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ABSTRACT

Salt concentrations on airfoils of compressors of commercial and military gas tur-
bine engines removed from aircraft for overhaul were measured and compared to con-
centrations reported to cause stress-corrosion damage in laboratory tests. Concentra-
tions in small local areas were determined, as well as the average concentrations for
entire airfoils or for the concave or convex sides alone. Qualitative distributions of salt
on airfoils were obtained with contact prints. Average salt concentrations from engines
used for long transoceanic flights (a relatively mild exposure) exceeded 0.1 mg/in.^{2}
(0.015 mg/cm^2). Local concentrations more than 10 times as great were found on some
blades.

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OF FLIGHT GAS TURBINE ENGINES

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SUMMARY

A field sampling program was undertaken to obtain first-hand data regarding the amounts of salt deposited on the airfoils of flight gas-turbine engines. Salt concentrations on the airfoils of compressors of commercial and military engines were measured from samples taken at several overhaul depots. It was found that a large commercial engine from a plane that had made many landings on an island in the Bahamas shortly before overhaul had a concentration over the entire surface of a stator vane that exceeded 0.66 milligram per square inch (0.10 mg/cm^2) and was greater than 1.0 milligram per square inch (0.15 mg/cm^2) on the concave side. The average concentration over the entire surface of a blade exceeded 0.18 milligram per square inch (0.03 mg/cm^2) and was greater than 0.3 milligram per square inch (0.05 mg/cm^2) on the concave side. Engines used under less severe conditions of exposure (transoceanic flights such as from New York City to London) had average salt concentrations over the entire airfoil surface of both vanes and blades from some stages that exceeded 0.1 milligram per square inch (0.015 mg/cm^2). Moreover, local concentrations as much as 10 times the average concentration were measured on compressor blades for various exposure conditions.

The salt concentrations observed in this field sampling program are considerably in excess of the least reported amounts (e.g., 0.05 and 0.033 mg/in.^{2} (0.008 and 0.005 mg/cm^2)) shown to have caused embrittlement of titanium alloys subjected to certain combinations of stress, temperature, and exposure time in laboratory tests. However, the relevance of laboratory tests to the behavior of titanium in an engine is as yet not well defined. Although no service failures due to hot-salt stress corrosion have been reported, there is concern that this may become a major problem with titanium alloys, particularly at the higher temperature and stress levels desired in advanced-design engines.

INTRODUCTION

In gas-turbine engines, great savings in weight can result from the use of titanium, particularly in the rotating parts of compressors. Current flight engines already use some titanium components in the early stages of the compressor, and it would be extremely desirable from the standpoint of saving weight to use titanium in as many stages as possible in compressors of advanced design engines. Such engines must operate at higher compressor pressure ratios and temperatures than present engines. This requirement results in a strength limitation that restricts the use of titanium. There may be another limitation, however, that is not as readily definable. It stems from the possibility that hot-salt, stress-corrosion cracking may occur.

Laboratory tests have revealed that prolonged exposure of titanium alloys to both stress and temperature in the presence of salt (sodium chloride and other halides) can cause stress-corrosion cracking (refs. 1 to 3). The higher the temperature for a given stress, the greater the likelihood that the threshold for cracking will be exceeded. Virtually all laboratory tests to date have been conducted in stationary air environments, and the relevance of laboratory tests to the behavior of titanium in an engine is not well defined. It is known, however, that the necessary combinations of stress and temperature for hot-salt, stress-corrosion cracking (on the basis of available laboratory test data) exist in the titanium components of current aircraft turbine engines. Although no service failures from this cause have been reported to date, there is concern that titanium hot-salt, stress-corrosion cracking may become a major problem, particularly at the higher stresses and temperatures anticipated in advanced engines.

Because of the concern over the possible occurrence of hot-salt, stress-corrosion cracking, it has appeared desirable to survey the amount of salt present in flight engines exposed to various salt-air environments. General Electric Company, Lynn, Massachusetts conducted such a survey and found average salt concentrations on a given compressor blade as high as 0.2 milligram per square inch (0.03 mg/cm^2) (private communication from L. P. Jahnke). In order to obtain first-hand data regarding the amounts of salt deposited on the airfoils of a variety of flight engines, a field sampling program was also undertaken by NASA. The purpose was (1) to establish whether the amounts of salt present were sufficient, on the basis of existing laboratory data, to justify concern for the safe operation of engines that have titanium alloy parts operating at high temperatures and stresses and (2) to determine the levels of salt concentration to use in laboratory tests that are intended to simulate engine operating conditions. Salt concentrations on the airfoils of compressors of commercial and military gas turbine engines were measured from samples taken at several overhaul depots. The average concentrations over the entire airfoil, or over the concave and convex sides separately, were determined, as were the salt concentrations in small localized areas. A qualitative picture of the salt distribution (salt prints) over the surfaces of selected airfoils was

also obtained. The results of the salt concentration measurements were compared on the basis of the severity of the exposure to which the engines had been subjected. The type of routes flown and number of flights in the last 100 hours before overhaul were used as a measure of the severity of exposure.

SAMPLING PROCEDURE

Salt samples were taken from flight engines being disassembled for overhaul. These samples were taken at two Navy installations - Quonset Point Naval Air Station, Rhode Island, and the Naval Ship Engineering Center in Philadelphia, Pennsylvania - and at two commercial airline overhaul depots - Eastern Airlines in Miami, Florida, and Pan American World Airways at John F. Kennedy Airport, New York, New York.

Engine Exposure Conditions

Table I lists, in order of decreasing severity of exposure to salt laden environments, 12 engines that were sampled for salt deposits. All the engines, except an FT4A, were removed from aircraft for overhaul. The flight engines sampled included five JT3D's, three JT8D's, two JT4's, and one T58. The ranking is based on the types and number of flights flown in the last 100 hours of service. These flights have been divided into five categories, which are, in order of decreasing severity, short over water, tropical zone; transoceanic to tropical points; short over water, temperature zone; transoceanic, temperate zone; and inland. The ranking of flight categories is based on the assumptions that the severity of exposure decreases with increasing altitude and increases with increasing humidity. Table I also shows the engine model number, serial number, and the type of aircraft from which each engine was removed.

The flight logs were available for all but one of the commercial aircraft listed, and that plane was known to have been in local Caribbean service. There was no record of whether any of the engines had been "washed" by flying through rain. It was, however, known that the JT8D engine (no. 649184) from the aircraft whose log was not available had been washed with fresh water as part of a routine maintenance schedule 194 hours before overhaul. As far as could be determined, none of the other commercial engines had been washed.

The FT4A, which is a free turbine version of the JT4, had been washed 5 hours prior to inspection. It was used in a land-based Navy rig simulating operation as a shipboard auxiliary power unit, and it was the only engine for which the exact amount of salt being ingested was known. The intake air to this engine contained 0.003 ppm sea

TABLE I. - SALT EXPOSURE CONDITIONS FOR ENGINES SAMPLED

Engine		Aircraft	Flight categories, decreasing severity (a)					Total flights over water	Predominant service or most severe exposure	Severity of environment
Model	Serial number		S	T	W	O	I			
			Number of flights in last 100 hr or since last wash							
T58	200430	SH3A	----	--	1	--	--	1	One hr hover 40 ft (12.2 m) over Atlantic (0.035 ppm sea salt est.)	Severe
JT4	611551	DC8	>100	8	12	--	20	120	Landing practice in Bahamas	
JT3D	642209	720	----	27	15	--	--	42	U.S. to San Juan	Intermediate
JT3D	643358	707	----	18	4	6	1	28	Transoceanic to tropical points	
JT8D	653743	727	----	--	26	--	66	26	Northeast coast to Miami	
JT4	611025	DC8	3	5	3	12	16	23	Caribbean Island routes	
JT8D	649184	727	----	--	--	--	--	--	Caribbean Island routes	
JT3D	644823	707	----	4	8	10	2	22	Transoceanic	Mild
JT3D	664770	707	----	3	9	8	15	20	Inland and transoceanic	
JT8D	648913	727	4	--	2	2	25	8	Inland	
JT3D	645451	DC8	----	--	4	10	6	14	Transoceanic	
FT4A	6100047	Land-based rig	----	--	--	--	--	0	0.003 ppm salt in intake air	

aS - short over water, tropical zone; T - transoceanic to tropical points; W - short over water, temperate zone; O - transoceanic, temperate zone; and I - inland.

salt in the form of particles less than 5 micrometers in diameter.

