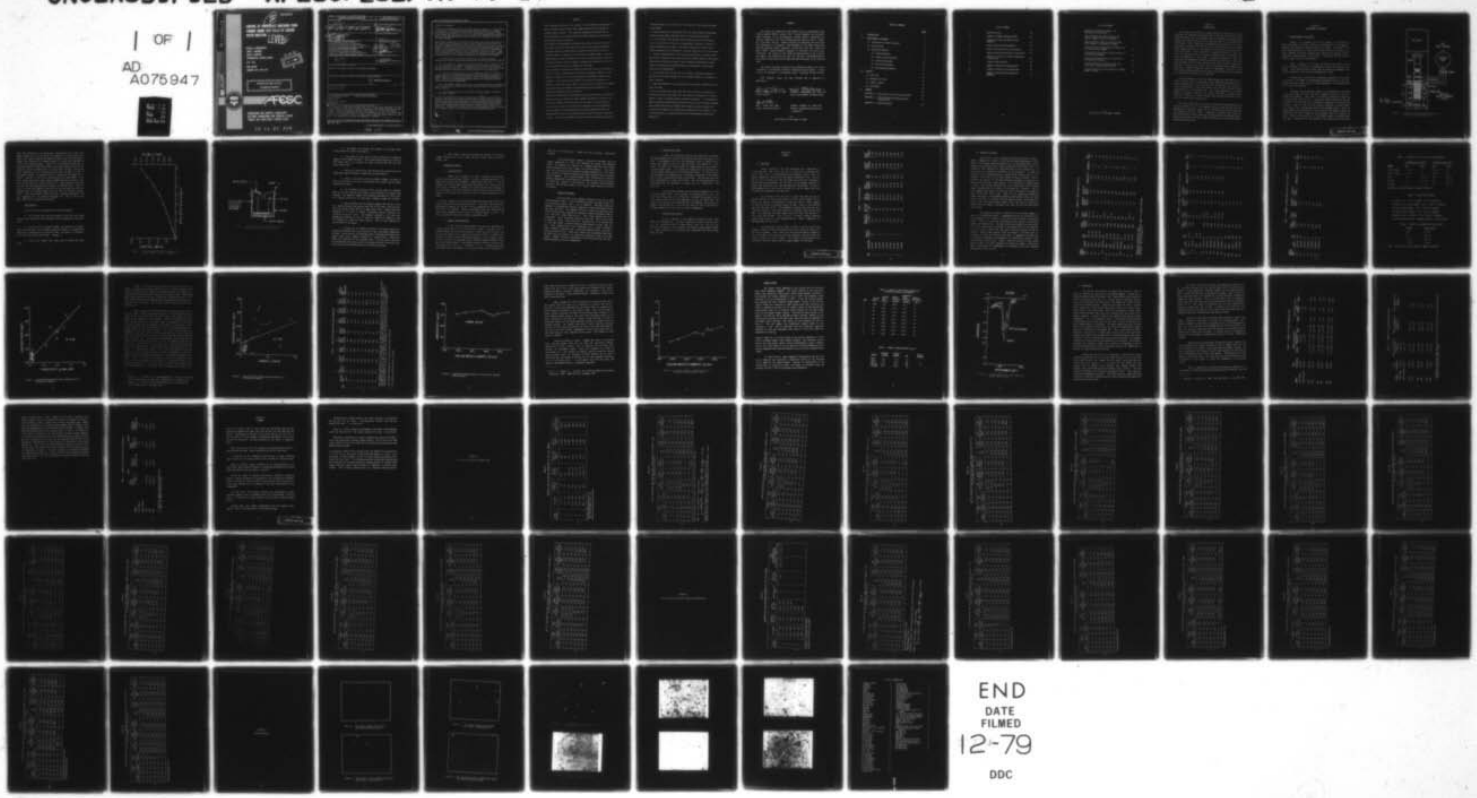
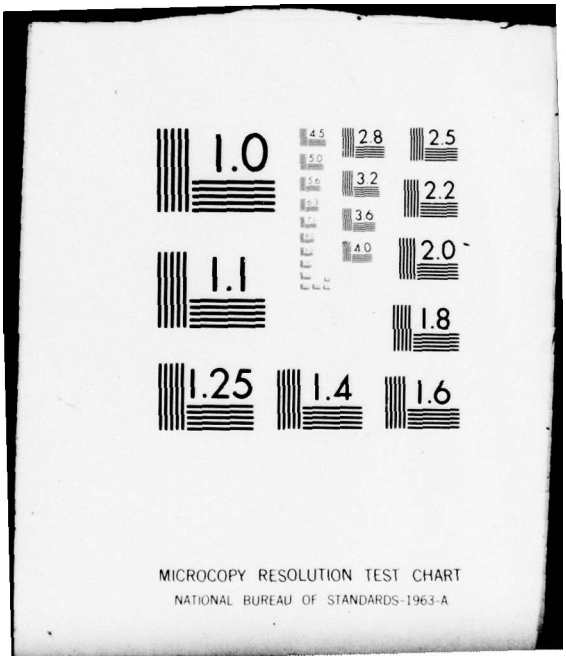
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CONTROL OF PARTICULATE EMISSIONS FROM TURBINE ENGINE TEST CELLS BY COOLING WATER INJECTION

LEVEL II

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The operation of DOD turbine engine test cells in California has been criticized by the State environmental regulatory agencies because smoke generated by some engines results in excessive opacity (visibility) of the test cell exhaust plume. Since the plume exceeds visibility standards for only a relatively small proportion of engines tested a low cost control technique which brings the test cell into compliance with opacity standards is required.

Water injection is practiced in may Air Force test cells for cooling the test

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cell walls to maintain their structural integrity, however, in the process, a steam plume is created precluding Ringelmann visibility measurements. This study was initiated to verify that, in addition to forming a steam plume, water used to cool the test cell walls also removes engine generated particulates and substantiates this procedure as a legitimate pollution control technique.

This study concentrated on determining the particle removal efficiency of the water spray by analysis of water samples collected in the test cell that would normally drain from the test cell when a J75-P17 engine is being tested. Solids in the water were analyzed by the Environmental Sciences Branch of the Engineering and Services Laboratory (ESL) and independently by the Fine Particles Group of the IIT Research Institute (IITRI). IITRI also performed particle sizing and counting and provided photomicrographs of the particles. The following summarizes the results of this study:

(1) Water injection for cooling the test cell walls removes a measurable portion of particulate emissions from the turbine engine exhaust.

(2) The 3028 ℓ/min (800 gal/min) water flowrate used at McClellan AFB for cooling results in removal of approximately 50 percent by weight of solids entrained in the water. The other 50 percent of solids in the water and particles not captured by the water spray are in the stack gases.

(3) Positive identification of the collected particles as turbine engine particles by comparison with engine particles sampled directly from exhaust gases was not possible because of their different morphology in water. However, differentiation between mineral and combustion related carbon particles was accomplished.

(4) The effluent water of the test cell contains significant numbers of particles which would normally be in the exhaust stream in the absence of water injection.

(5) Some hydrocarbons are also removed from the exhaust, especially at low power settings.

It can be concluded from this study that water injection as practiced at McClellan AFB test cell results in significant (~ 50% by weight) control of turbine engine particulate emissions. It is postulated that the process could be made more efficient by the use of better designed spray nozzles which would increase water droplet particle contact and inclusion of a demister to increase water removal from the exhaust. This is being studied in a separate project by the Engineering and Services Laboratory.

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SUMMARY

This study was performed at the request of the HQ USAF/SG to determine the mass of turbine engine particulates removed from test cell exhaust by cooling water injection. The study was performed at McClellan AFB CA with assistance of the USAF Occupational Health Laboratory and Sacramento Air Logistics Center personnel.

The operation of Department of Defense (DOD) turbine engine test cells in the State of California has been criticized by the State environmental regulatory agencies because smoke generated by some engines results in excessive opacity (visibility) of the test cell exhaust plume. Since the plume exceeds visibility standards for only a relatively small proportion of engines tested, a low cost control technique which brings the test cell into compliance with opacity standards is required.

Water injection is practiced in many Air Force test cells for cooling the test cell walls to maintain their structural integrity, however, in the process, a steam plume is created precluding Ringelmann visibility measurements. This study was initiated to verify that, in addition to forming a steam plume, water used to cool the test cell walls also removes engine generated particulates and substantiates this procedure as a legitimate pollution control technique.

This study concentrated on determining the particle removal efficiency of the water spray by analysis of water samples collected in the test cell that would normally drain from the test cell whan a J75-P17 engine is being tested. Solids in the water were analyzed by the Environmental Sciences Branch of the Engineering and Services Laboratory (ESL) and independently by the Fine Particles Group of the IIT Research Institute (IITRI). IITRI also performed particle sizing and counting and provided

photomicrographs of the particles. The results of this study are summarized below:

1. Water injection for cooling the test cell walls removes a measurable portion of particulate emissions from the turbine engine exhaust.
2. The 3028 ℓ/min (800 gal/min) water flowrate used at McClellan AFB for cooling results in removal of approximately 50 percent by weight of solids entrained in the water. The other 50 percent of solids in the water and particles not captured by the water spray are in the stack gases.
3. Positive identification of the collected particles as turbine engine particles by comparison with engine particles sampled directly from exhaust gases was not possible because of their difference morphology in water. However, differentiation between mineral and combustion related carbon particles was accomplished.
4. The effluent water of the test cell contains significant numbers of particles which would normally be in the exhaust stream in the absence of water injection.
5. Some hydrocarbons are also removed from the exhaust, especially at low power settings.

It can be concluded from this study that water injection as practiced at McClellan Air Force Base (AFB) test cell results in significant (~ 50% by weight) control of turbine engine particulate emissions. It is postulated that the process could be made more efficient by the use of better designed spray nozzles which would increase water droplet particle contact and inclusion of a demister to increase water removal from the exhaust. This is being studied in a separate project by the Engineering and Services Laboratory.

PREFACE

This study was requested by HQ USAF/SG and was accomplished under Program Element 62601F, project 1900. Project Engineer was Lieutenant James Tarquinio of the Environmental Sciences Branch, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida. Sample collection at McClellan Air Force Base was performed by Lt Tarquinio, Capt Normington of the USAF Occupational and Environmental Health Laboratory, Brooks Air Force Base, Texas and Major Banner, Bioenvironmental Engineer at McClellan Air Force Base, California. The success of this study was made possible by the outstanding support and cooperation of test cell operators, SM-ALC/MA personnel and others at McClellan Air Force Base who gave assistance to the sampling team.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I
INTRODUCTION

This study was initiated to verify that water injection is a valid technique for removing particulate matter from aircraft turbine engine exhausts during test cell operation and to determine the optimum water flowrate for particle control, still achieving test cell cooling and water conservation. This investigation concentrated on analysis of the resulting aqueous effluent from the test cell to provide evidence of turbine engine generated particles and increases in the solids concentrations in the cooling water. Water injection is practiced in many Air Force test cells for cooling the test cell walls to maintain their structural integrity; concomitantly a steam plume is sometimes generated. Under this condition, the Ringelmann visibility standard is not violated. This study was initiated to verify that increasing the water flow rate beyond that necessary to cool the cell walls, thus insuring steam plume formation and visibility standards compliance under all atmospheric conditions, would also remove engine-generated particulates and substantiate this technique as a legitimate pollution control technique.

