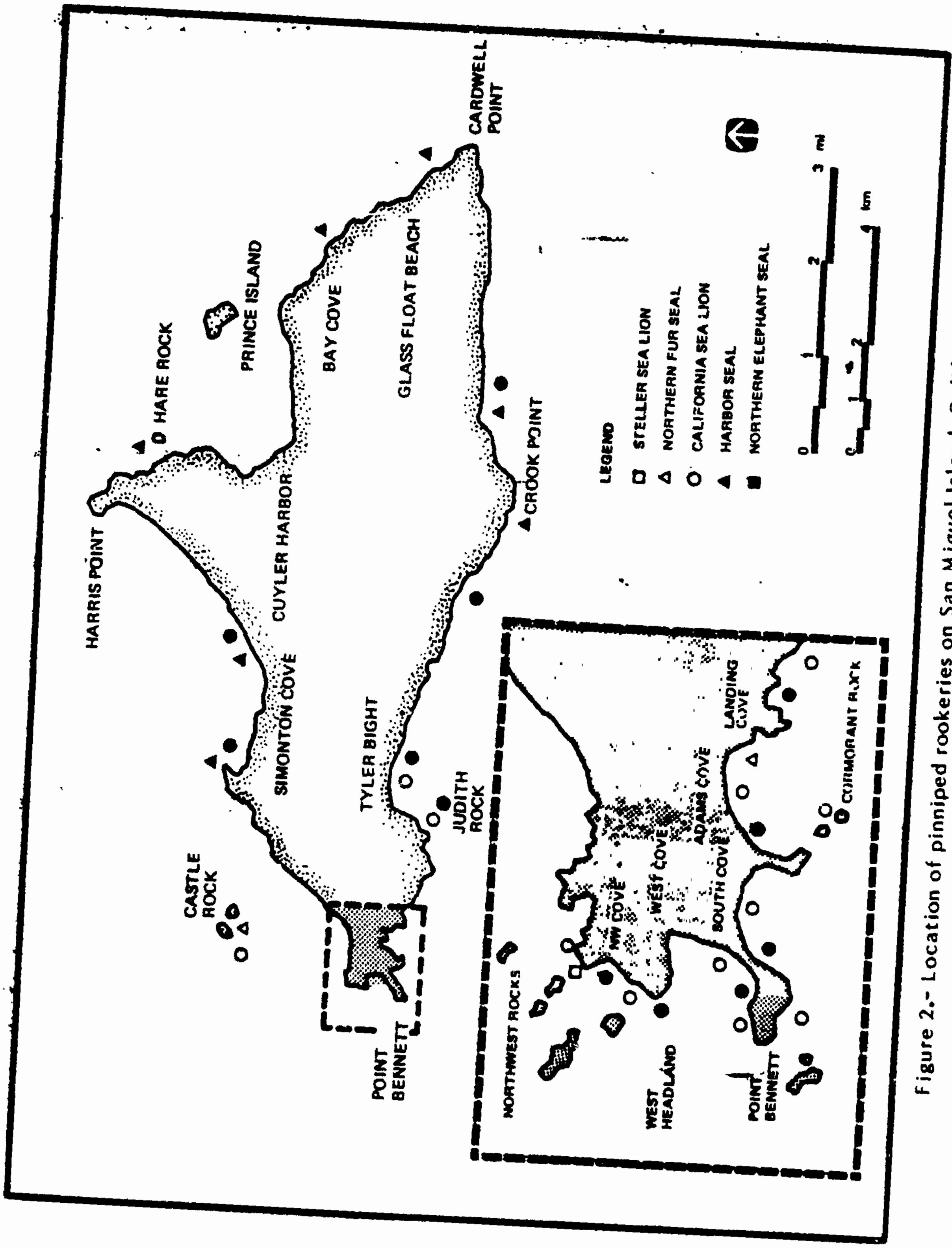

Figure 2.- Location of pinniped rookeries on San Miguel Island, California.