The most severely exposed engine was from a Navy helicoper that had hovered at 40 feet (12.2 m) over the Atlantic immediately before engine disassembly. The helicopter engine was a type T58GE8B from a Navy helicopter model SH3A. The hovering flight of 1-hour duration was part of a 4 hour over-water flight, which was the only flight to which the engine was subjected after it was last washed. After each "dip" or hovering flight close to the ocean, Navy helicopter engines are washed with fresh water and then sprayed with a rust inhibitor (ref. 4). During the hovering flight, the wind velocity was 7 to 12 knots (13 to 22.2 km/hr). It is estimated that the average concentration of sea salt in the intake air was approximately 0.035 ppm (private communication from R. C. Fox of Naval Air Propulsion Test Center).

The only other engine that was considered to have had severe exposure conditions was a JT4 engine from a DC8 aircraft which had been used for pilot training. In its last

100 hours before overhaul, this engine was used on a variety of routes including inland flights as well as flights into and within the Caribbean region. It was then used for pilot training for two days, primarily for practice landings on an island in the Bahamas. Finally, just before overhaul, the engine was used on six trips between New York and Miami.

The engines in the intermediate exposure category were used largely on flights in and around the Caribbean region. The engines in the mild exposure category were used predominantly on transoceanic flights, although some of these flights were over land.

Sampling Methods

For the most part, salt samples from the rotor blades were taken before the compressor wheels had been debladed. The stator vanes were sampled in shrouded assemblies. No distinction was made between titanium and steel parts, since the object was to obtain a salt distribution profile of the entire compressor. Salt on steel blades in the high-pressure stages that might eventually be designed to use titanium was of as much, if not more, interest than salt on the low-pressure stages already made from titanium. Because airfoil areas can be measured, it was possible to convert sample weight to concentrations by dividing sample weight by area sampled. The steps in taking samples are shown in figure 1.

Airfoil area averages. - The amount of salt on the entire surface of an airfoil or on the concave or convex surfaces taken separately, was determined. The procedures used in obtaining the average amount of salt deposited on an airfoil were modifications of techniques developed by H. M. Green of the General Electric Company, Lynn, Mass. The use of gauze sponges and isopropyl alcohol was suggested by R. J. Lagomarsino of Ledoux and Company, Teaneck, New Jersey. The surfaces to be sampled were first wiped with gauze sponges, which are gauze pads 2 inches (5 cm) square, or with absorbent cotton swabs. Early in the program large airfoils were wiped by hand with gauze sponges. Usually three sponges were used. The first was moistened with isopropyl alcohol to remove oil or dirt from the airfoil. The airfoil was then wiped with two sponges moistened with distilled water to collect the salt. When an airfoil was particularly oily or dirty, it was necessary to use more than three gauzes to clean the surface. After sampling four complete compressors, it was found that a considerable salt background resulted from barehanded sampling. For all subsequent engines rubber gloves were worn when wiping with gauze sponges.

Small or closely spaced airfoils were sampled with small absorbent cotton swabs wound around the ends of wooden sticks about 5 inches (13 cm) long. The wiping sequence was: one swab moistened with isopropyl alcohol followed by two moistened with

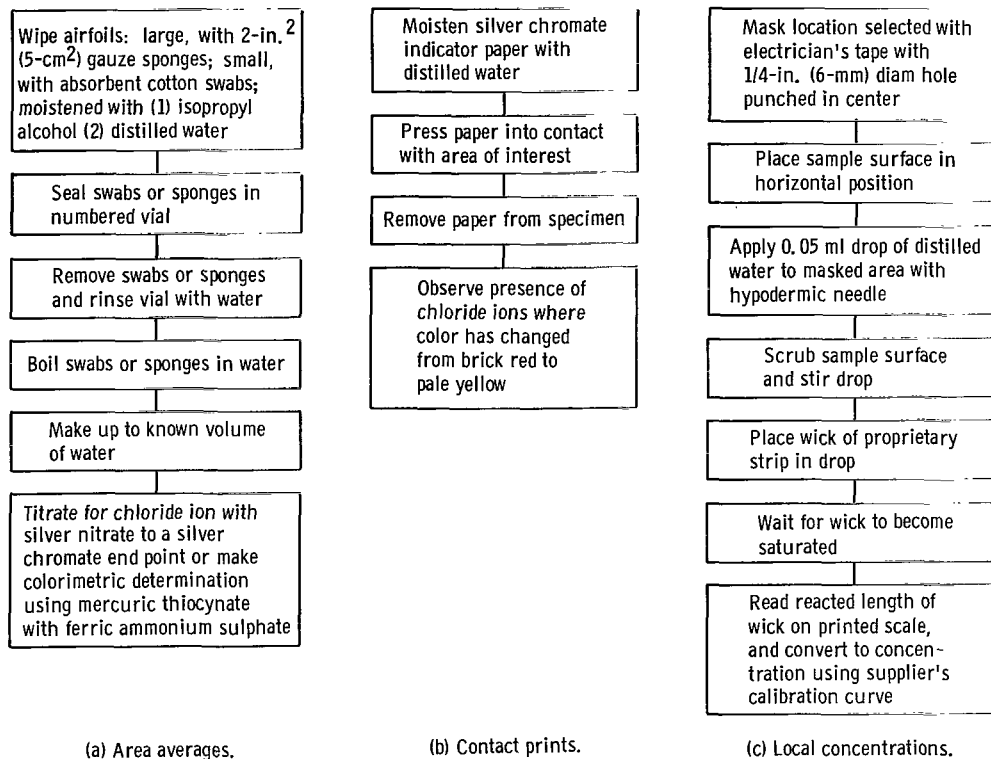| (a) Area averages. | (b) Contact prints. | (c) Local concentrations. |

Figure 1. - Sampling methods.

distilled water. After an airfoil was wiped, a length of stick about an inch (2.5 cm) long was clipped from that end of the stick which held the swab. For each sample, the wiping material, either gauze sponges or cotton swabs, was placed in a numbered vial for safe keeping for later chemical analysis.

Depending on their size, from one to five airfoils from a given compressor stage were wiped to obtain a sample. Early in the program both sides of an airfoil were combined in a given sample, but later separate samples were taken from the concave and convex sides of the airfoils.

The airfoil areas used in converting weight of salt to concentration were obtained from the engine manufacturers. They were the product of mean chord and mean span. Salt concentrations are reported in the mixed unit of milligrams per square inch both because it has been used by earlier investigators and also, because it is the natural consequence of dividing the sample weight, reported in milligrams by the chemist, by the areas, reported in square inches by the engineer. Salt concentrations are also given in milligrams per square centimeter for the convenience of those who use the International System of units.

Qualitative salt prints. - A qualitative picture of the distribution of salt over the

surfaces of selected airfoils was obtained by making contact prints. A silver nitrate paper prepared in their own laboratories had been used by General Electric Co. to obtain contact prints showing salt distribution on airfoils. In the present work a proprietary silver dichromate paper was used. The paper containing silver dichromate was moistened with distilled water and then pressed into contact with an airfoil surface. In those areas where salt was present on the airfoil, the test paper changed from a brick red to a pale yellow. The silver chromate paper was supplied by the manufacturer of the device (ref. 5) used to measure local salt concentrations.