Previous attempts to verify the effectiveness of water injection as a control process using conventional stack sampling procedures were of limited success due to the large stack area of the test cell, low particulate concentrations in the gas stream, and the high dissolved solids concentration of the cooling water. The study reported here, although giving an indirect indication of control efficiency, provides direct evidence for removal of turbine engine generated particulate matter from the gas stream by the cooling water.

This report summarizes the results of analysis by the Engineering and Services Laboratory (ESL), Environmental Sciences Branch of the Air Force Engineering and Services Center and the Fine Particles Research Group of IIT Research Institute (IITRI). Analytical assistance from IITRI was desirable because of their experience in measuring and identifying turbine engine particulates and their extensive facilities for sizing and photographing small particles.

SECTION II
EXPERIMENTAL PROCEDURES

(1) Water Flowrate Calibration

Figure 1 is a schematic of test cell number 3 at McClellan Air Force Base (AFB), California, showing the configuration of the augmentor, diffuser and sampling containers used in this study. The intent of the water injection system is cooling of the test cell walls; therefore, the water flowrate is normally automatically controlled to maintain the wall temperature desired below a preset value. The system can also operate manually under control of the operator.

Water is supplied to the test cell from a 61,000 liter (16,000 gallon) storage tank which is automatically filled from the base well system. Three pumps feed three spray rings surrounding the augmentor tube and the flowrate is controlled by calibrated ball valves.

Because water flowrate was an important parameter for this study the output of the pumps was determined by measuring the water level depression in the storage tank (143 liters/centimeter, 95.66 gallon/inch) over a known time interval.

Normally the cooling water which is not evaporated or entrained in the gas stream exits the test cell through two drains in the floor beneath the diffuser. This water is eventually processed through the industrial waste treatment plant. During this study a method was required to determine the fraction of the inlet water remaining in the exhaust and exiting through the stack and the fraction available to remove engine particulates which subsequently enters the drainage system. This was accomplished by sealing the drains in the floor of the exhaust chamber and determining the water volume in this retangular area as a function of depth. Drains were sealed with a thin plastic sheet and weighted with sand bags. Sand bags were also placed in the augmentor tube to prevent

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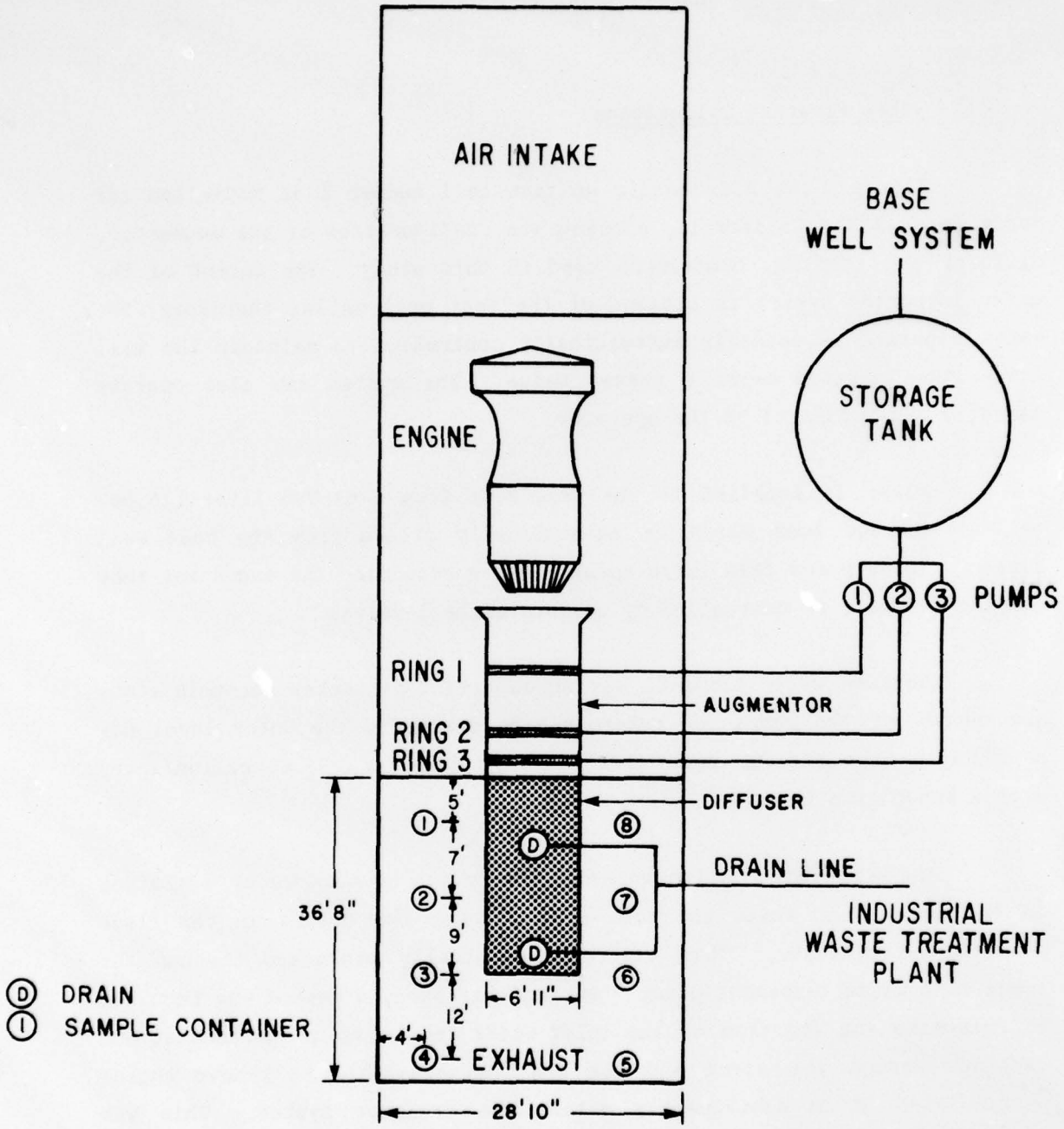


Figure 1. Schematic of Test Cell Number 3 at McClellan AFB California

water from draining out the engine end. Known quantities of water were added through ring 3 by measuring the depression of the storage tank. Using a dip stick to measure the depth of water on the floor, the exhaust chamber was calibrated for volumes between 1135 liters (300 gallons) to 15,141 liters (4000 gallons). Figure 2 is a calibration curve used to calculate the water volume which flows to the drain system and then to the industrial waste treatment plant in normal engine testing. During the study, immediately at the conclusion of each run, the depth of water in the exhaust chamber was measured prior to removal of the sample con0 - tainers. Because of the error associated with the measurement of the water volume other water inputs such as combustion water and water in the inlet air was ignored in the calculations (i.e., both combustion and inlet air water are only approximately 6 percent of injected water). Both the inlet air water and combustion water are in the gas phase and would not condense into the drainage system since the exit air requires an additional ∿ 1000 liters/minute (ℓ/min) of water to become saturated at the exit temperature of ∿ 38 degrees centigrade (C°). This is one of the major sinks for the injected cooling water.

Test Protocol

The test runs were performed in the following manner:

a. The storage tank inlet was closed so that the total added cooling water volume could be calculated from the depression of the water level.

b. The drains in the exhaust chamber were sealed with a plastic sheet and sand bags, and the sample containers (Figure 3), designed and constructed at McClellan Air Force Base (AFB), were placed in the appropriate locations around the diffuser. (Figure 1)

c. Inlet water samples were taken from the pumps and spray rings.

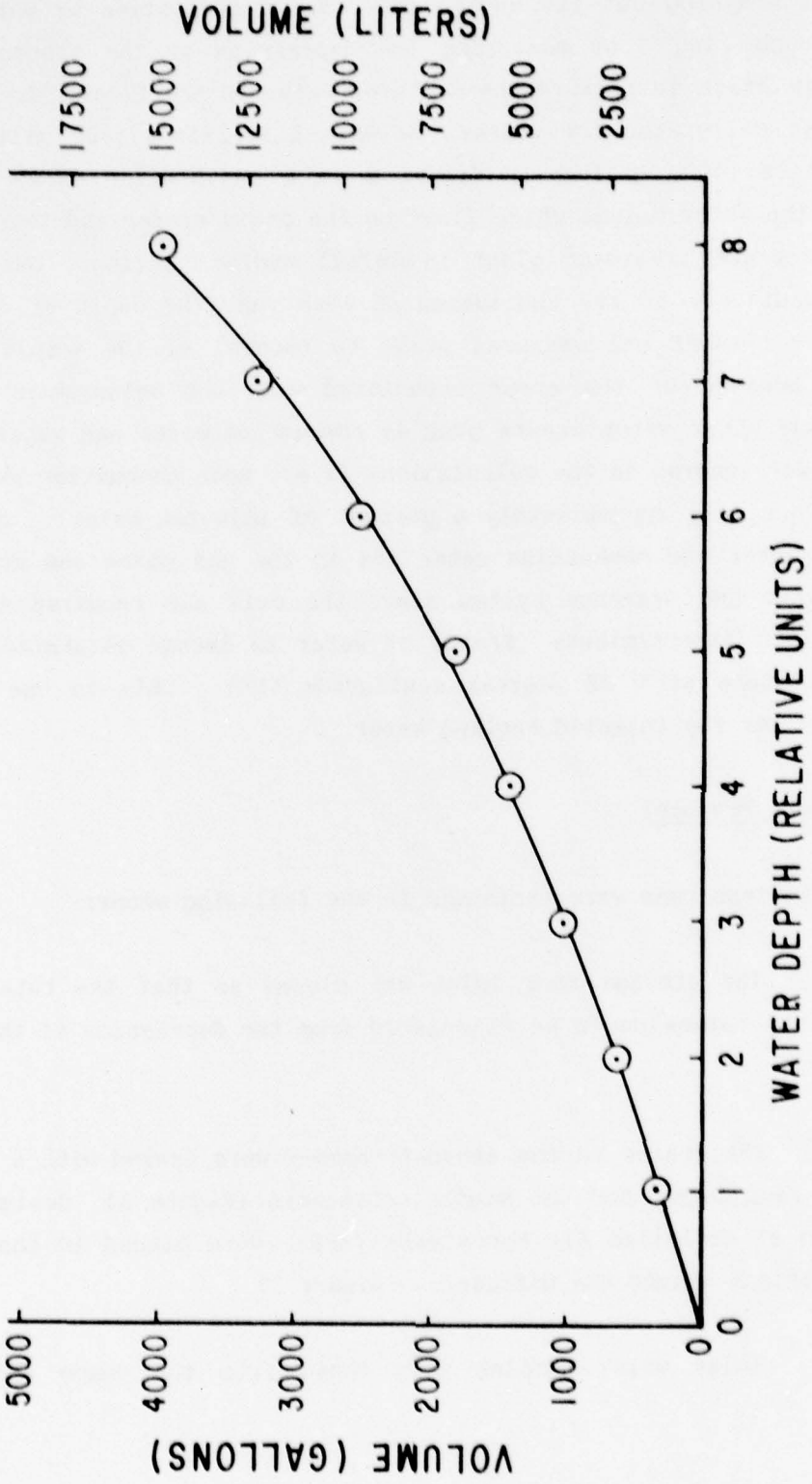


Figure 2. Water Volume Versus Water Depth in the Exhaust Chamber of Test Cell Number 3