LONG-TERM MONITORING PLANS

- FUTURE PLANS FOR ENVIRONMENTAL MONITORING AT KSC
  Knott and Koller
- VANDENBERG AIR FORCE BASE BIOLOGICAL MONITORING PLAN
  Wooten

FUTURE PLANS FOR ENVIRONMENTAL MONITORING AT KSC

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NASA - John F. Kennedy Space Center, Florida

INTRODUCTION

Recommendations for environmental monitoring activities at the John F. Kennedy Space Center (KSC) which are to be conducted in association with future STS launches are outlined below.

The analysis of data collected by KSC personnel provide the basis for these recommendations which are intended to solve several problems in fully understanding Space Shuttle launch effects. For example, no severe acute effects have been noted except at the launch pad; however, there is good evidence for downrange deposition and the possibility of long-term chronic effects. A better understanding of the characteristics of the launch cloud and study of subsequent deposition are expected to provide a better understanding of the potential effects. Under the present experimental design, inconsistencies in the water, soil, and sediment chemistry at the pad necessitates further sampling to delineate launch-caused changes. Prelaunch and postlaunch monitoring alone has not provided the data necessary to evaluate chronic effects; it is necessary to integrate specific monitoring of the event with a broader center-wide KSC program to allow the segregation or launch-caused changes for contrast with the natural changes.

RECOMMENDATIONS

The major areas of monitoring and respective recommendations for each area are as follows:

1. Launch cloud characteristics
   - Photographically document the exhaust cloud at each launch
   - Correlate ambient meteorological data with cloud characteristics
   - Collect data needed to refine predictive model
2. Ground-level gaseous measurements
   - Restrict to pad area to locate source of HCl
3. Water, sediment, and soil chemistry
   - Determine change in deluge water over time
   - Clarify water, sediment, and soil chemistry at the pad
   - Determine long-term effect of exhaust cloud on soil, water, and sediments
4. Particulates and deposition measurements
   - Restrict particulate measurements to pad at postlaunch
   - Footprint acidic deposition and verify pH
   - Modify the model so that it accurately predicts the deposition
5. Acoustic noise measurements
   - Measure acoustic noise at two sites
6. Biota
   - Determine long-term effect of exhaust cloud on vegetation

- Integrate launch monitoring with long-term monitoring and collect statistically comparable data from established sites

7. Personnel experiences

   - Continue to monitor, document, and interview personnel exposed to downrange cloud deposition

VANDENBERG AIR FORCE BASE BIOLOGICAL MONITORING PLAN

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INTRODUCTION

Biological monitoring incorporates regular use of biological assessment methodologies to determine the influence that potential environment hazards may have on the affected system. The assessment of a potential pollutant, or stress, is generally based on indicator species or the species diversity of an ecological system. Floral and faunistic species respond to their total environment and the stress applied to that environment; they can measure acute, chronic, cumulative, and synergistic effects of pollutants and/or stresses introduced into the receiving ecological system, and can also document natural ecological changes independent of man-imposed stress. The development of a biological monitoring system for Vandenberg Air Force Base (VAFB) is the logical result of three factors: the uniqueness of the area as an ecological transitional zone; its existence as one of the few undeveloped natural areas in coastal California; and the extraordinary level of U.S. Air Force (USAF) activity (e.g., STS, M-X, Minuteman) conducted at the base. The objective of the Biological Monitoring Plan (BMP) is to determine, define, and measure potential environmental stresses applied to VAFB ecosystems. Additional use of this program will be to provide assistance in the development of pollution abatement and/or mitigation procedures when necessary.

CONCEPT

Environmental pollutants, which vary in toxicity and concentration, can exert severe, immediate impacts on ecosystems which result in death of many floral and faunistic species. These impacts are readily documented, and causative factors can generally be defined with a high degree of confidence. However, pollutants are generally insidious, and the sublethal, chronic effects can be widespread and persistent. Chronic effects are often difficult to detect, but over the long term can severely impact species by disrupting or reducing physiological processes, behavior, growth, and reproduction. Ecosystems often cannot readily adapt to stresses imposed by exotic materials or influences, and instabilities introduced into these natural systems can result in the development of less desirable ecosystems.