Determination of local salt concentrations on airfoils. - On the basis of salt prints and visual evidence of localized salt deposits, a few areas of individual airfoils were selected for in place "titration" using a proprietary "titrator" (ref. 5). This device consists of a small strip of silver dichromate indicator paper laminated into a transparent plastic sheath with a printed scale. When a water solution of chlorides is drawn up the paper wick, silver chloride forms, changing the color from brick red to yellow. When the wick becomes saturated with water, the color change stops. The concentration of chlorides in the volume of water being titrated can then be determined from the length of reacted paper by means of a calibration chart.

Areas of interest were masked (fig. 2) by a 3/4-inch (1.9-cm) wide strip of electricians tape in which a 1/4-inch (6-mm) diameter hole had been punched. The surface of the masked airfoil was then placed in a horizontal position, and a 0.05 milliliter drop of distilled water was applied to the masked area with a hypodermic syringe. The test area was scrubbed with a corner of the plastic sheath holding the test paper to loosen and stir in adherent salt. The wick end of the test strip was then placed in the water drop (fig. 3) to obtain a reading. Once the salt concentration in the drop had been determined from the length of paper reacted, the local-area concentration of salt was determined by cal-
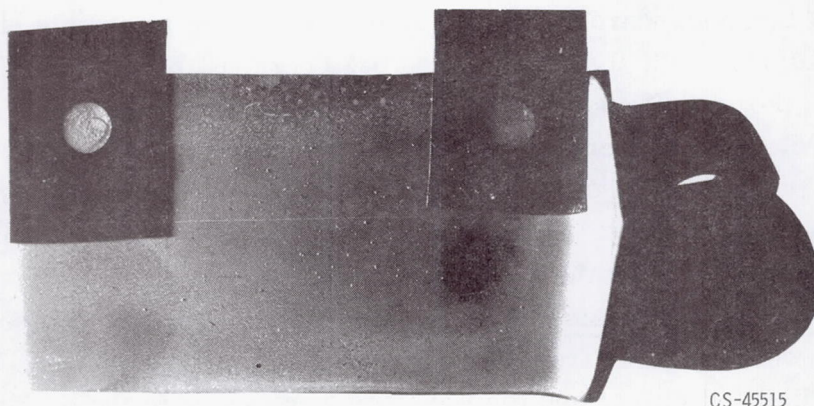

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Figure 2. - Seventh stage compressor rotor blade from JT8D engine (No. 648913) masked for in place titration.
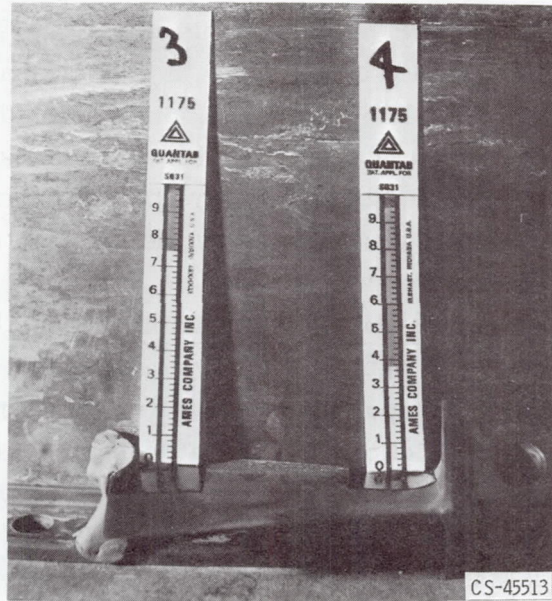
Figure 3. - Local salt concentrations being determined by in
place titration of 0.05-milliliter drops on 1/4-inch (6-mm)
diameter areas on seventh-stage blade from JT8D engine
(No. 648913).

culating the weight of salt in the water drop and dividing by the area within the mask. It should be noted that this type of local titration could be done on any flat surface, such as a compressor disk, that could be masked and placed so as to prevent a drop of water from running off. This process can also be used in less accessible areas such as bolt holes by plugging one end of the hole and trimming the test strip sheath to fit the hole.

The manufacturer of the test strips reports an absolute error of ±10 percent of true value (ref. 5). To verify this report, five test strips were used to measure the concentration of each of three standard solutions. For a 0.20 percent sodium chloride solution, the results were 0.16, 0.18, 0.18, 0.20, and 0.20 percent, or a range of error from -20 to 0 percent. For a 0.05-percent sodium chloride solution the results were 0.05, 0.05, 0.045, 0.053 and 0.05 percent or an error range of -10 to 6 percent. And for a 0.01-percent sodium chloride solution, 0.0096, 0.010, 0.0096, 0.0096 and 0.011 or an error range of -4 to 10 percent. In all but one of the 15 check readings made, the results were within the range stated by the manufacturer.

Laboratory chemical analysis. - In the laboratory, the gauze or absorbent cotton wiping materials were removed from their vials and placed in beakers. The vials were washed out with distilled water, and the washings were added to the beaker containing the corresponding wiping materials. The materials were boiled for 1/2 hour in water, which was then made up to a known volume for analysis.

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The initial analyses were made by titrating for the chloride ion with silver nitrate to a silver chromate end point. When it became apparent that some of the salt concentrations were quite low, a more sensitive colorimetric method was adopted using mercuric thiocyanate with ferric ammonium sulphate (ref. 6). All analyses for chlorides were reported as sodium chloride.

Corrections Applied to Salt Samples

Appropriate corrections were applied to the salt samples to account for salt introduced by the particular technique used.

Correction for barehanded sampling. - Salt from the sampler's bare hands was a source of error in some of the earlier samples. To determine the amount of body salt that might be absorbed by the sampling material during wiping an airfoil the following test was made. A strip of stainless steel 1 by 5 by 0.03 inch (2.5 by 13 by 0.08 cm), which had been ultrasonically cleaned, was sampled for salt, barehanded, four times in succession. For each sample three gauze sponges (which is typical of the number used for most airfoil samples) were used. The first sponge was moistened with isopropyl alcohol and the other two with distilled water. The amount of salt determined from four successive samples was 0.53, 0.51, 0.51 and 0.56 milligram. A correction of -0.53 milligram was made for each airfoil salt sample taken using bare hands.

Correction for gloved hand sampling. The background from gloved hand sampling was only about one-fourth of that from barehanded sampling. For example, when a strip of ultrasonically cleaned titanium, 1 by 5 by 0.02 inch (2.5 by 13 by 0.05 cm), was sampled repeatedly for salt, using three gauze sponges (held with rubber gloves) per sample, the salt determined for the successive samples was 0.125, 0.132, 0.129, 0.129, 0.129, 0.120, and 0.129 milligram. A correction -0.13 milligram was applied to each sample taken while wearing gloves.

Corrections for absorbent cotton swabs. - Two types of cotton swabs on wooden sticks were used. One type, used for only one engine, required a correction of -0.03 milligram per swab for the salt it originally contained. The second type had a very low salt content and required a correction of only -0.002 milligram per swab.
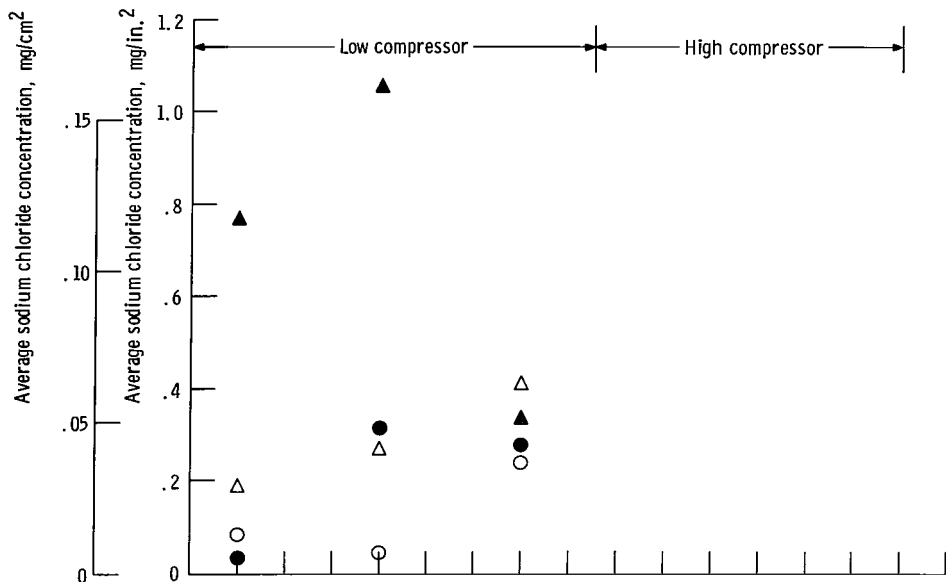
RESULTS AND DISCUSSION