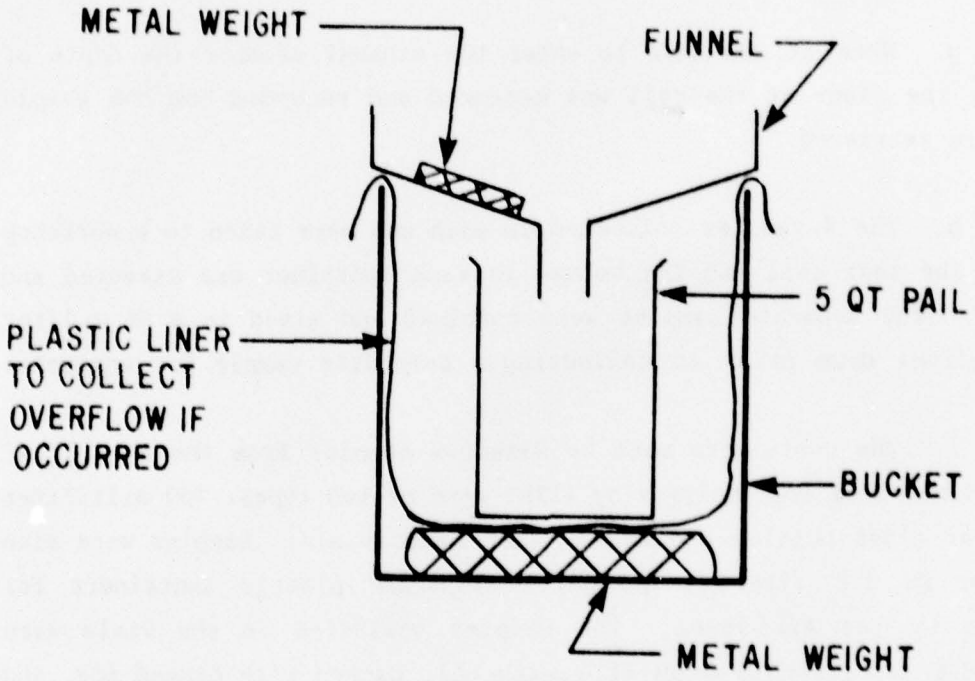


Figure 3. Sample Container Used to Collect Cooling Water Samples in the Exhaust Chamber

d. The engine was started and brought to the proper power setting before the water was turned on.

e. The engine run was timed to allow collection of sufficient sample in each sample container. This varied from 20 minutes at idle with only spray ring 1 to 3 minutes for some 95 percent RPM runs with only spray rings 2 and 3.

f. After the required run time the water was turned off and the engine shut down according to standard operating procedures.

g. When it was safe to enter the exhaust chamber the depth of water on the floor of the cell was measured and recorded and the sample containers retrieved.

h. The 8 samples collected in each run were taken to a workshop next to the test cell and the volume in each container was measured and recorded. The separate samples were combined and mixed in a 66.2 liter (17.5 gallon) drum prior to collecting a composite sample for analysis.

i. The containers used to withdraw samples from the 66.2 liter (17.5 gallon) drum for analysis by IITRI were of two types: 700 milliliter (ml) clear glass bottles and 25 ml amber glass vials. Samples were also withdrawn in 3.8 liter (1 gallon) collapsible plastic containers for retention by the Air Force. The samples collected in the vials were immediately acidified to a pH of 2 with HCl, packed with canned ice, and air freighted to IITRI for carbon analysis. The 3.8 liter samples were not preserved in any manner.

j. Aliquots of the samples collected in the glass bottles were filtered at McClellan AFB in preparation for their microscopic examination at IITRI. The filtration was performed using a straight-sided funnel with ground glass filter support attached to a vacuum flask. Particulate matter was filtered onto 25 millimeter (mm), 0.45 micro meter (μm) pore size Millipore® filters for optical microscopy and both 25 mm and 47 mm, 0.03 μm pore size Nuclepore® filters for electron microsopy.

k. After sample collection the drains were opened in the exhaust chamber allowing the cell to empty and the storage tank refilled for another test.

Analytical Methods

a. Solids Analysis

Samples were analyzed for total, dissolved and suspended solids at ESL using procedure (208 a, c and d) in Standard Methods for the Examination of Water and Wastewater, 14th Edition (Std. Meth.). A 100 mℓ aliquot was filtered under vacuum and the filters and residue dried at 103°C prior to weighing. Whatman 5.0 cm GF/C filters were utilized for all filtrations. For total dissolved solids 50 mℓ were slowly reduced in volume at 96°C before final drying at 103°C to avoid splattering of the sample.

At IITRI, samples were filtered through Reeve Angel Type 934-A glass fiber filters and the residue dried at 105°C. Total dissolved solids were determined by drying the filtrate from the suspended solids analysis at 180°C prior to weighing. Volatile suspended solids were determined by heating the suspended solids filters to constant weight at 550°C. The loss in weight was reported as volatile suspended solids.

b. Organic Carbon Analysis

At ESL Chemical Oxygen Demand was utilized to determine the soluble organic matter in the cooling water samples. Procedure (508) in Standard Methods was used except mercuric sulfate was deleted due to the low chloride content of the samples and the policy of ESL to eliminate the discharge of mercury unless absolutely necessary. On one sample, grease and oil analysis was performed using Standard Methods procedure 502B, Partition-Infrared Method. This method involves extraction of the acidified sample with freon (1,1,2 trichloro - 1,2,2, - trifluoroethane) and then measuring the absorbance of C-H stretch region of the IR spectrum at

2930 cm^{-1} (3.41 micrometers). Hexane was used to prepare a hydrocarbon standard.

The acidified water samples, collected in the amber vials and shipped immediately to IITRI, were analyzed for organic and inorganic carbon. The samples were analyzed on a Beckman Model 915 Total Organic Carbon Analyzer fitted with a Model 215A Infrared Analyzer. The instrument was calibrated using potassium hydrogen phthalate for total carbon and a mixture of sodium bicarbonate and sodium carbonate for an inorganic carbon standard. The acidified samples were ultrasonically treated to break-up agglomerates and purged with nitrogen gas just prior to analysis to remove CO_2. Because of acidification, the carbonate and bicarbonate portion of the inorganic carbon in the original sample would be lost prior to analysis.

c. Optical Microscopy

All microscopy on the samples filtered on site and at IITRI was performed at IITRI. A Lietz Ortholux microscope was used to count and size particles greater than 1 μm in diameter. Polarized light was employed to differentiate between combustion related particulate matter and other particles. The membrane filters on which the particles were filtered from the water samples were mounted on glass microscope slides in 1.515 refractive index immersion oil. This fluid rendered the filter transparent. Three microscope objectives--40X, 25X, and 6.3X were used for particle sizing. These objectives, coupled with a 12.5X eyepiece and a 1.25X tube length, provided nominal magnifications of 625X, 390X, and 98X. Exact magnifications were determined with a stage micrometer. Feret's diameter, measured with a calibrated eyepiece scaler, was used to determine particle size. Seven size classes were established and either 200 particles were sized or 50 fields were observed in each of the size classes. Number and mass distributions were calculated from the data. Photomicrographs are given in Appendix C.

d. Electron Microscopy

A JEOL 100C Analytical Electron Microscope and a Quantimet 720 Image Analyzer were used to count and size particles less than 1 μm in size. A rectangular section of the Nuclepore filter on which the particles were deposited was cut from mid-radius and mounted on a glass slide. The filter was carbon coated in a vacuum evaporator and mounted in a carbon sample holder. All filters were inspected in the Scanning Electron Microscope (SEM) mode of the electron microscope. The filter section was surveyed at low magnification to determine uniformity of the deposit and to select representative areas for analysis. The selected areas were then photographed at 6000X and 10,000X. The 10,000X photographs were interrogated by the Quantimet to obtain the size information on the particles.

The Quantimet measures various particle parameters in units of picture points (pp). The instrument is calibrated with a rule. For this study 508 pp equalled 3 cm @10,000X. Therefore 508 pp equal 3 μm or 1 pp equals 0.0059 μm and 1 pp^2 represents an area of 0.000035 μm^2. The area of each particle was determined with the Quantimet and the particle diameter calculated from a circle of area equal to that of the particle. Photomicrographs of the particles are given in Appendix C.

e. Miscellaneous Analysis

At ESL, turbidity of the samples was measured using a Hach Model 2100A Turbidimeter. The units reported are relative and are useful only for evaluating trends in these samples since the scale was normalized at 90 percent scale reading for the highest reading sample (number 9). Sample conductivity was measured with a Barnstead Conductivity Bridge Model PM-70CB.

SECTION III
RESULTS

(1) Test Runs

Initial checkout of the test procedures was accomplished on 13 February 1979. The J75-P17 was run at 95 percent (%) RPM and spray ring 1 (580 ℓ/min, 153 gallon/minute) was manually turned on when the exhaust temperature reached 38°C (100 degrees Fahrenheit) (°F). The test was run for 10 minutes and then the engine was turned off according to normal operating procedures and the water in the chamber measured to insure that sufficient water had accumulated for measurement. All procedures appeared to be satisfactory and the test runs for sample collection by IITRI were scheduled for the next day.

On 14 February 1979, test runs 1,2 and 3 were made at idle, 85 percent RPM and 95 percent RPM using a J75-P17, Serial Number 611769. These test runs were accomplished in order for IITRI to collect samples for particle analysis at different power settings. Tests on the following day using the same J75-P17, were designed to evaluate the effect of cooling water flowrate on particulate removal at a constant power setting (95% RPM). The flowrates evaluated ranged from 1900 ℓ/min (502 gal/min) to 3770 ℓ/min (996 gal/min). The 3.79 liter (1 gallon) samples collected during these tests were only analyzed by ESL. Table 1 summarizes the operating data for all tests.

Some additional results shown in Table 2 were determined from samples collected at McClellan AFB when the initial concept of these tests was being discussed. These samples are also from the exhaust chamber of test cell number 5 and were collected with stainless steel pans during the normal testing of a J75-P17 engine. The results of these analysis are included in the data summary and have sample numbers 101 and above.

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TABLE 1. ENGINE RUN DATA

RUN	DATE/TIME	DURATION (MIN)	INLET AIR TEMPERATURE (°C)	INLET AIR REL. HUM. (%)	STATIC PRESSURE (mm Hg)	FUEL FLOWRATE (Kg/min)	RPM (%)	COOLING WATER (LITERS)	DRAIN WATER (LITERS)
1	14/1112	20	11.6	61	760.98	11.30	58	16,656	11,746
2	14/1423	5	11.6	45	761.49	28.56	85	16,205	11,746
3	14/1604	3	12.2	42	762.00	67.13	95	9,278	3,850
4	15/0910	5	7.8	68	763.27	63.43	95.1	9,505	2,649
5	15/1008	5	9.4	61	763.02	62.52	95.1	11,045	3,596
6	15/1047	5	10.0	51	763.02	61.84	95.1	14,165	6,435
7	15/1312	3	11.6	48	760.73	60.18	94.8	10,137	4,921
8	15/1352	3	11.6	45	761.49	62.44	95.0	11,314	6,245
9	15/1428	3	12.2	43	760.73	62.29	95.1	9,777	5,110

(2) Analysis of Solids

The results of solids analysis by the ESL are given in Table 2. Table 3 compares the results of the ESL and those determined by IITRI. There is an average sample difference (54 ± 25 milligrams/liter (mg/ℓ)) between the dissolved solids values reported by the ESL and IITRI. The reason for this difference in dissolved solids is not known but must be the result of a systematic difference in the procedures. To check the accuracy of the solids analysis a prepared salt solution was run as a standard. The result was 221 mg/ℓ versus 220 mg/ℓ calculated. Table 4 presents the results of replicate analyses performed to determine the precision of the total solids analysis. For 8 replicates of sample number 1 (run 9) the standard deviation was only 10 mg/ℓ which for an average sample concentration of 318 mg/ℓ is a variance of 3.1 percent. Table 4 also compares the analysis of the inlet water collected at the pump and after exiting the spray rings. There is not significant difference between the pump or ring samples documenting that minimal solids are added by the rings prior to injection into the exhaust stream. The average (223 mg/ℓ) of all inlet water samples (pump, ring 1 and ring 2-3) was used to correct all the samples collected in the test cell for the inlet water total solids.

