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SULFUR OXIDE MEASUREMENT IN AIRCRAFT TURBINE ENGINE EXHAUST

Gerald R. Slusher

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16. Abstract

A limited investigation was conducted to measure the oxides of sulfur in aircraft turbine engine exhaust. The objective was to establish the ratio of sulfur trioxide (SO_3) to sulfur dioxide (SO_2) to be utilized in support of the climatic impact assessment program. The SO_3 concentration was found to be 13.8 percent of the SO_2 concentration as determined by wet chemistry analysis. Sulfur recovered in the samples was approximately 50 percent of the total sulfur in the fuel.

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FOREWORD

The assistance of Mr. James M. Clingenpeel, Chemist, Energy Research and Development Administration, Bartlesville, Oklahoma, was essential to the measurement of the oxides of sulfur. Mr. Clingenpeel's contribution is acknowledged with sincere thanks and grateful appreciation.

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INTRODUCTION

PURPOSE.

The purpose of the test results reported herein was to measure the sulfur trioxide (SO_3) and sulfur dioxide (SO_2) in aircraft turbine engine exhaust and to establish the ratio of SO_3 to SO_2.

BACKGROUND.

The quantity of sulfur oxides emitted by aircraft turbine engines is low because of the sulfur limits imposed on commercial jet-A fuel. Sulfur was considered to be a problem in the early development of turbo-jet engines because hot turbine components were susceptible to sulfur corrosion. Jet-A fuel specification limits the quantity of sulfur to 0.3 percent by weight. The actual sulfur content in jet-A fuel, however, is significantly less than the limit with average values generally ranging from 0.04 to 0.12 percent by weight. Sulfur dioxide emissions from turbine engines vary from 5 to 10 parts per million (ppm) and are almost totally a function of the sulfur content of the fuel (reference 1). Calculations in support of the work show that the minimum sulfur dioxide emissions from turbine engines reported herein is less than 3 ppm.

The investigation of SO_2 and SO_3 was conducted in support of the climatic impact program and required the establishment of the SO_3 to SO_2 ratio.

Sulfur trioxide exists as a gas above 625° F and as temperature is decreased, the gas combines with surrounding moisture and becomes sulfuric acid (H_2SO_4) mist. Experimental results reported in reference 2 show that for low concentrations of SO_3 the acid dewpoint is significantly less than a temperature of 625° F.

Measurement of SO_3 in turbine engine exhaust had been unsuccessful to date. The severe sample conditions, consisting of a high-temperature gas stream at or near a dynamic pressure equivalent to Mach 1, has prevented the collection of samples by conventional methods. Sulfur trioxide or H_2SO_4 samples should be collected with a quartz-lined probe and a glass sample train of filters and scrubbers to prevent chemical reaction with the materials in contact with the sample and permit recovery of the acid mist by washing the collection train.

DISCUSSION

ANALYTICAL MEASUREMENT METHODS.

Measurement methods employed wet chemistry involving the assessment of color changes or intensities produced by sulfur oxide chemical reactions. A modified West-Gaeke method was utilized for SO_2 measurement. This method was selected because of its adequate sensitivity and accuracy in the SO_2 concentration range of turbine engine exhaust. The method involves the collection of exhaust gas samples in a scrubber with sodium tetrachloromercurate. To provide information concerning required flow rates and to assure a maximum flow rate, two modified Greenburg-Smith impingers in series each containing 100 milliliters of sodium tetrachloromercurate were used in the sample collection train. Pararosaniline in hydrocloric acid and formaldehyde solutions were added following sample acquisition. The intensity of the color change from clear to red violet depends on the quantity of SO_2 present. The absorbency (optical density) of the sample was measured at 560 nanometers. The quantity of SO_2 was determined in relation to a blank and from the calibration. The standard West-Gaeke method, reference 3, was modified to eliminate nitrogen dioxide interference, reference 4, by the addition of 0.06 percent sulfuric acid to 0.1 molar sodium tetrachloromercurate.

Test method 8, reference 5, was employed for determination of SO_3 or sulfuric acid mist from samples collected in turbine engine exhaust. The sample train consisted of a 2-inch glass filter followed by two modified Greenburg-Smith impingers in series each containing 100 milliliters of four-to-one proportion of isopropanol to water. Two impingers were used to determine the maximum sample flow rate and to assure collection of all of the samples in the first impinger. Total sample flow was 2.9 cubic feet at a flow rate of 0.225 cubic feet per minute. The samples were processed by adding two to four drops of thorin indicator and titrated with barium perchlorate from yellow to a stable pink color.