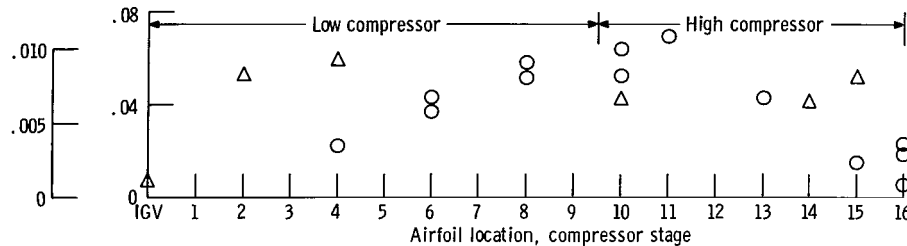## Average Salt Concentrations on Airfoils

Figures 4(a) to (k) show the average concentration of salt on the compressor airfoils sampled, arranged by compressor stage for each engine. The abscissas are labeled from
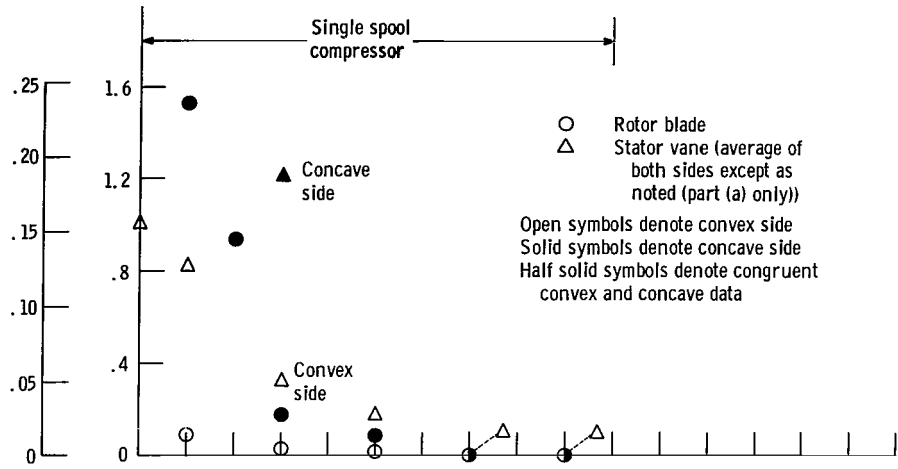
(a) Engine, T58GE8B; serial number, 200430; aircraft, SH3A. Severe exposure: helicopter hovered 40 feet (12.2 m) over ocean for 1 hour.
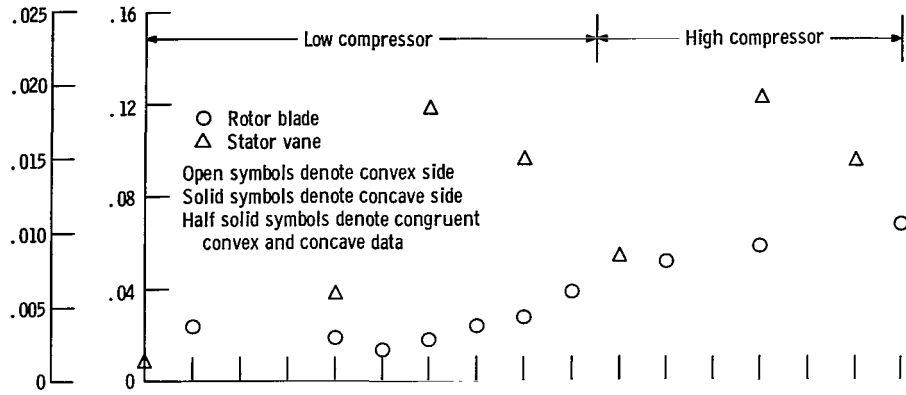
(b) Engine, JT4; serial number, 611551; aircraft, DC8. Severe exposure: landing practice on island in Bahamas.
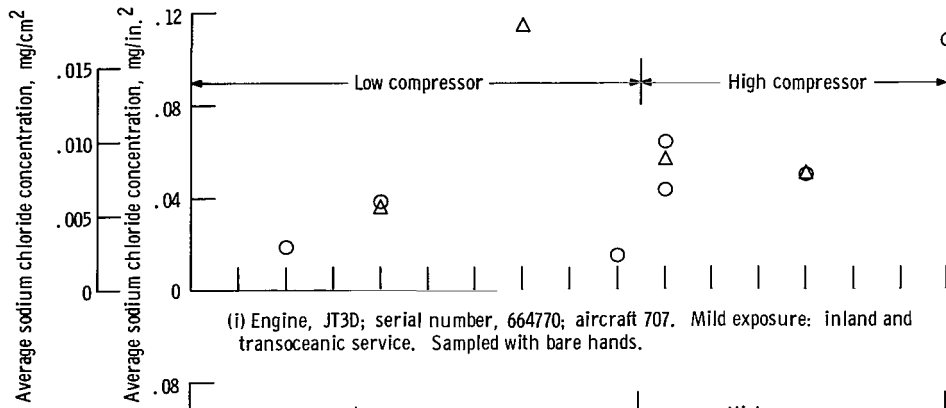
(c) Engine, JT3D; serial number, 642209; aircraft, 720. Intermediate exposure: U.S.A. to San Juan. Sampled with bare hands.

Figure 4. – Average salt concentrations on compressor airfoils. (IGV denotes inlet guide vane.)

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(d) Engine, JT3D; serial number, 643358; aircraft, 707. Intermediate exposure: transoceanic service to tropical points. Sampled with bare hands.

O   Rotor blade
△   Stator vane

Open symbols denote convex side
Solid symbols denote concave side
Half solid symbols denote congruent
    convex and concave data

(e) Engine, JT8D; serial number, 653743; aircraft, 727. Intermediate exposure: east coast points to Miami.

(f) Engine, JT4; serial number, 611025; aircraft, DC8. Intermediate exposure: Caribbean service. Sampled with bare hands.

Airfoil location, compressor stage

(g) Engine, JT8D; serial number, 649184; aircraft, 727. Intermediate exposure: Caribbean service.

Figure 4. - Continued.

Average sodium chloride concentration, mg/cm^2

Average sodium chloride concentration, mg/in.^{2}

Average sodium chloride concentration, mg/cm² (left axis)
Average sodium chloride concentration, mg/in.² (axis)

Legend:
○ Rotor blade
△ Stator vane
Open symbols denote convex side
Solid symbols denote concave side
Half solid symbols denote congruent convex and concave data

Low compressor — High compressor

(h) Engine, JT3D; serial number, 644823; aircraft, 707. Mild exposure: transoceanic service.

(i) Engine, JT3D; serial number, 664770; aircraft 707. Mild exposure: inland and transoceanic service. Sampled with bare hands.
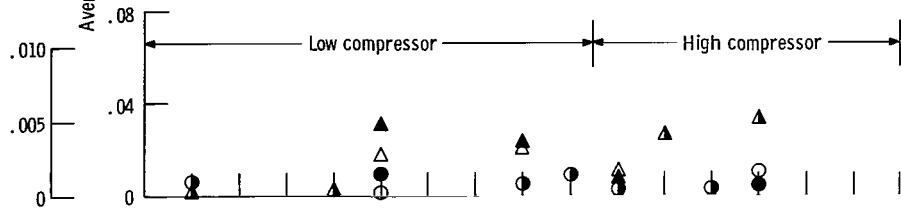
(j) Engine JT3D; serial number, 645451; aircraft, DC8. Mild exposure: transoceanic service.