The greatest increase in solids for the collected samples is shown in the dissolved fraction. Suspended particles are increased only 8 mg/ℓ compared to the increase of 40 to well over 100 mg/ℓ for dissolved solids. Figure 4 is a plot of the dissolved solids content of each sample against the conductivity. The good correlation between these two parameters (0.96) shows that the increase in dissolved solids is due primarily to ionic material rather than just small particles passing through the filters. These soluble species could be sulfates or nitrates from the oxidation of sulfur and nitrogen in the fuel, or oxygenates of carbon such as aldehydes, carbonates, and carbonyls, all of which are soluble in water and relatively non-volatile. Table 5 gives the results of total solids analysis before and after sequential filtration of sample 1 (95 percent RPM) illustrating the predominance of dissolved solids and suspended solids smaller than 0.45 μm.

TABLE 2. SUMMARY OF SAMPLE ANALYSIS BY ESL

SAMPLE NUMBER/ RUN	SOURCE	RPM (%)	WATER FLOWRATE (ℓ/min)	TOTAL SOLIDS (mg/ℓ)	SUSPENDED SOLIDS (mg/ℓ)	DISSOLVED SOLIDS (mg/ℓ)	CONDUCTIVITY	TURBIDITY	COD (mg/ℓ)
16*	Pump	Idle (B)	833	223 (2)	<1	223	2.05	7	19
22	Pump	Idle (A)	833	216 (2)	<1	216	2.05	4	15
10*	Ring 1	Idle (B)	833	235	2.7	232	2.06	72	23
11	Ring 1	Idle (A)	833	237	1.2	236	2.07	7	23
9/1*	Effluent	Idle	833	331 (2)	1.8	329	2.75	90	200
13	Pump	85 (B)	3240	231	0.9	230	2.07	5	19
12	Pump	85 (A)	3240	230 (2)	2.1	228	2.11	10	19
18	Ring 2-3	85 (B)	3240	207	2.3	205	2.10	22	23
19	Ring 2-3	85 (A)	3240	219	1.5	217	2.12	8	15
4/2*	Effluent	85	3240	266	3.1	263	2.60	20	28
17	Pump	95 (B)	3093	211	1.2	210	2.12	7	15
20	Pump	95 (A)	3093	212 (2)	1.9	210	2.11	5	11
21	Ring 3	95 (B)	3093	217	1.2	216	2.08	9	15

* Samples also analyzed by IITRI
Parenthesis after result indicates number of analyses averaged
(B) Before, (A) after engine run

TABLE 2. SUMMARY OF SAMPLE ANALYSIS BY ESL (Continued)

SAMPLE NUMBER/ RUN	SOURCE	RPM (%)	WATER FLOWRATE (ℓ/min)	TOTAL SOLIDS (mg/ℓ)	SUSPENDED SOLIDS (mg/ℓ)	DISSOLVED SOLIDS (mg/ℓ)	CONDUCTIVITY	TURBIDITY	COD (mg/ℓ)
14	Ring 3	95 (A)	3093	245	1.3	245	2.1	10	19
7/3*	Effluent	95	3093	327	8.1	319	3.01	53	19
23	Pump	95 (B)		221	0.5	221	2.08	3	15
15	Pump	95 (B)		231	0.7	231	2.09	5	19
6/4	Effluent	95	1900	387 (2)	13.4	374	3.34	33	28
5/5	Effluent	95	2209	371 (2)	9.5	362	3.42	31	25
2/6	Effluent	95	2833	347	19.0	328	3.25	25	25
1/9	Effluent	95	3259	318 (8)	7.2	311	3.03	37	36
8/7	Effluent	95	3380	319 (2)	8.2	311	2.95	45	23
3/8	Effluent	95	3770	313 (2)	25.7	287	2.99	30	21
102	Ring 1	Idle	579		1.0			17	25
108	Ring 1	Idle	579		1.6			33	17.5
109	Ring 1	Idle	579		1.2			22	10
101	Effluent	Idle	579		4.3			80	256
104	Effluent	Idle	579		3.5			76	232

TABLE 2. SUMMARY OF SAMPLE ANALYSIS BY ESL (Concluded)

SAMPLE NUMBER/ RUN	SOURCE	RPM (%)	WATER FLOWRATE (ℓ/min)	TOTAL SOLIDS (mg/ℓ)	SUSPENDED SOLIDS (mg/ℓ)	DISSOLVED SOLIDS (mg/ℓ)	CONDUCTIVITY	TURBIDITY	COD (mg/ℓ)
106	Effluent	Idle	579		4.2			63	194
110	Effluent	70	579		2.3			68	248
111	Effluent	70	579		4.6			73	240
112	Effluent	70	579		1.6			69	235
103	Effluent	95	1650		10.7			65	29
105	Effluent	95	1650		10.6			66	18
107	Effluent	95	1650		10.0			58	17

TABLE 3. COMPARISON OF ESL AND IITRI SOLIDS ANALYSIS

	SUSPENDED SOLIDS (mg/l)		DISSOLVED SOLIDS (mg/l)	
SAMPLE	ESL	IITRI	ESL	IITRI
Inlet at pump	< 1 (2)	0	221 (2)	26
Inlet at Ring 1	2.0 (2)	<1.0	236 (2)	274
Idle	1.8	2.0 (3)	330	362 (3)
85% RPM	3.1	4.3 (3)	263	354 (3)
95% RPM	8.1	7.7 (3)	319	387 (3)

Parentheses indicates number of samples averaged.

TABLE 4. TOTAL SOLIDS ANALYSIS

Precision - (σ = ± 10 at 318 mg/l, 3.1% (8 replicates)

Average of inlet water samples - 224 ± 12 mg/l (18 samples)

Average of pump samples - 221 ± 11 mg/l (12 samples)

Average of Ring 1 samples - 236 ± 2 mg/l (2 samples)

Average of Ring 2-3 samples - 220 ± 16 mg/l (4 samples)

Standard sample analysis - standard 220 mg/l, 221 mg/l found

TABLE 5. EFFECT OF FILTRATION ON TOTAL SOLIDS

FILTER	TOTAL SOLIDS
none	321 (2)
GFC	333 (2)
0.8 μm	325 (2)
0.45 μm	325 (2)

Note: Parenthesis indicate number of samples considered

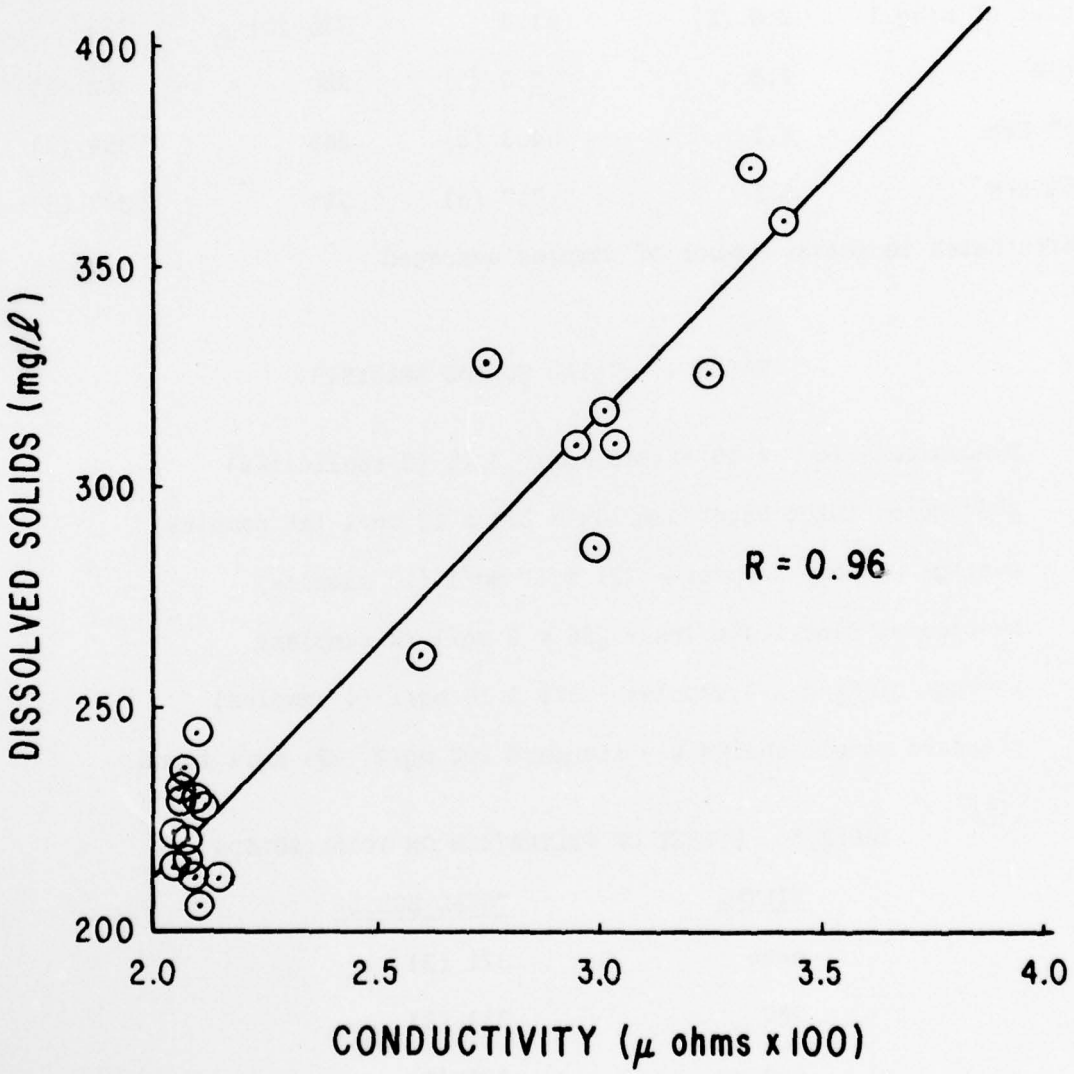


Figure 4. Dissolved Solids Content Versus Conductivity for Cooling Water Samples

Figure 5 shows measured dissolved solids plotted against turbidity. A positive correlation coefficient of 0.41 indicates that a small portion of the material defined as dissolved solids is probably non-filterable particles which have the ability to scatter light. Even though small particles would contribute a small mass, evidence that water injection removes them from the exhaust stream is important because they are a principal cause of opacity. This will be shown more fully in section III, subsection 4.