A BMP can document and evaluate short-term, severe impacts and provide recommendations to preclude further damage; such a plan can also investigate long-term, chronic effects and provide similar information. Utilization of this BMP will provide 'real-time' estimates of hazard risks and enable the monitor to differentiate between natural ecological changes and man-induced changes. The BMP will provide, in essence, an 'early warning system' against toxic or hazardous elements introduced to the area ecosystems.

Proposed actions and events for the Vandenberg area will be preceded by environmental assessments or impact statements. These assessments provide estimates of the nature, severity, and duration of impacts resulting from proposed actions (e.g., Space Transportation System (STS) Environmental Impact

Statement (EIS), hypergolic storage EA, etc.]. The BMP provides for the monitoring of activities during both construction and operational phases to determine acute and chronic impacts.

The BMP is composed of four monitoring schemes developed to adequately determine USAF activity impacts on area ecosystems. Those are: (1) establishment of an ecological baseline; (2) long-term, chronic, and cumulative monitoring; (3) short-term, action, and specific monitoring; and (4) endangered species monitoring.

DETERMINATION OF ECOLOGICAL BASELINE

A species survey was accomplished by the center of Environmental Studies, San Diego State University, California, during 1974-1975 (Ecological Assessment, Vandenberg AFB, 1975). This survey provided quantitative and qualitative documentation of the biotic and abiotic conditions present in the VAFB area from August 1974 to June 1975. Also included in the study was the development of a computer-based environmental planning system. This survey will be reaccomplished in 1984-85, just prior to the first STS launch at VAFB and will be programmed to occur every decade. This will assist in differentiating impacts due to USAF activities from natural changes. It will also become a part of the long-term component to the BMP.

THE LONG-TERM COMPONENT

This component will measure those impacts which may not be readily apparent as acute or immediately damaging, but may be ultimately harmful over the lifetime of a specific activity. Separating man-induced changes from natural changes can be difficult; vegetative indicators, reference stands, and remote sensing procedures will be utilized to document man-influenced environmental impacts in the area.

Plant species were selected as indicator organisms because they are often sensitive to air pollutants, have characteristic responses to particular pollutants, are stationary, and are relatively easy to inspect and maintain. The selected floral species are indiginous to the Vandenberg area (table 1).

The following considerations were applied for selecting these indicators: toxicant response, plant sensitivity, ecological significance, economic importance, distribution, abundance, and consistency of response.

Transects will be located in each of the major vegetation types. All transects will be read on a 10-year cycle and can be incorporated into the 10-year base-wide ecological inventory. Several selected transects will be surveyed every 2-3 years. Selection of the indicator transects will ensure that some are located near proposed activities (i.e., M-X, STS) and some are removed from activity areas. Comparison of changes between reference stands in affected areas and away from these areas will provide a gauge of any man-produced environmental impacts. This can be a difficult determination; the 'controls' are actually not isolated from all of man's influences. Any changes in species compositions or numbers must be measured in conjunction with both natural environmental factors; e.g., rainfall, fire, pest infestation, and etc., and man-induced effects such as construction, 10 to 15 STS launches per year, or frequent spills of hypergolics. In addition to the basic composition sampling of the major vegetation types, the range management areas will be sampled on an annual schedule as a requirement of the grazing leases. This sampling will be coordinated with the range conservationist and incorporated into the long-term monitoring.

Two plant species have been identified in the Vandenberg area as special interest plants. These are the Lompoc Yerba Santa, Eriodictyon capitatus, and Surf Thistle, Cirsium rhothophilum. A permanent transect will be established in areas where these species occur, and these transects will be surveyed every 2 to 3 years.