IGV 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Airfoil location, compressor stage
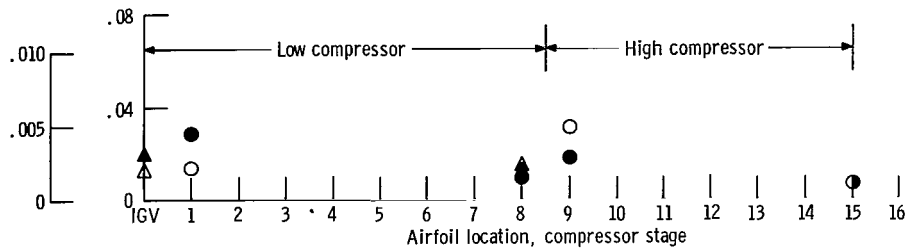
(k) Engine, FT4A-2; serial number, 610047. Mild exposure: Navy test installation (land-based rig); 5-hour test; sea salt content in intake air, 0.003 ppm.

Figure 4. - Concluded.

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the inlet guide vane (IGV) to the highest stage number for a given engine, and the stages included in the high- and low-pressure compressors are indicated. The circular data points represent the average concentrations on rotor blades, and the triangular data points the average concentrations on stator vanes. Where only open symbols are used, the samples include salt from both sides of the airfoil. Where both open and closed symbols are used, the open symbol represents the average concentration on the convex side of the airfoil, and the closed symbol the concentration on the concave side.

The highest average concentration of salt measured was on the T58GE8B helicopter engine. The concave side of the first stage blades had a concentration of over 1.5 milligrams per square inch (0.23 mg/cm^2) as shown in figure 4(a). The convex side of the first stage blade had a concentration of only 0.09 milligram per square inch (0.01 mg/cm^2). In this engine, the salt concentration dropped off rapidly in passing toward the rear of the compressor; at the third stage, the average concentration on the rotor blade was 0.17 milligram per square inch (0.026 mg/cm^2) on the concave side and 0.04 milligram per square inch (0.006 mg/cm^2) on the convex side. At the seventh stage, the amount of salt present was less than that of the blank and could therefore not be evaluated. The same trend of reduced salt concentration with successive compressor stages was also observed on the stator vanes. Salt samples were obtained for both the concave and convex side of only the third stage stator vanes. The greater concentration was observed on the concave side.

Although the greatest salt concentration in the T58 compressor was found on the concave side of a first stage rotor blade, extrapolation of the stator vane data suggests that a higher concentration (about 2.0 mg/in.^{2} or 0.3 mg/cm^2) might have been found on the concave side of the first stage stator vane. This would be in keeping with the results observed for the large commercial engines where, as will be shown later, the salt concentrations on the concave sides of the stator vanes were also usually greater than those on the concave sides of the rotor blades.

The commercial engine with the highest salt concentration was JT4 (No. 611551) from a DC8 aircraft. This plane had been assigned to pilot training in the Bahamas for two days shortly before overhaul. On such duty as many as 50 to 60 landings are made in a single day. As an example of the large amount of salt present in the air in this region, (private communication from Captain E. F. Russell), it is normal for salt to build up on the windshields of the aircraft at about 500 feet (153 m) altitude. However, on a humid day after a storm, this can occur as high as 3000 feet (915 m). Salt deposits also form on the leading edges of the wings in this type of service. In this JT4 engine, the highest average concentration measured (fig. 4(b)) was 1.05 milligrams per square inch (0.163 mg/cm^2) on the concave side of the fourth stage vanes. The convex side of the fourth stage vanes had an average concentration of only 0.26 milligram per square inch (0.04 mg/cm^2). The blades from this stage also had higher concentrations on the

concave sides than on the convex sides. No samples from the high-perssure compressor were obtained for this engine. Of particular significance is the persistence, under less severe environmental conditions, of salt deposits that had been formed under more severe conditions; for example, the concentration of salt at overhaul was high even though this aircraft made six flights between New York and Miami after the pilot training duty.

The intermediate exposure category included two JT3D engines, a JT4, and two JT8D's. In all but one of these engines, some of the blades had average salt concentrations over the entire airfoil as great or greater than 0.05 milligrams per square inch (0.008 mg/cm^2). In one JT3D (fig. 4(d)) and one JT4 (fig. 4(f)), one stage of stator vanes
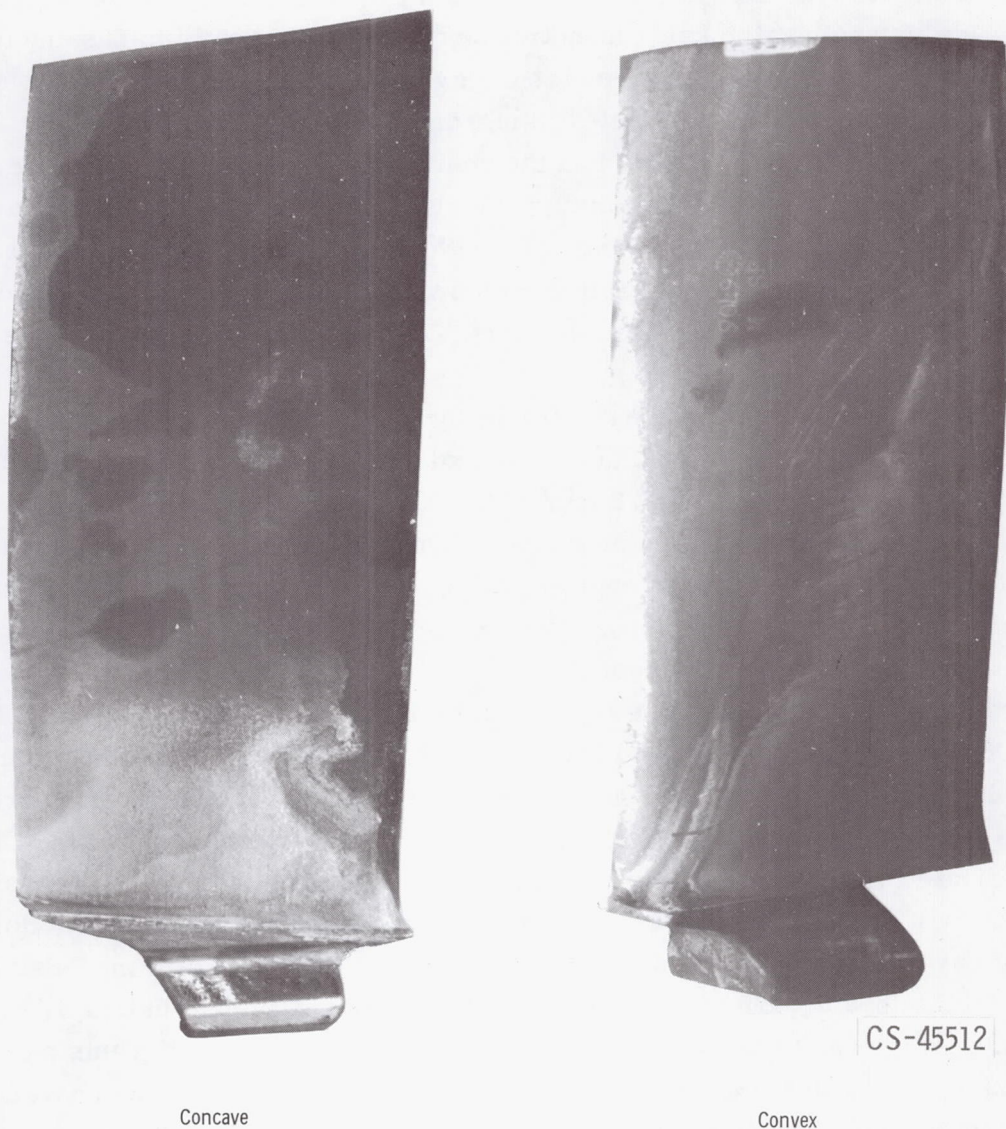

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Concave   Convex

Figure 5. - Seventh-stage compressor rotor blade from JT-4 engine (No. 611551). Note nonuniformity of salt deposits.

had average salt concentrations above or near 0.10 milligram per square inch (0.0155 mg/cm^2).