Table 6 summarizes calculations of the solids emissions from the test cell under varying cooling water flowrates. By subtracting the total solids in the inlet water from the total solids in each sample the solids added by the engine can be calculated. Figure 6 illustrates that the total solids entrained in the water spray is independent of the water injection rate as would be expected if the analysis is not biased. Total solids captured by the water averages 323.8 ± 14.3 grams/minute (g/min). Assuming that all the solids emitted in the turbine engine exhaust are captured in the water spray, the solids emission rate can be calculated from the concentration of solids in the drain water and the total cooling water flowrate. This also requires assuming that the distribution of solids in the water exiting the test cell in the exhaust stream has the same solids concentration as the drain water. This was not confirmed during this study, however, comparing the emission rate calculated in this manner, 5.2 grams/kilogram (g/Kg) of fuel, with that measured by the USAF Occupational and Environmental Health Laboratory (USAFOEHL)*, using Environmental Protection Agency (EPA) Method 5 air sampling techniques in the exhaust stack, 5.6 g/Kg of fuel indicates that this assumption may be valid. This is reasonable since 80 percent of the aerosol mass is contributed by particles > 0.5 μm and these relatively large particles are more likely captured.** The emission rate calculated total solids in the

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* Gokelman, J.J., Stevens, J.E., and Normington, W.E, "Effects of Cooling Water on Engine Test Cell Emissions," OEHL-TR-78-113, November 1978.

** Lundgren, D., "Low Efficiency Control Measures for Jet Engine Test Cells," CEEDO-TR-78-53, September 1978.

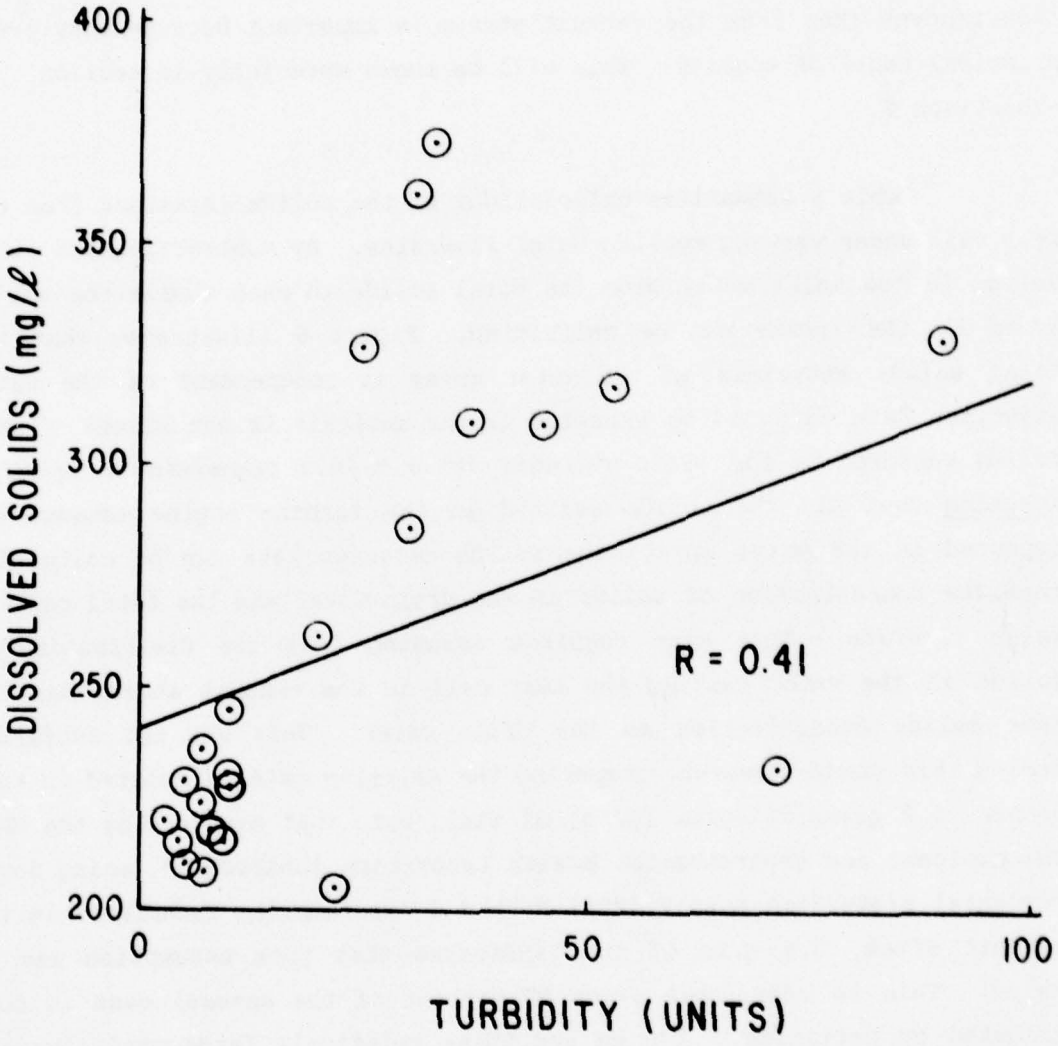


Figure 5. Dissolved Solids Content Versus Turbidity for Cooling Water Samples

TABLE 6. ENGINE PARTICULATE EMISSION CALCULATIONS

RUN	PERCENT RPM	A FUEL FLOWRATE (kg/min)	B COOLING WATER (ℓ/min)	C DRAIN WATER (ℓ/min)	D (B-C) STACK[1] WATER (ℓ/min)	E ENGINE[2] SOLIDS (mg/ℓ)	F (E-C)[2] DRAIN SOLIDS (g/min)	G (E-D)[2] STACK SOLIDS (g/min)	H (F+G)[2] TOTAL SOLIDS (g/min)	I (H/A)[3] EMISSION RATE (g/kg Fuel)
1	Idle	11.3	833	591	242	108	63.7	26.1	89.8	8.0
2	85	28.6	3240	2351	889	39	92.4	34.9	127.3	4.5
3	95	67.1	3093	1283	1810	103	132.3	186.6	318.9	4.8
4	95	63.4	1901	530	1370	163	87	223.7	310.3	4.9
5	95	62.5	2209	719	1492	147	106	219.8	325.7	5.2
6	95	61.8	2833	1287	1544	123	158.3	189.9	348.2	5.6
7	95	60.2	3380	1640	1740	95	156.0	165.5	321.4	5.3
8	95	62.4	3770	2082	1688	89	185.3	150.2	335.5	5.4
9	95	62.3	3259	1703	1556	94	160.4	146.6	306.9	4.9

1 Only considers water which it is assumed has the same solids concentrations as the drain water. Water contributed by combustion and inlet air are not included. An additonal approximately 1000 ℓ/min of water is required to saturate the exhaust air at 38°C, the exhaust temperature, so these two sources of water with no solids would not dilute the water collected in the test cell and effect the concentration of solids in the samples.

2 Total solids corrected for inlet water total solids (224 mg/ℓ)

3 Total engine solids emissions collected

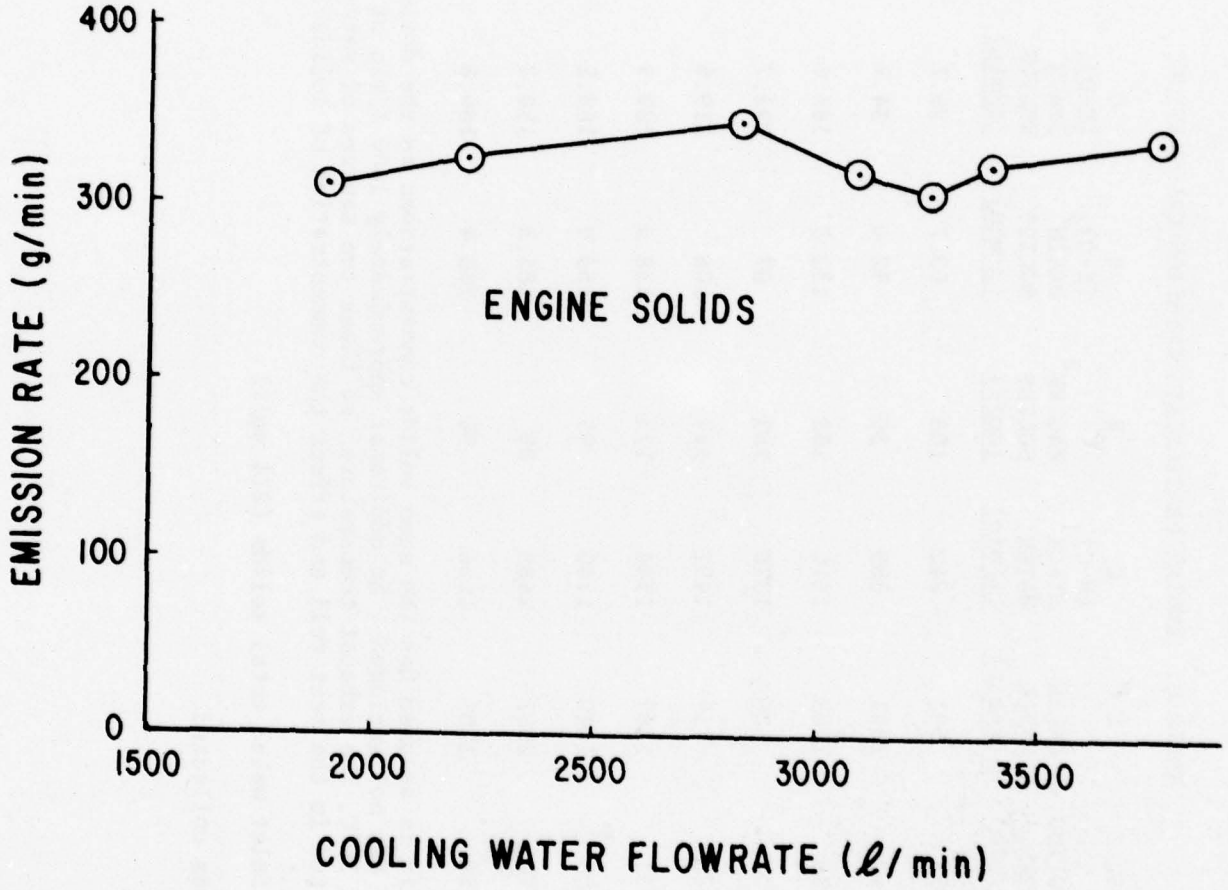


Figure 6. Emission of Engine Solids as a Function for Cooling Water Flowrate

water phase should not be compared with the 1.08 g/Kg fuel emission index reported for the J-75-P17* since other species not measured in the turbine engine particulate emissions measurement are included in the solids analyzed in the water. These include sulfates, carbonates, nitrates and other dissolved solids.

Again assuming the solids concentration in both the drain water and exhaust water are equal it is possible to calculate the relative portions of the solids generated by the engine which are removed which would normally be present in the exhaust plume. This is also shown in Figure 6 which illustrates the effect of the cooling water flowrate on the split between engine solids in the drain water and engine solids in the water remaining in the stack gas. Figure 7 shows this data in terms of percentage removal of the engine emissions (solids in the drain water are assumed removed). The removal efficiency of water injection increases from 28% at 1900 ℓ/min (502 gal/min) to 55% at 3770 ℓ/min (996 gal/min). The 3028 ℓ/min (800 gal/min) recommended for particulate control by the USAF OEHL based on stack sampling results gives ∿ 50% removal of total solids at 95% RPM.