Composition sampling of all construction sites that have received revegetation treatments will be accomplished annually with an analysis made of native plant reestablishment.

Remote sensing techniques will provide overall documentation of floral changes in the area. Native vegetation will be photographed using high altitude photography every 2 years. Vegetation will then be mapped and analyzed for long-term effects.

Monitoring of faunistic species concentrate primarily on endangered and special interest organisms and their habitats. Methodologies will be developed to meet the requirements identified by the U.S. Fish and Wildlife Service in Biological Opinion written in response to the USAF's request for formal consultation, pursuant to Section 7 of the Endangered Species Act of 1973, as amended (PL 95-632). Protocol for monitoring each of the seven endangered species identified by the U.S. Fish and Wildlife Service is given in table 2.

MONITORING FOR SHORT-TERM, ACTION SPECIFIC EFFECTS

This component of the BMP will determine acute environmental impacts which may result from specific events associated with the various activities. Indigenous plant species will serve as the indicator organisms. Transects will be established near all launch sites in areas most likely to be impacted. Launch impacts generally include noise, heat, and exhaust cloud products. Launch effects from recent STS launches at the John F. Kennedy Space Center (KSC) have demonstrated impacts more severe than initially anticipated.

An unexpected impact resulting from STS launch exhaust products was the formation of acid-coated aluminum particles. These particles had measured pH values of approximately 1.0. When deposited on foliage, the acid particles produced damage ranging from total plant destruction to necrotic spotting. In the KSC area, this damage occurred up to 8 mi to 9 mi distant from the launch pad and resulted in minor environmental impacts. However, the Vandenberg area is considerably different from the KSC area in that heavy agrarian interests are in close proximity to the launch areas.

These concerns have resulted in the initiation of a toxicology research project to determine the effects of designated pollutants on plant species. The specific aims of this project are to identify and characterize $HCl\text{-}Al_2O_3$ acid deposition injury to plants; verify past occurrences of this pollution; and define the nature and mode of action of the deposition. Selected plants are those which occur in the Vandenberg area and represent agrarian interests. This project should be completed by fall of 1983, and project results will be incorporated into the BMP at this time.

Plant species will serve as the indicator organisms for this monitoring scheme. Transects will be established near all launch sites in areas most likely to be impacted by launch activities. Coordination will be made with USAF Weather personnel to determine likely directions of winds. Launch impacts are most likely to involve noise, heat, and exhaust cloud products (acid deposition). The vegetation types and associated indicator species listed in table 1 will be surveyed immediately prior to and after (twice over a 48-hour period) each launch for the first 2 years. The need for additional sampling will be determined at the end of 2 years of launches.

The two special interest plants, Lompoc Yerba Santa and the Surf Thistle, will be monitored during the first 2 years to measure potential launch impacts. The permanent transects established for long-term monitoring will be used.

Faunistic concerns of short-term biological monitoring primarily involve threatened and endangered species and their habitats. The six species identified as endangered on VAFB and recommendations for their monitoring needs will be similar to the described long-term monitoring.

STS operations are not expected to significantly impact the survival of the following endangered species on VAFB: Southern Sea Otter, California Condor, California Brown Pelican.

The American Peregrine Falcon was reported by the U.S. Fish and Wildlife Service as "likely to be an area visitor to the base." However, more recent surveys of the American Peregrine Falcon and its potential habitat on Vandenberg indicate there may be a greater probability of this species being in the STS area during a launch. Short-term monitoring of this species will take into consideration that birds may be present near the STS area in the near future and monitoring protocol should be developed accordingly. This effort will be coordinated with the U.S. Fish and Wildlife Service and the California Department of Fish and Game.

The California Least Tern (Sterna albifrons browni) will require specific monitoring needs during the construction and operational phases of the STS program. During construction of the STS testing facilities, designated Environmental Control Officers will be scheduled to be onsite at all times to oversee the implementation of erosion control. When STS construction is complete, base personnel will be responsible for continued monitoring of this area.