The first two engines, both JT3D's, listed in the mild exposure category had one or more blades or vanes with the average salt concentrations as high as those found in the intermediate category. In neither of the last two engines listed in the mild exposure category (a JT3D and the FT4A) were any average salt concentrations on the airfoils found to be greater than 0.04 milligram per square inch (0.006 mg/cm^2).

The results of this survey confirm the results of a similar study by General Electric (private communication from L. P. Jahnke). In that work, concentrations of over 1.0
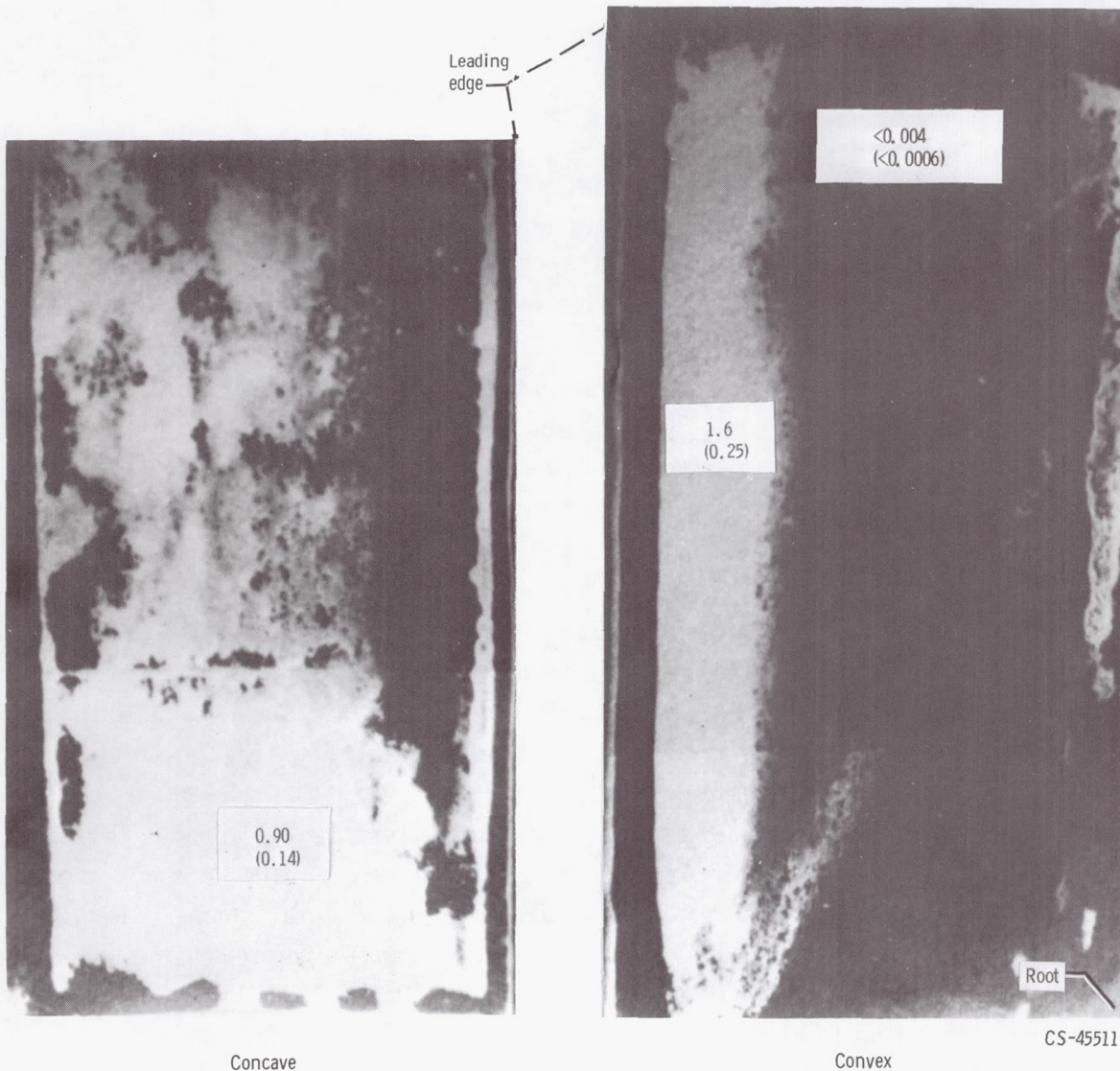

Figure 6. – Salt prints reproduced in reverse to show correspondence to seventh-stage blade (fig. 5) from JT4 engine (No. 611551). (All concentration units are in mg/in.^{2} (mg/cm^2).) Average salt concentration on five other blades from this stage were 0.24 milligram per square inch (0.037 mg/cm^2) for convex side and 0.28 milligram per square inch (0.043 mg/cm^2) for concave side.

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milligram per square inch (0.15 mg/cm^2) were found in a T58-8 engine from a helicopter. The average salt concentration on the blades dropped off sharply from 1.7 milligrams per square inch (0.26 mg/cm^2) on the first stage to 0.7 milligram per square inch (0.1 mg/cm^2) on the fourth stage. A similar rapid decrease from stage to stage, but at the much lower maximum concentration of 0.1 milligram per square inch (0.01 mg/cm^2), was found in another small engine, a CJ610. Each of five large engines (CJ805's) had some stages with average concentrations greater than 0.1 milligram per square inch (0.01 mg/cm^2), but less than 0.2 milligram per square inch (0.03 mg/cm^2), and two had their highest concentrations on the highest rotor stage sampled (e.g., 0.15 mg/in.^{2} (0.02 mg/cm^2)) for stage 11 and 0.135 mg/in.^{2} (0.02 mg/cm^2) for stage 17.

Salt Distributions on Individual Airfoils

Salt prints were made of selected airfoils from several of the engines examined. The salt prints supplemented visual observations of salt deposits and discriminated between deposits of salt and other materials. The prints also made the presence of salt obvious on some airfoils where it was not otherwise readily observed. For example, the distribution of salt on a seventh stage JT4 blade (fig. 5) is more obvious in the salt print shown in figure 6 than in the photograph of the blade itself. The salt prints also showed that the salt deposits were by no means uniform over the airfoil surfaces. On the blade in figure 5, which came from the JT4 engine used for pilot training (severe exposure conditions), a heavy deposit of salt formed along the leading edge of the convex side of the airfoil. The intensities of the local concentrations were measured by test strip titration and are shown in figure 6. The concentration on the convex side was 1.6 milligrams per square inch (0.25 mg/cm^2) near the leading edge, while the average concentration was only 0.24 milligram per square inch (0.037 mg/cm^2). The local concentration measured near the base of the airfoil on the concave side was 0.90 milligram per square inch (0.13 mg/cm^2) compared with an average concentration of only 0.28 milligram per square inch (0.043 mg/cm^2).

The lack of uniformity in salt deposits over the surface of stator vanes is shown in figure 7, which shows salt prints for three stages of vanes from the severely exposed JT4 (No. 611551, see table I). The areas shown are from only the midspan portion of the airfoils. It is evident that the heaviest salt deposits are near the center of the concave sides and near the leading edge of the convex sides.