Results presented in Table 7 suggest that there is no optimum water flowrate between 1900 and 3770 ℓ/min for particulate removal. Observations indicate, however, that at flowrates of 3770 ℓ/min (1000 gal/min) and presumably higher, black water droplets are found on surrounding cars. This fallout of droplets could be caused by lowered plume buoyancy and/or the existance of large droplets due to lack of sufficient heat and energy in the test cell to cause complete aerosolization of the excess water. It would appear that the 3028 ℓ/min (800 gal/min) recommended would be a reasonable compromise.

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* Scott, H., Naugle, D., "Aircraft Air Pollution Emission Estimation Techniques - ACEE," CEEDO-TR-78-33, September 1978.

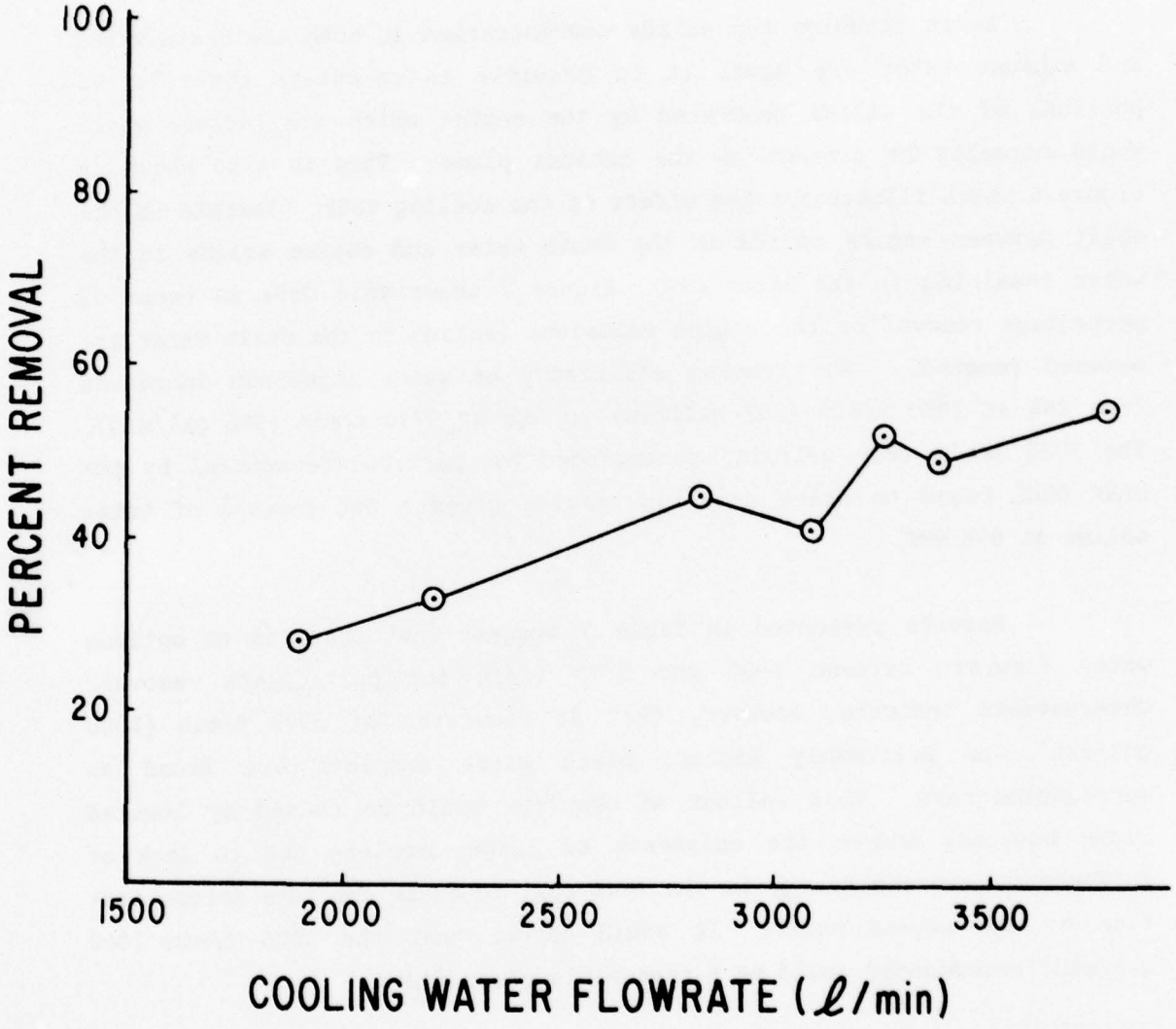


Figure 7. Percentage Removal of Engine Solids as a Function of Cooling Water Flowrate

Organic Carbon

The organic carbon component of the cooling water was analyzed using three different methods. The carbon content of the unfiltered samples was analyzed at IITRI using a Total Carbon Analyzer differentiating between the carbon oxidized to CO_2 at 950°C and inorganic carbon converted to CO_2 by acidification at 150°C. At ESL the filtered samples were analyzed for their Chemical Oxygen Demand. Review of the volatile organic carbon data reported in IITRI results shows that filtration may remove a significant portion of the organic carbon at 85% and 95% RPM. Interestingly there are no volatile solids reported for the idle sample which had the highest organic content. The volatile solids content of the samples collected was 53% at 85% RPM and 69% at 95% RPM. Removal of this fraction by filtration at ESL gave lower CODs than would be expected for the higher power settings. The results of both analyses are given in Table 8. The only sample with significant organic carbon is that collected at idle. This is consistent with the inefficient combustion exhibited at idle and represents that portion of the fuel carbon not oxidized to CO and CO_2.

Figure 8 shows the C-H stretch region of the infrared spectrum of a Freon extract of Sample number 9 and a hexane standard. This technique, used to measure oils and greases, gives a value of approximately 3 mg/ℓ. Examination of the other peaks in the IR spectra discloses predominately oxygenated compounds which would be expected from a partially oxidized hydrocarbon.

As noted earlier, these oxygenated hydrocarbons and the inorganic carbonates may constitute a significant portion of the dissolved solids added by the engine exhaust. Because of acidification of the samples prior to analysis at IITRI, the values for inorganic carbon are probably low due to loss of carbonates and bicarbonates.

TABLE 7. EFFECT OF INLET WATER FLOWRATE ON PERCENTAGE ENGINE SOLIDS REMOVAL

RUN	PERCENT RPM	COOLING WATER ℓ/min	ENGINE EMISSION (g/min)	CORRECTED STACK EMISSION (g/min)	REMOVAL EFFICIENTY (%)
1	Idle	833	89.8	26.1	71
2	85	3240	127.3	34.9	73
3	95	3093	318.9	186.6	41
4	95	1900	310.3	223.7	28
5	95	2209	325.7	219.8	33
6	95	2833	348.2	189.9	45
7	95	3380	321.4	165.6	49
8	95	3770	335.5	150.2	55
9	95	3259	306.9	146.6	52

TABLE 8. ORGANIC CARBON ANALYSIS (mg/ℓ)

SAMPLE	INORGANIC CARBON	ORGANIC CARBON	COD	OIL & GREASES
Pump	8.5	3.0	19	
Ring 1	8.5	5.5	23	
Idle	6.0	70.0	200	3.3
85% RPM	12.0	11.0	28	
95% RPM	12.0	20.5	19	

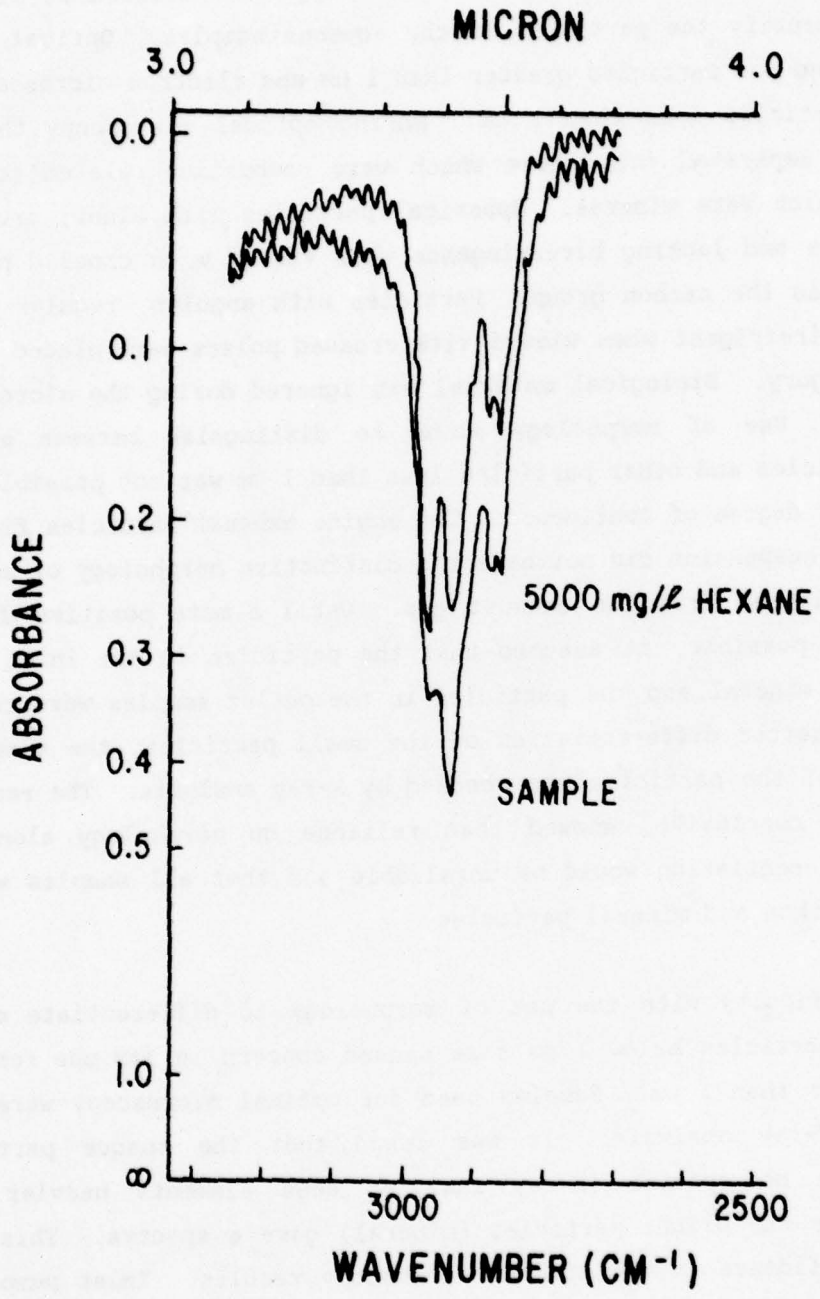


Figure 8. Infrared Spectrum of Freon Extract of Sample Number 9 (Idle)

(4) Microscopy

Both optical and electron microscopy were utlized at IITRI to count and identify the particles in the aqueous samples. Optical microscopy was used for particles greater than 1 μm and electron microscopy was used for particles less than 1 μm. During optical microscopy the particles were separated into those which were combustion related (carbon) and those which were mineral. Spherical particles with blunt, irregular edges, opaque and lacking birefringence when viewed with crossed polars, were placed in the carbon group. Particles with angular, regular edges, bright and birefrigent when viewed with crossed polars were placed in the mineral category. Biological material was ignored during the microscopic examination. Use of morphology alone to distinguish between exhaust related particles and other particles less than 1 μm was not possible with even a modest degree of confidence. The engine exhaust particles filtered from a water suspension did not have the distinctive morphology of exhaust particles filtered from the exhaust gas. Until a more positive differentiation is possible, it assumed that the particles in the inlet water samples were mineral and the particles in the outlet samples were carbon. To obtain a better differentiation of the small particles, the elemental composition of the particles was checked by X-ray analysis. The results, although not conclusive, showed that reliance on morphology alone for particle differentiation would be unreliable and that all samples were a mixture of carbon and mineral particles.