During the operational phase of the STS program, one monitoring concern is the effects that launches will have on the nesting least terns. Since the terns nest in different areas (within the mapped habitat on Vandenberg) from year to year, the monitoring scheme should remain flexible. Protocol will include strategically locating instrumentation for monitoring pressures and sound levels, visual behavior information, and climatic data near a nesting site during an STS launch. In addition to monitoring the first STS launch, the first launch that occurs during the least tern nesting season will be monitored. If there are no significant impacts observed, then two more STS launches will be monitored during the nesting season. If there are no significant effects observed during the three STS launches monitored during nesting season then the monitoring program can be reduced significantly in this area. Throughout this monitoring effort, USAF personnel will coordinate with the U.S. Fish and Wildlife Service in "determining levels of significance of least tern behavorial reactions." If significant adverse impacts are observed during STS launches, the U.S. Fish and Wildlife Service recommends: "discontinuing launches during the tern nesting season as per the Biological Opinion."

The Unarmored Threespine Stickleback (Gastroesterus aculeatus williamsoni), an endangered fish species, will be closely monitored during STS activities.

The construction and operational phases of the STS program have the potential for degrading essential habitat for the Unarmored Threespined Stickleback. The U.S. Fish and Wildlife Service has made several recommendations for monitoring of M-X construction and operations which will be applied to STS activities.

During construction, a water quality monitoring scheme was planned and implemented by Martin-Marietta Corporation. This monitoring scheme involves regular sampling of the San Antonio Creek at several locations and includes sampling all of the recommended parameters. Refer to the water quality monitoring plan prepared by Martin-Marietta Aerospace for exact locations.

Following construction, sampling should be reduced to a lower frequency to monitor the exhaust cloud and sewer system effluents. This sampling will occur 1 day before, immediately following, and 1 day after an STS launch. Parameters to be measured will include turbidity, pH, dissolved oxygen, temperature, nitrates, phosphates, chloride, and cloriform bacteria.

During both construction and operational phases of the M-X program, the U.S. Fish and Wildlife Service and the California Department of Fish and Game will be consulted in reviewing all water quality data from San Antonio Creek.

Sonic booms produced by STS launches are considered to have potentially deleterious effects on indigenous fauna. Launch path configurations may focus sonic boom overpressures in a narrow area partially impacting on the Channel Islands. These islands provide habitats to several species of birds and marine mammals. A recent study by San Diego State University and Hubbs Sea Worlds (Tech. Rpt. 80-2 for USAF Space and Missile Systems Operations) indicates little, if any, damage is expected to occur to these organisms. However, the USAF will take a census of selected areas for certain bird and pinniped populations before and after the first several launches. During the first launch, observations (via onsite observations or time lapse photography) of behavorial reactions to the launch will be attempted. These observations will determine later needs for monitoring or mitigating procedures.

ENDANGERED SPECIES

There are several species in the Vandenberg area considered rare, endangered, or threatened. Special monitoring plans for species in these categories will not be developed at this time; however, both short- and long-term monitoring programs will include schemes to identify and monitor special category species and their habitats.

SUMMARY

The Biological Monitoring program at Vandenberg was developed to protect an environmental and ecological region subjected to a high level of USAF activity. Implementations of the BMP are necessary to provide the following:

1. Early warning of environmental deteriorations in affected areas.
2. Quantification and documentation of acute impacts followed by decision as to acceptability of damage and mitigation necessary.
3. Hazard assessment to determine true commercial loss for restoration and compensation when appropriate and to protect against unwarranted litigations.
4. Determinations of future monitoring needs.
5. Definitions of environmental quality of the region.

6. Establishment of pollution indices to ensure compliance with state and federal regulations, assist in development of abatement priorities, and assess efficiency of present environmental quality policies.