The wide variation in local salt concentration on a single airfoil is further shown in figure 8. This salt print was taken from one of several seventh stage blades from the JT8D engine (No. 648913, see table I). The blades were an isolated sample from only one stage of the compressor. The rest of the engine had already been processed through
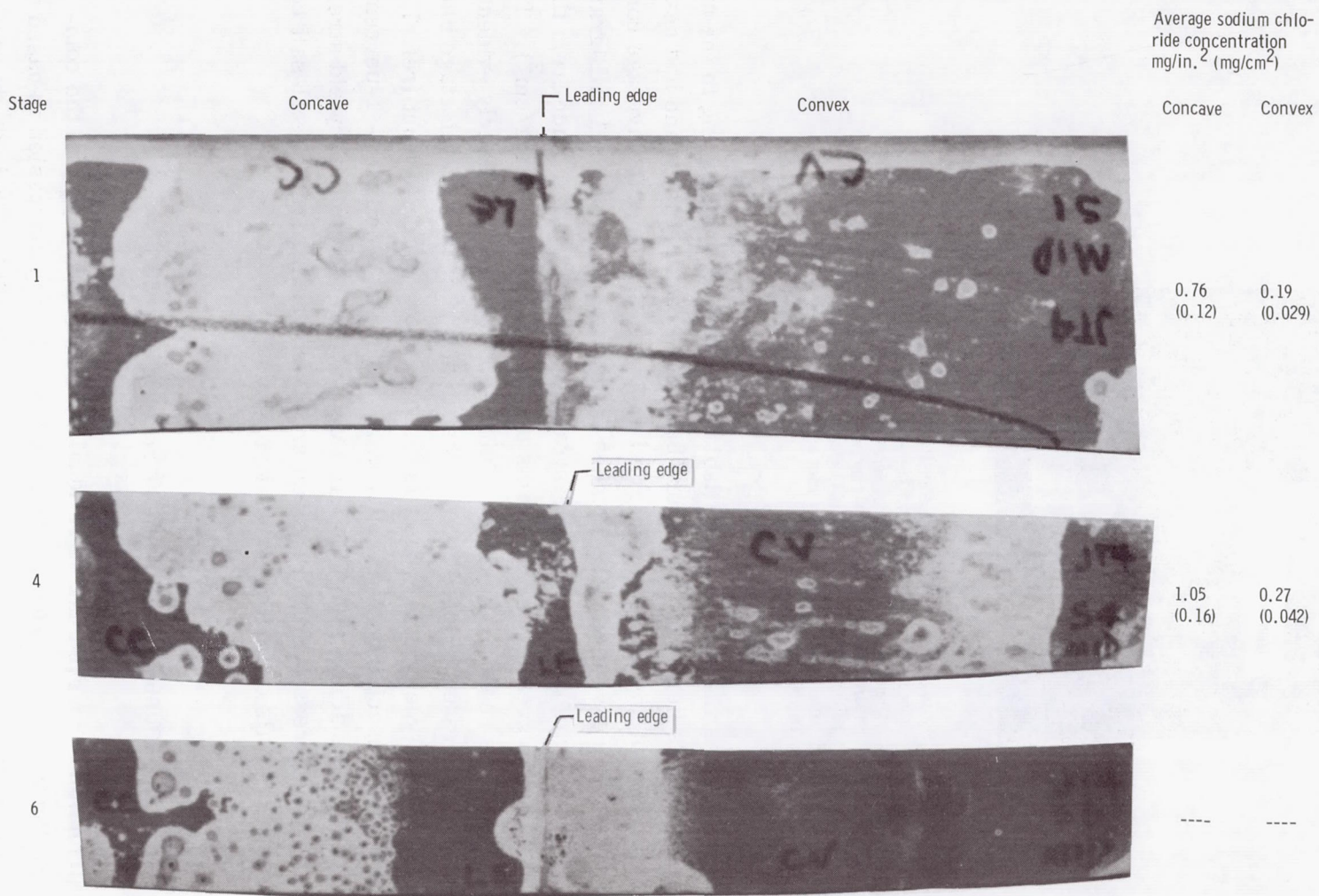
Figure 7. – Salt print made at midspan on compressor stator vanes of JT4 engine (No. 611551) showing greater concentrations of chlorides on concave side and at leading edge of convex side.
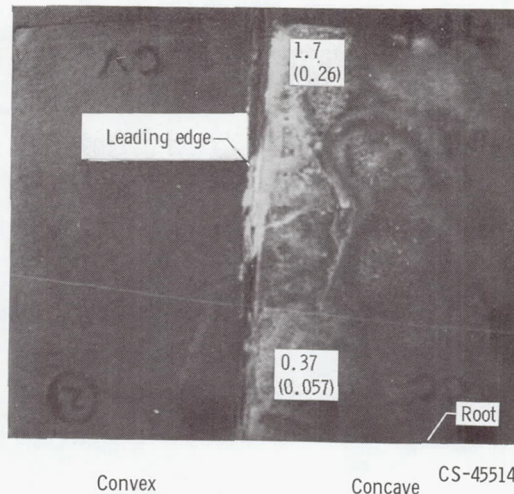
Figure 8. - Salt prints from seventh-stage compressor blade from JT8D engine (No. 648913). Average concentrations of sodium chloride from five blades were 0.11 milligram per square inch (0.017 mg/cm^2) for concave side and 0.03 milligram per square inch (0.004 mg/cm^2) for convex side. (Local concentration values on print are in mg/in.^{2} (mg/cm^2).)

a cleaning operation and was therefore not available for sampling. According to the number and categories of flights in the last 100 hours before overhaul, this engine had next to the least severe exposure of any of the commercial engines. Although the average concentration of salt on the concave side of five blades from this stage was 0.11 milligram per square inch (0.02 mg/cm^2), the local concentration near the tip of a blade from this stage was over 10 times as great, 1.7 milligrams per square inch (0.26 mg/cm^2). The nature of the salt deposit is shown in figure 9. Cubic salt crystals are clearly evident in the micrograph. The area considered is near the tip of one of the seventh stage blades from engine 648913. This type of salt deposit is similar to one which Rideout (ref. 7) showed on laboratory test specimens of the titanium - 8-percent aluminum - 1-percent molybdenum - 1-percent vanadium alloy (Ti-8Al-1Mo-1V) stressed to their yield stress at 650° F (343° C). The stressed specimens had cracks emanating from metal-salt contact spots were cubic crystals of salt had been deposited.

Comments Concerning Salt Distribution

The salt distributions observed can be rationalized both with respect to the compressor stages and the individual airfoils. Some of the following discussion is based on unpublished work which the General Electric Co. had done in 1961. Their study concerned the mechanism of deposition of salt on helicopter gas turbine compressor blades

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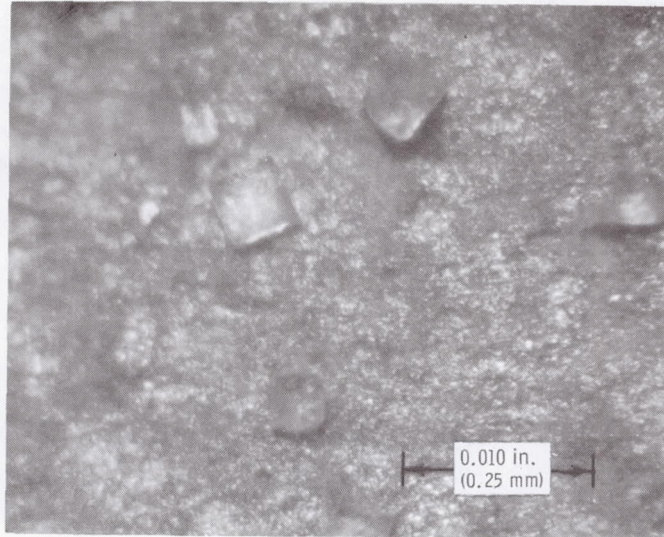
CS-45509

Figure 9. - Salt crystals on area near tip of seventh-stage compressor rotor blade from JT8D engine (No. 648913).

when hovering over the ocean. Under those conditions, a large fraction of large-diameter salt-water droplets would be expected to impinge on the airfoils of the early stages of a compressor. This could account for the difference in salt distribution through the compressor between the helicopter engine and the large commercial engines. The salt entering the engine of a hovering helicopter would be expected to be in the form of droplets that were relatively large compared with those ingested by the engines of a jet aircraft at higher altitudes. A large portion of these droplets could impinge on the early stages of of the helicopter compressor, resulting in a gradual decrease in concentration on successive stages. On the other hand, many of the smaller droplets ingested by the larger engines could survive through more stages until they impinged on airfoils further back in the compressor. Since the flow path becomes more circuitous as the airfoils become smaller, the small particles which may have survived to a greater distance through the compressor have a greater chance of depositing on the small latter stages than the large early stages of a large compressor.