Difficulty with the use of morphology to differentiate carbon and mineral particles below 1 μm size caused concern in its use for particles greater than 1 μm. Samples used for optical microscopy were submitted for X-ray analysis. It was found that the opaque particles (carbon) gave no spectra (X-ray analyzer sees elements heavier than sodium), while the bright particles (mineral) gave a spectra. This data increases confidence in the optical microscopy results. Inlet pump particles were predominantly mineral. The spray ring water sample contained a mixture of materials, possible particles from the piping and deposits of carbon from the spray ring.

The results of particle analysis are summarized in Tables 9 and 10. The mass concentrations of the particles were calculated using a density of 0.18 grams/cubic centimeter (g/cm^3) for the carbon particles and 2.7 g/cm^3 for particles in the mineral category. The 2.7 g/cm^3 for the mineral particles is the average for calcite and quartz and would be common for most minerals. The 0.18 g/cm^3 chosen for the combustion related particles was calculated by multiplying the density of amorphous carbon by 0.1. This number is speculative and the mass concentrations should be viewed with this in mind. A value of 0.04 g/cm^3 has been reported by Horvath and Charlson* for carbon flocs which would give considerably lower mass concentrations than shown in Table 9.

Analysis of the optical microscopy data discloses a trend in the number of particles entrained in the water with increased power. Total particle numbers increase from an average of 3.25×10^4 particles/mℓ at idle to 7.0×10^4 particles/mℓ at 85% RPM and 46×10^4 particles/mℓ at 95% RPM. This increase would agree with the increase in particulate emission observed with higher power settings. In contrast there is no significant difference in the numbers of submicrometer particles for idle, 85% RPM and 95% RPM.

Comparing the calculated mass concentration data in Table 9 with the suspended solids analysis reported in Table 3 suggests that the 0.18 g/cm^3 assumed for the density of the carbon particles maybe too high. The mass calculated for the mineral fraction alone accounts for the majority of the suspended material found in the samples. Although there are large numbers of particles below 1 μm, these small particles would make a minor contribution to the weight of either the suspended or the dissolved solids.

Table 11 summarizes the optical microscopy size analysis of all the samples including differentiation between those filtered on site and

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* Horvath, H., Charlson, R., Amer. Ind. Hyg. Assoc. J., 30, 500 (1969).

TABLE 9. SUMMARY OF OPTICAL MICROSCOPY DATA

Sample	Date of Filtration	Number Concentration particles/mℓ			Mass Concentration mg/ℓ		
		Carbon	Mineral	Total	Carbon	Mineral	Total
Inlet Pump	2/14/79	-	1.8×10^2	-	-	1.32	-
Spray Ring #1	2/14/79	-	2.2×10^2	-	-	1.28	-
Idle	2/14/79	3.7×10^4	1.6×10^3	3.9×10^4	2.45	1.91	4.36
Idle	2/21/79	2.5×10^4	1.3×10^3	2.6×10^4	0.59	2.20	2.79
85%	2/14/79	7.6×10^4	2.3×10^3	7.8×10^4	1.02	3.17	4.19
85%	2/21/79	5.9×10^4	3.0×10^3	6.2×10^4	0.74	2.46	3.20
95%	2/14/79	5.7×10^5	1.0×10^4	5.8×10^5	11.68	6.45	18.13
95%	2/21/79	2.9×10^5	5.0×10^4	3.4×10^5	12.85	6.01	18.86

TABLE 10. SUMMARY OF ELECTRON MICROSCOPY DATA

Sample	Date of Filtration	Number Concentration particles/mℓ Total	Number Concentration particle/mℓ Carbon*	Mass Concentration mg/ℓ Carbon
Inlet Pump	2/21/79	2.83×10^7	-	-
Spray Ring #1	2/21/79	3.02×10^7	-	-
Idle	2/14/79	11.5×10^7	8.62×10^7	0.14
Idle	2/21/79	8.40×10^7	5.47×10^7	0.08
85%	2/14/79	6.77×10^7	3.85×10^7	0.11
85%	2/21/79	5.35×10^7	2.42×10^7	0.05
95%	2/14/79	9.67×10^7	6.75×10^7	0.47
95%	2/21/79	4.79×10^7	1.86×10^7	0.18

* Assumption is made that inlet water particles are not carbon and thus are subtracted from the concentration with the engine running.

those filtered later at IITRI. Except for the mineral fraction count median diameter there is no difference between the samples filtered on site and those at IITRI. Because this analysis represents only 1 sample each, the difference in the mineral median diameter may be random or could represent agglomeration of the particles during storage. A slight trend toward smaller particles with increased power is seen in the carbon particles which is consistent with reported data on turbine engine exhausts. It should be cautioned that the size determinations were made on engine particles collected in water and that the reported distributions are not necessarily representative of the particles as they exist in the engine exhaust gas. Also, the count median diameters reported in Table 10 were, in some cases, determined by extrapolating the size distributions plotted on log-probability paper. While this procedure is reasonably acceptable for determining the mean size, caution should be used in making any judgement about the particle size distribution for particles smaller than the count mean size.

TABLE 11. SUMMARY OPTICAL MICROSCOPY SIZE ANALYSIS

Sample	CARBON		MINERAL	
	Count Median Diameter, Mg (μm)	Geometric Standard Deviation, σg	Count Median Diameter, Mg (μm)	Geometric Standard Deviation, σg
Inlet pump	-	-	1.2*	4.5*
Spray Ring #1	-	-	2.3*	3.1*
Idle	1.1*/0.95**	3.1/2.6	0.8/1.4	3.8/3.1
85%	0.78/0.78	2.7/2.4	0.66/1.2	4.5/2.8
95%	0.49/0.49	3.3/3.9	0.86/1.4	3.1/2.9

* Result for sample filtered at McClellan AFB
** Result for sample filtered at IITRI

SECTION IV
SUMMARY

Due to the limited scope of this study any conclusions must be made cautiously. Samples were taken from only one test cell and using only one engine. Environmental conditions were similar during all test runs so that the effect of large changes in temperature and humidity of the inlet air was not evaluated. The data presented in this report is summarized below:

Water exiting the test cell through the drainage system contains a significantly increased solids concentration over the inlet water.

The majority of the increased solids content is either dissolved ionic species or very small particles not filtrable by 0.45μm filters.

Based on effluent solids corrected for the solids present in the inlet water, water injection removes a significant percentage of the total engine generated solids entrained in the water.

Within the range of studied cooling water flowrates, percentage particle removal increases with increases in the cooling water flowrate. However, because of droplet fallout in the test cell area at high flowrates, water addition at or in excess of 3770 ℓ/min (996 gal/min) is not recommended.

The 3028 ℓ/min (800 gal/min) flowrate now established as normal procedure appears to be a reasonable value for 95 percent RPM. This will give a ∿ 50 percent by weight removal of total water entrained engine solids.

Cooling water also removes hydrocarbons from the exhaust gases, however, this is only significant at low power settings.

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Differentiation between mineral and carbon particles by morphology was possible for the larger, > 1μm particles, however, this was not possible for small, < 1 μm particles.

There is a large increase in the number of particles in the effluent water from the test cell. The largest increase is in the < 1 μm fraction.

Generating reliable data on removal efficiencies would be very difficult using conventional stacking sample methods. This is due to the high solids content of the inlet water and the relatively low particulate mass generated by the engine.

In conclusion, based on this limited study, the addition of cooling water to a test cell as practiced at McClellan AFB appears to result in low efficiency (∿ 50% by weight) control of turbine engine particulate emissions from test cells. It is hypothesized that the process could be made more efficient by incorporating better designed nozzles to increase water droplet particle contact and inclusion of a demister to increase water removal. This is being studied by ESL in a separate research project.

APPENDIX A

IITRI OPTICAL PARTICLE COUNTING DATA

Table A1

CONSTANTS USED FOR OPTICAL MICROSCOPY OF TEST CELL SAMPLES

Size Category	Size Range μm	Geometric Mid Size d, μm	Volume Mid Size d^3, μm^3	Microscope Objective used*	Field of View Area mm^2	Ratio Filtration Area/ Field of View†
1	1.1 - 3.3	1.9	6.9	40X	0.0335	6154.8
2	3.3 - 7.2	4.9	116	25X	0.0870	2368.5
3	7.2 - 14.4	10.2	1.06×10^3	25X	0.0870	2368.5
4	14.4 - 28.8	20.4	8.45×10^3	6.3X	1.3920	148.0
5	28.8 - 57.6	40.7	6.76×10^4	6.3X	1.3920	148.0
6	57.6 - 86.4	70.5	3.511×10^5	6.3X	1.3920	148.0
7	86.4 - 115.2	99.8	9.930×10^5	6.3X	1.3920	148.0

*Eyepiece magnification 12.5
Tube length magnfication 1.25

†Effective filtration area 206 mm^2

Table A2

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT IDLE
5 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n*	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^6$	Mass Distribution mg/ℓ†	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	10	222	1.37×10^5	1.37	73.7	0.95	0.02	0.02	0.7
2	17	209	2.91×10^4	1.66	89.4	3.37	0.06	0.08	3.3
3	31	208	1.59×10^4	1.82	98.0	16.77	0.32	0.40	16.2
4	10	206	3.05×10^3	1.85	99.6	25.75	0.49	0.88	36.1
5	50	201	595	--	--	40.20	0.76	1.64	67.1
6	50	27	80	--	--	28.06	0.53	2.17	88.7
7	50	5	15	--	100.0	14.70	0.28	2.45	100.0

*Particles counted ÷ field counted x ratio filter area to field of view area

†Mass = $\frac{\pi}{6}$ Σ nd^3 x density‡ ÷ liquid filtered

$$\frac{\pi}{6} \times \frac{1.298 \times 10^8 \mu m^3}{1} \times \frac{0.18 g}{cc} \times \frac{1}{5\ ml} \times \frac{10^3 ml}{\ell} \times \frac{10^3 mg}{g} \times \frac{cc}{10^{12} \mu m^{-3}} = 2.45\ mg/\ell$$

‡Assumed density of carbon is 0.1, the handbook density of 1.8 g/cc.
Assumed density of mineral particles is the average of calcite and quartz, 2.7g/cc.