The level of interest in STS operations at VAFB is high, and we are presently coordinating with more than nine state and federal agencies. Several concerns have been expressed including sonic booms, acid fallout, water quality, ocean dredging, and wetlands protection. We believe that all concerns and questions will be adequately addressed, and we are confident our monitoring plan will afford the environment and the necessary amount of protection without applying undue constraints to Space Shuttle operations.

TABLE 1.- VEGETATION TYPES AND INDICATOR SPECIES IN THE VANDENBERG AREA

Type stand	Indicator species
Bishop Pine Forest	Pinus miricata
Tanbark Oak Forest	Lithocarpus densiflora
Foothill Woodland	Opercus agrifolia
Riparian Woodland	Salix caseolepis
Chaparral	Arctostaphylos viridissima Ceanothus impressus
Coastal Sage Scrub	Artemisia californica Salvia mellifera

TABLE 2.- MONITORING PROTOCOL OF THE SEVEN ENDANGERED SPECIES LOCATED AT VANDENBERG AIR FORCE BASE (VAFB)

[Identified by the U.S. Fish and Wildlife Service]

Species	Monitoring protocol
Southern Sea Otter (Enhydra lutris nereis)	Otters have been observed near Point Sal and the Boathouse area during 1981 and 1982; however, USAF activities are not expected to preclude use of the marine waters off VAFB by the otters. Protocol will include monthly surveys on the status of the sea otter population on VAFB. The surveys should include several hours of observation from strategic locations between Point Sal and Point Arguello.
California Condor (Gymnogyps californianus)	The probability of this species being impacted by USAF operations is very low. No monitoring requirements are planned other than maintaining coordination with the California Department of Fish and Game and the U.S. Fish and Wildlife Service on progress of the condor's recovery efforts.
California Brown Pelican (Pelecanus occidentalis californicus)	The California Brown Pelican is not expected to be significantly impacted. However, long-term monitoring of this species at Vandenberg will include periodic observations of the pelicans' traditional roosting sites between Point Arguello and Point Sal with the purpose of documenting trends in use of the roost areas.
American Peregrine Falcon (Falco peregrinus austeum)	The Peregrine Falcon is expected to be a more permanent inhabitant of Vandenberg due to several areas of highly favorable habitat. The U.S. Fish and Wildlife Service indicated that the peregrine is "likely to be a very rare visitor to the Base." However, a more recent survey indicates there have been more frequent observations than previously reported on South Vandenberg. Management goals will be planned to establish one or more breeding pairs on or near the base either by natural means or with a hacking program. This species should be considered in all biological monitoring efforts on Vandenberg. Long-term monitoring will include annual surveys to determine the status of this species on the base. The California Department of Fish and Game and the U.S. Fish and Wildlife Service will be contacted and coordinated with to determine the type and degree of surveillance needed.

TABLE 2.- CONCLUDED

Species	Monitoring protocol
California Least Tern (*Sterna albifrons browni*)	Long-term monitoring of the California Least Tern will include an annual survey of all potential nesting habitats. This survey will be coordinated with the California Department of Fish and Game and the U.S. Fish and Wildlife Service to determine specific surveillance needs. Past surveys have included weekly visits to the nesting sites to make population estimates of breeding pairs and reproductive success.
Unarmored Threespined Stickleback (*Gastroesterus aculeatus williamsoni*)	The long-term effort will include a review and analysis of water quality data. Also, biological surveys of the San Antonio Creek areas will be initiated in February 1983, with emphasis placed on *Gastroesterus aculeatus*, the Tidewater Goby, the Least Bells' Vireo, and other special interest plant and animal species. Vegetation will be monitored to detect changes in species composition due to aquifer overdraft or introduction of pollutants to the systems.
Deer	Although deer are not considered endangered, deer/human conflicts may intensify with further Vandenberg development. Increased USAF activities will result in decreased deer habitat and increased deer populations due to closure of hunting areas. Proper management of the area deer herds will require a comprehensive life history analysis. This study will include management recommendations to avoid or reduce human/deer conflicts and also to prevent range deterioration resulting from over population.