DESCRIPTION OF EQUIPMENT.

A TF30 mixed-flow turbofan engine served as the test vehicle for this investigation. The engine was modified by removing the afterburner assembly and installing a fixed-area jet nozzle. Test conditions were selected at maximum continuous power where the engine developed 9,800 pounds thrust, used 6,000 pounds per hour of jet-A fuel, and pumped 222 pounds per second of air. The fuel contained 0.05 percent by weight of sulfur.

The sample probe assembly, 3 feet in length, was constructed of 1-inch diameter by 0.065-inch wall, stainless steel with a quartz liner and incorporating an electrical heating element and a thermocouple. Maximum operating temperature of the probe was 800° F.

A 2-inch stainless steel tip turned 90° was installed on the sample end of the probe and a 28/15 millimeter (mm) outer spherical ball joint of quartz was on the outlet end.

The sample train (figure 1) was located 2.5 feet under the engine jet exhaust nozzle and consisted of a 90° Pyrex adapter with 28/15 mm inner ball joints for connecting the probe to the glass filter. Filters of glass fiber were used in a 2-inch glass filter body. "U" shaped glass adapters with 28/15 mm joints were employed between the outlet of the filter and the inlet of the first

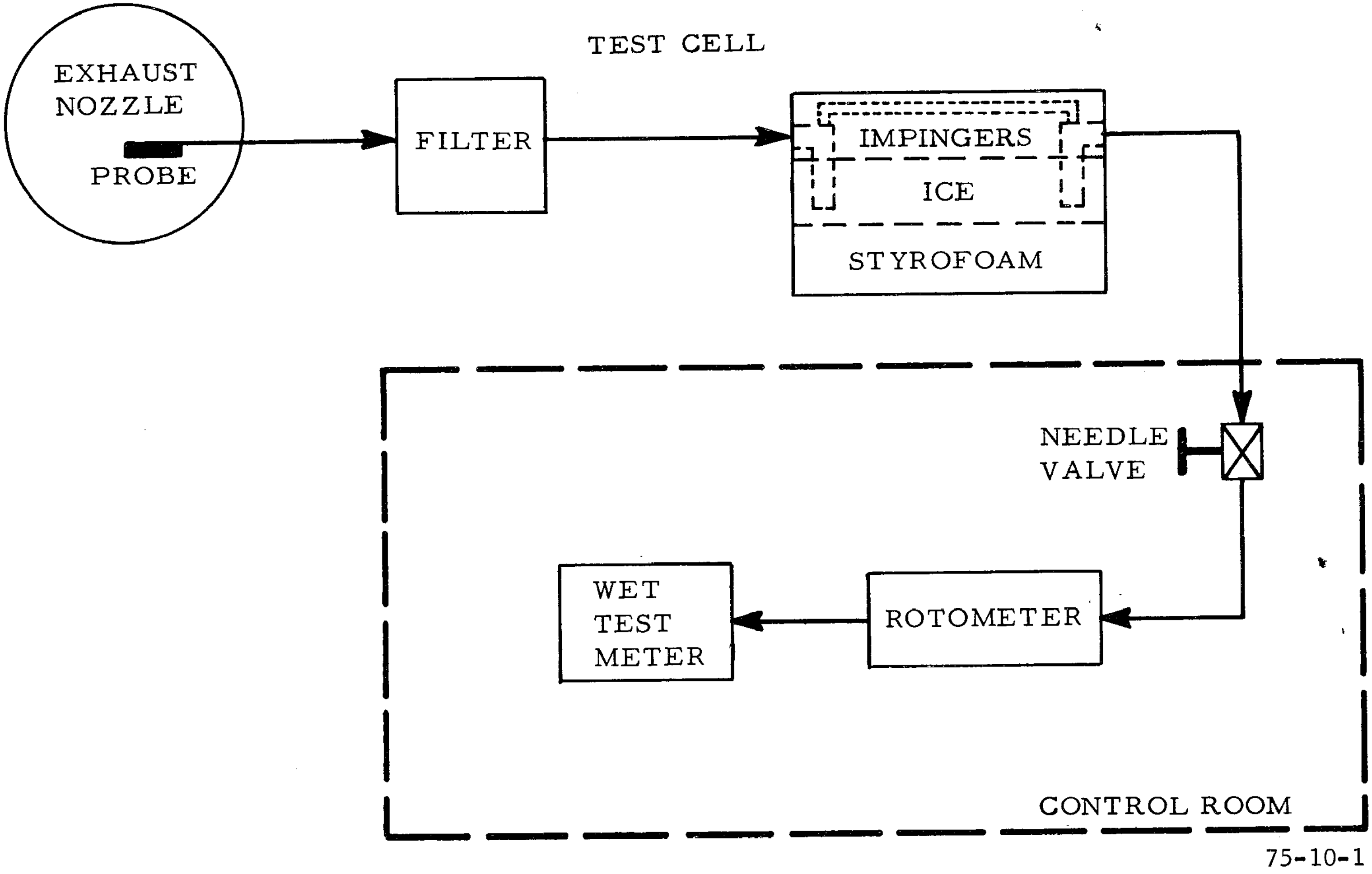

FIGURE 1. SAMPLE TRAIN SCHEMATIC

modified Greenburg-Smith impinger and between the outlet of the first impinger and the inlet of the second impinger. The exhaust from the second impinger was routed into the control room where the flow was throttled, the rate set to a rotometer indication, and the volume measured with a wet test meter.

The impingers were chilled in a 4-inch deep ice bath for sample acquisition.

SAMPLE ACQUISITION.

The glass sample train and the impingers and filters, in particular, were designed to operate under sample pressures less than atmospheric. Exhaust pressure of the TF30 engine at maximum continuous power was 27 inches of mercury above atmospheric or 56.9 inches of mercury absolute. Under this pressure, the bubbler or stopper, with wide rubber band restraint, will rise out of the impinger bottle with resultant gas sample leaks. This problem was reduced in intensity by safety wiring the stopper to the bottle similar to the wire on a wine cork and bottle. As some leakage was observed, even with safety wire, the test and sample collection procedures were changed to reduce the pressure. Engine stabilization in mode prior to sample acquisition was eliminated and the sample flow was started immediately upon acceleration to the maximum continuous power conditions to release the pressure to a level where the safety wire and clamp-supported seals could be maintained.

The second problem was to eliminate glass breakage resulting from the forces exerted on the sample probe by pressure, vibration, and high-noise levels. Two ball joints were installed between the probe and the glass filter to facilitate alignment and thereby minimizing these problems. The impingers were shock-mounted on a 4-inch thick sheet of styrofoam in the ice bath.