Most of the large engines examined showed a maximum salt concentration on the airfoils near the separation of the high- and low-pressure compressors. The decreasing concentration in the hottest stages may have been due to a temperature effect. By the time the salt, which was initially present in the form of droplets, reached the eighth or ninth stage, it may have been dried enough to exist only as solid particles. Dry salt particles would not stick to a surface as well as wet droplets, and might therefore produce a lighter buildup of salt in the final and hottest stages of the compressors.

In addition to the amount of salt deposited being different, at different compressor stages, differences between the amount of salt on stator vanes and rotor blades and on the concave and convex surfaces of the airfoils were observed. Centrifugal force may sling enough salt from the rotor blades to account for the greater amounts of salt usually found on stator vanes. Centrifugal force may also account for the heavier salt concentrations observed near the tips of some rotor blades as compared with the rest of the airfoils. The probable greater impingement of salt on the concave side of blades and vanes could account for the larger amount of salt found on the concave side of both blades and vanes.

RELEVANCE OF LABORATORY TESTS TO SALT IN ENGINES

To put in proper perspective the salt concentrations found on the compressor airfoils of the engines sampled, the concentrations that have caused embrittlement of titanium alloys in laboratory tests should be considered. In our laboratory, a significant loss of ductility was observed when relatively small salt concentrations were applied to test specimens. For example, the elongation in a room-temperature tensile test at a low strain rate (crosshead speed, 0.005 in./min or 0.01 cm/min) was 19 percent for an unsalted specimen of the Ti-8Al-1Mo-1V alloy after it had been exposed to a stress of 50 000 psi (345 MN/m^2) for 100 hours at 800° F (427° C) (ref. 8). The elongation dropped to 5 percent for a salt coated specimen similarly exposed. The average salt coating was 0.18 milligram per square inch (0.03 mg/cm^2). At higher strain rates (crosshead speed, 0.05 in./min or 0.1 cm/min) or at a higher test temperature (300° F or 150° C), embrittlement was not observed. General Electric Company reported somewhat similar results (private communication from L. P. Jahnke). A loss of ductility was observed in low-strain-rate room-temperature tensile tests of titanium - 6-percent aluminum - 2-percent molybdenum - 4-percent zirconium - 2-percent tin (Ti-6Al-2Mo-4Zr-2Sn) alloy after it was exposed to a stress of 30 000 psi (207 MN/m^2) at 800° F (427° C) for 100 hours. The salt coating, in this case, was 0.05 milligram per square inch (0.008 mg/cm^2). At higher strain rates and temperatures, loss of ductility was not observed, even at higher salt concentrations up to 1.0 milligram per square inch (0.15 mg/cm^2). A chloride concentration, equivalent to a sodium chloride concentration as low as 0.033 milligram per square inch (0.005 mg/cm^2) (ref. 9), has been reported to cause microcracks in the Ti-8Al-1Mo-1V alloy at 700° F (371° C) when exposed to an unstated stress. In this survey only three engines had average salt concentrations less than 0.033 milligram per square inch (0.005 mg/cm^2) on their compressor airfoils. Even in those engines, the local concentrations would have been substantially higher.

For the engines examined in this survey, there is conclusive evidence of the presence of salt on compressor airfoils in excess of that found to cause hot-salt stress-corrosion cracking or embrittlement in laboratory tests. Presumably, the same levels of salt could be found in many other engine models exposed to similar service conditions. The question yet to be answered is why no such cracking has been observed in flight service. Some possible reasons are listed as follows:

(1) Titanium parts in current commercial engines may be operating outside the time-temperature-stress-region required to cause hot-salt, stress-corrosion. In the engines sampled, the latter compressor stages were made from steel.

(2) The operating times on military engines may be too short to allow hot-salt stress-corrosion to occur, even where the stresses and temperatures are high enough to cause it.

(3) Laboratory tests may detect changes in properties (e.g., embrittlement in low-strain-rate tensile tests) that may occur in engine parts yet not cause failure under normal operating conditions including varying temperatures and stain rates.

(4) The cyclic operation of flight jet engines may preclude the incubation of hot-salt, stress-corrosion cracks. For example, it has been suggested (ref. 10) that cracking might not occur on exposure of titanium alloys to salt, provided the time at temperature was less than that required to form titanium dichloride and the time at room temperature between cycles was greater than that required for titanium dichloride to decompose.

(5) The engine may provide its own protective coating for at least the forward stages of the compressor. All the engines examined had oil on the airfoils of the early compressor stages. This gradually changed to a black, somewhat greasy deposit on the stages operating at intermediate temperatures, but no such deposit was evident on the hottest stages. The higher temperatures probably caused the oil to decompose. How far back in the compressors an organic coating of any sort might persist was not determined.

CONCLUDING REMARKS

In current flight engines, salt concentrations have been observed that are in excess of the amount shown to have caused hot-salt, stress-corrosion cracking in laboratory tests of titanium alloys. To date, no service failures of titanium engine components have been reported as a result of this phenomenon. Many reasons have been advanced why such cracking has not been observed in flight service. These involve various aspects of engine operation and their relation to the hot-salt stress-corrosion process. However, because of the large salt concentrations observed, there is reason for concern that titanium hot-salt, stress-corrosion cracking may become a major problem, particularly at the higher temperatures and stresses anticipated for the use of titanium in advanced

engines. It is, therefore, essential that research be continued to obtain a better understanding of the hot-salt stress-corrosion mechanism in titanium alloys, and how engine operating environments affect the stress-corrosion process.

SUMMARY OF RESULTS

The following results were obtained from conducting a field survey of salt deposits on compressor airfoils of commercial and military gas turbine engines:

1. After severe exposure in a salt laden environment, the average salt concentration over the entire surface of a stator vane for a commercial engine exceeded 0.66 milligram per square inch (0.10 mg/cm^2) and was greater than 1.0 milligram per square inch (0.15 mg/cm^2) on the concave side. The average concentration over the entire surface of a blade exceeded 0.18 milligram per square inch (0.03 mg/cm^2) and was greater than 0.3 milligram per square inch (0.05 mg/cm^2) on the concave side.

2. Under intermediate-to-mild conditions of exposure, the average salt concentrations over the entire airfoil surface of some stages of both vanes and blades from some commercial jet engines exceeded 0.1 milligram per square inch (0.01 mg/cm^2), which is considerably in excess of the very small concentrations (e.g., 0.05 and 0.033 mg/in.^{2} (0.008 and 0.005 mg/cm^2)), reported to have caused embrittlement of titanium in laboratory tests.

3. Local concentrations can be 10 times as great as the average for a compressor airfoil.

4. The average salt concentration on compressor airfoils decreased rapidly from front to rear stages in a military helicopter engine that had been exposed to a severely salt laden environment.

5. The average salt concentration on airfoils for most of the commercial engines sampled increased to a maximum near the separation between the high- and low-pressure compressors.

6. Salt deposited under severe conditions of exposure apparently persisted after limited exposure to mild service conditions.

7. Stator vanes usually had higher average salt concentrations than rotor blades.

8. The concave sides of both rotor and stator airfoils usually had higher average concentrations of salt than the convex sides.

9. A technique was developed for determining local concentrations of salt in small, 1/4-inch (6-mm) diameter, areas on an airfoil surface. This technique can also be applied to other portions of the engine such as bolt holes in disks, flat areas of disks or stator shrouds.

10. A technique was developed for obtaining qualitative distributions of salt on compressor blades and vanes by using silver chromate paper to make contact prints.

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   National Aeronautics and Space Administration,
      Cleveland, Ohio, September 24, 1968,
         129-03-06-05-22.

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