TEST RESULTS

The sample probe was preheated and maintained at a temperature of 550° F. Tests of the probe and filter were negative in regard to collection of sulfuric acid, and was therefore concluded that the samples consisted of SO_3. Sample flow and collection procedures were modified as required for collection of the total sample in the first impinger. Three SO_3 measurements of the samples collected in the first impinger were each 0.31 ppm. Two SO_2 measurements were 2.13 and 2.37 ppm, which averaged 2.24 ppm. The concentration of SO_3 was 13.8 percent of the SO_2 concentration. The total SO_2 plus SO_3, was 2.56 ppm. Sulfur balance calculations were accomplished based on the fuel containing 0.05 percent by weight of sulfur as determined by analysis of the fuel. For one-engine-operating-hour at maximum continuous power, an equivalent of 2.997 pounds of sulfur in the fuel was consumed by the engine. The total mass of air and fuel per operating hour was 805,377 pounds. Using 13.8 percent SO_3-to-SO_2 and assuming that all of the sulfur is oxidized, sulfur balance calculations indicate that the exhaust contained an average concentration of 0.4 ppm SO_3 and contained an average concentration of 2.9 ppm SO_2 for a total of 3.3 ppm. Based on these figures, the sulfur recovered in the sample was 77 percent of the total sulfur in the fuel.

Subsequent to the collection and measurement of sulfur oxides, detailed traverses conducted across the exhaust plume of the TF30 engine measured exhaust gas temperatures and emissions including carbon dioxide (CO_2). This information is utilized in this analysis. The point of sample acquisition was selected in reference to a gas temperature in excess of 625° F. The sample point is shown on the iso-therm map of figure 2 and is in an exhaust gas temperature location of 1,100° R. The iso-emission map of CO_2 is shown in figure 3. At the sample point, the CO_2 concentration is 2.10 percent while the traverse average CO_2 is 1.35 percent. Since the pollutants in the exhaust of turbine engines are generally distributed in the same pattern as the CO_2, it is assumed that the sulfur oxides are also distributed in patterns similar to that of CO_2. A correction of traverse average CO_2 divided by the concentration of CO_2 at the sample point is applied to the total measured SO_2 plus SO_3 to establish a sulfur oxide concentration representing the average for the entire exhaust:

$$(1.35/2.10) \times 2.56 = 1.65 \text{ ppm}$$

The measured sulfur oxides as corrected is then 1.65 ppm less than that of the sulfur balance, and the sulfur recovered was 50 percent of the sulfur in the fuel. The sulfur which was not measured could have consisted, in part, of sulfides, sulfates, and sulfur.

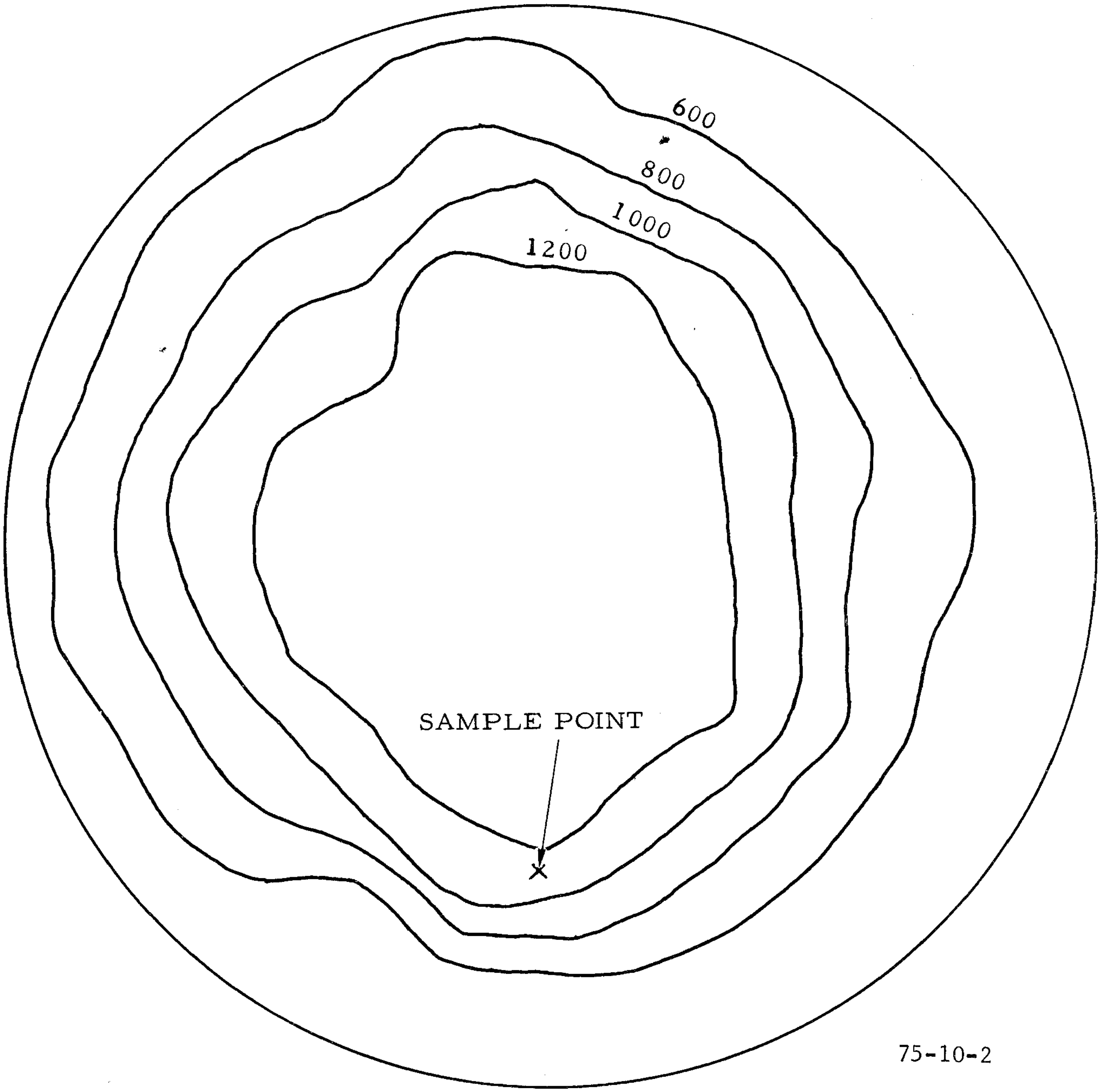

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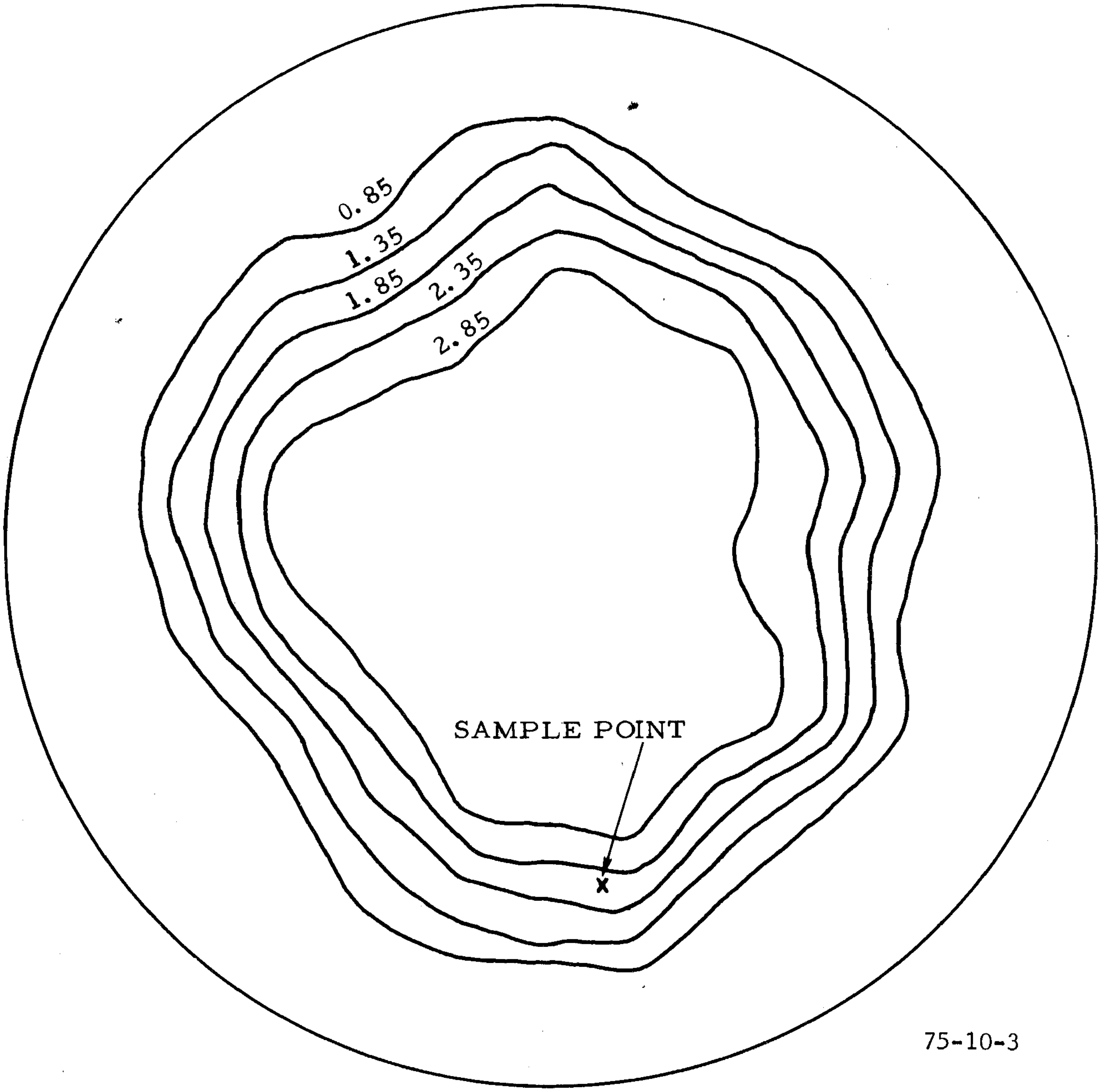
FIGURE 2. ISO-THERM MAP AND SULFUR OXIDE SAMPLE POINT



CO_2 VALUES INDICATED ARE IN PERCENT

FIGURE 3. CO_2 ISO-EMISSION MAP AND SULFUR OXIDE SAMPLE POINT

CONCLUSIONS

It is concluded that:

1. The oxides of sulfur in aircraft turbine engine exhaust include detectable quantities of sulfur trioxide.

2. Although the oxides of sulfur can be measured by wet chemical methods, acquisition of the sample in aircraft turbine engine exhaust by these methods require further development.

3. The severe sample collection environment and the low concentration of sulfur oxides in turbine engine exhaust plus the limited scope of this investigation resulted in a low total sulfur recovery.

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