Table A3

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE AT IDLE
5 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	50	6.15×10^3	6.15	75.6	4.26	0.01	0.01	0.6
2	50	30	1.42×10^3	7.58	93.0	16.46	0.05	0.06	3.1
3	50	6	284	7.86	96.5	29.99	0.08	0.14	7.5
4	50	74	219	8.08	99.2	184.98	0.52	0.67	34.9
5	50	22	65	8.14	100.0	439.98	1.24	1.91	100.0
6	50	0	--	--	--	--	--	--	--
7	50	0	--	--	--	--	--	--	--

Table A4

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT IDLE
5 ml FILTERED AT ITTRI 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^5$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	13	200	9.45×10^4	0.95	76.8	6.54	0.01	0.01	2.1
2	21	200	2.26×10^4	1.17	95.1	26.12	0.05	0.06	10.4
3	50	110	5.21×10^3	1.22	99.3	54.97	0.10	0.17	28.0
4	40	202	747	1.23	99.9	63.12	0.12	0.28	48.2
5	50	36	107	--	--	72.00	0.14	0.42	71.2
6	50	3	9	--	--	31.18	0.06	0.48	81.2
7	50	2	6	--	100.0	58.79	0.11	0.59	100.0

Table A5

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE AT IDLE
5 ml FILTERED AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	32	3.94×10^3	3.94	61.1	2.73	0.01	0.01	0.4
2	50	37	1.75×10^3	5.69	88.3	20.30	0.06	0.07	3.0
3	50	9	426	6.12	94.9	44.98	0.13	0.19	8.8
4	50	90	266	6.38	99.1	224.97	0.64	0.83	37.7
5	50	19	56	6.44	100.0	379.99	1.07	1.90	86.6
6	50	1	3	--	--	103.92	0.29	2.20	100.0
7	50	0	0	--	--	--	--	--	--

Table A6

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE 85% RATED POWER
5 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^6$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	4	202	3.11×10^5	3.11	81.6	2.15	.04	.04	4.0
2	8	205	6.07×10^4	3.72	97.5	7.03	.13	.17	17.0
3	50	161	7.63×10^3	3.81	99.5	8.05	.15	.32	31.9
4	20	201	1.49×10^3	--	--	12.56	.24	.56	55.2
5	50	70	207	--	--	14.00	.26	.83	81.9
6	50	7	21	--	--	7.27	.14	.96	94.6
7	50	1	3	--	100.0	2.94	.06	1.02	100.0

Table A7

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE AT 85% RATED POWER
5 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	72	8.86×10^3	8.86	76.0	6.13	0.02	0.02	0.5
2	50	32	1.52×10^3	10.38	89.0	17.56	0.05	0.07	2.1
3	50	20	947	11.33	97.1	99.95	0.28	0.35	11.0
4	50	78	231	11.56	99.1	194.98	0.55	0.90	28.4
5	50	35	104	11.66	100.0	699.97	1.98	2.88	90.7
6	50	1	3	--	--	103.92	0.29	3.17	100.0
7	50	0	0	--	--	--	--	--	--

Table A8

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT 85% RATED POWER
5 ml FILTERED AT IITRI 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^5$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	5	202	2.49×10^5	2.49	84.5	17.21	.03	.03	4.4
2	12	204	4.03×10^4	2.89	98.2	46.63	.09	.12	16.3
3	50	83	3.93×10^3	2.93	99.6	41.48	.08	.20	26.9
4	27	208	1.14×10^3	2.94	100.0	96.29	.18	.38	51.5
5	50	44	130	--	--	88.00	.17	.55	73.9
6	50	7	21	--	--	72.74	.14	.68	92.5
7	50	1	3	--	--	29.39	.06	.74	100.0

Table A9

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE 85% RATED POWER
5 ml FILTERED AT IITRI 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^4	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	84	1.03×10^4	1.03	69.1	7.16	0.02	0.02	0.8
2	50	78	3.69×10^3	1.40	93.7	42.79	0.12	0.14	5.7
3	50	10	474	1.45	96.9	49.98	0.14	0.28	11.5
4	50	145	429	1.49	99.7	362.46	1.02	1.31	53.1
5	50	10	30	1.50	100.0	199.99	0.57	1.87	76.1
6	50	2	6	--	--	207.84	0.59	2.46	100.0
7	50	0	0	--	--	--	--	--	--

Table A10

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE 95% RATED POWER
1 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^6$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	3	240	4.92×10^5	4.92	87.1	3.41	0.32	0.32	2.7
2	9	221	5.82×10^4	5.51	97.4	6.73	0.63	0.96	8.2
3	41	207	1.20×10^4	5.63	99.5	12.62	1.19	2.14	18.4
4	14	215	2.27×10^3	5.65	99.9	19.19	1.80	3.95	33.8
5	50	198	586	--	--	39.60	3.73	7.69	65.8
6	50	21	62	--	--	21.82	2.06	9.74	83.4
7	50	7	21	--	--	20.57	1.94	11.68	100.0

Table A11

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE AT 95% RATED POWER
1 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	63	7.76×10^3	7.76	76.5	5.37	0.08	0.08	1.2
2	50	36	1.71×10^3	9.46	93.3	19.75	0.28	0.36	5.5
3	50	11	521	9.98	98.4	54.97	0.78	1.13	17.5
4	50	45	133	10.11	99.7	112.49	1.59	2.72	42.2
5	50	8	24	10.14	100.0	159.99	2.26	4.98	77.2
6	50	1	3	--	--	103.92	1.47	6.45	100.0
7	50	0	0	--	--	--	--	--	--

Table A12

OPTICAL MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE 95% RATED POWER
1 ml FILTERED AT IITRI 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^5	Number Cumulative Frequency %	nd^3 μm^3 $x10^6$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	5	202	2.49×10^5	2.49	84.5	1.72	0.16	0.16	1.3
2	18	250	3.29×10^4	2.82	95.7	3.81	0.36	0.52	4.1
3	50	170	8.05×10^3	2.90	98.4	8.50	3.12	1.32	10.3
4	8	212	3.92×10^3	2.94	99.7	33.12	3.12	4.44	34.6
5	48	206	635	--	--	42.92	4.04	8.49	66.1
6	50	36	107	--	--	37.41	3.53	12.01	93.5
7	50	3	9	--	100.0	8.82	0.83	12.85	100.0

Table A13

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE AT 95% RATED POWER
1 ml FILTERED AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution 1 mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	25	3.08×10^3	3.08	61.7	2.13	0.03	0.03	0.5
2	50	30	1.42×10^3	4.50	90.3	16.46	0.23	0.26	4.4
3	50	6	284	4.78	96.0	29.99	0.42	0.69	11.4
4	50	61	181	4.96	99.6	152.48	2.16	2.84	47.3
5	50	6	18	4.98	99.9	120.00	1.70	4.54	75.5
6	50	1	3	--	100.0	103.92	1.47	6.01	100.0
7	50	0	0	--	--	--	--	--	--

Table A14

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE OFF, INLET PUMP
45 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution 1 mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	41	5.05×10^3	5.05	62.0	3.49	0.00	0.00	0.0
2	50	34	1.61×10^3	6.66	81.7	18.65	0.01	0.01	0.5
3	50	18	853	7.51	92.2	89.96	0.03	0.04	2.7
4	50	122	361	7.87	96.6	304.97	0.10	0.13	9.9
5	50	70	207	8.08	99.2	1399.95	0.44	0.57	43.2
6	50	23	68	8.15	100.0	2390.14	0.75	1.32	100.0
7	50	0	-	-	-	0.00	0.00	-	-

Table A15

OPTICAL MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE OFF, SPRAY RING #1
30 ml FILTERED ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^3	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution 1 mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	50	23	2.83×10^3	2.83	42.9	1.96	0.00	0.00	0.0
2	50	43	2.04×10^3	4.87	73.7	23.59	0.01	0.01	0.9
3	50	25	1.18×10^3	6.05	91.6	124.94	0.06	0.07	5.6
4	50	125	370	6.42	97.2	312.47	0.15	0.22	17.1
5	50	50	148	6.57	99.5	999.96	0.47	0.69	54.0
6	50	12	36	6.61	100.0	1247.03	0.59	1.28	100.0
7	50	0	0	-	-	0.00	0.00	-	-

Size Category							
1							
2							
3							
4							
5							
6							
7							

*Particle

†Mass =

‡Assume
Assume

APPENDIX B

IITRI ELECTRON MICROSCOPY PARTICLE COUNTING DATA

Table B1

CONSTANTS USED FOR ELECTRON MICROSCOPY OF TEST CELL SAMPLES

Size Category	Size Range μm	Geometric Mid Size d, μm	Volume Mid Size d^3, μm^3	Magnification $x10^4$	Field of View Area mm^2, $x10^{-5}$	Ratio Filtration Area / Field of View Area	
						47mm Filter*	25mm Filter†
1	0.03 - 0.12	0.06	2.04×10^{-4}	1	9.83	1.018×10^{7}	2.10×10^{6}
2	0.12 - 0.17	0.14	2.81×10^{-3}	1	"	"	"
3	0.17 - 0.26	0.21	9.40×10^{-3}	1	"	"	"
4	0.26 - 0.39	0.32	3.14×10^{-2}	1	"	"	"
5	0.39 - 0.58	0.47	0.105	1	"	"	"
6	0.58 - 0.86	0.71	0.351	1	"	"	"
7	0.86 - 1.29	1.06	1.180	1	"	"	"

*Effective filtration area 1001mm^2

†Effective filtration area 206mm^2

Table B2

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES*, ENGINE AT IDLE
1 ml FILTERED† ON SITE 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n^3 **	Number Cumulative Frequency 10^7	Number Cumulative Frequency %	nd^3 μm^3 x10^3	Mass Distribution mg/ℓ‡	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	6	62	2.17×10^7	2.17	18.8	4.42	0.00	0.00	0.2
2	6	99	3.46×10^7	5.63	48.8	97.33	0.01	0.01	4.8
3	6	87	3.04×10^7	8.67	75.2	286.02	0.03	0.04	18.3
4	6	63	2.20×10^7	10.87	94.2	692.31	0.07	0.10	50.9
5	6	15	5.24×10^6	11.40	98.9	551.20	0.05	0.15	76.8
6	6	4	1.40×10^6	11.54	100.0	491.44	0.05	0.20	100.0
7	6	0	--	--	--	--	--	--	--

*All particles counted as carbon

†25mm Nuclepore^R filter

**Particles counted ÷ fields counted x ratio filter area to field of view area

‡Mass = $\frac{\pi}{6} \Sigma nd^3 \times$ density ÷ liquid filtered

$$\frac{\pi}{6} \times 2.12 \times 10^6 \mu m^3 \times \frac{0.18g}{cc} \times \frac{1}{1m\ell} \times \frac{10^3 m\ell}{\ell} \times \frac{10^3 mg}{g} \times \frac{cc}{10^{12} \mu m^{-3}} = 0.20 \text{ mg}/\ell$$

Table B3

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT IDLE
10 ml FILTERED* AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^8	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	6	103	1.75×10^8	1.75	20.9	3.56	0.00	0.00	0.3
2	6	161	2.73×10^8	4.48	53.4	76.87	0.01	0.01	5.9
3	6	153	2.60×10^8	7.08	84.4	244.26	0.02	0.03	23.8
4	6	58	9.85×10^7	8.06	96.2	309.50	0.03	0.06	46.5
5	6	13	2.21×10^7	8.29	98.8	231.97	0.02	0.08	63.5
6	6	5	8.49×10^6	8.37	99.8	298.31	0.03	0.11	85.4
7	6	1	1.70×10^6	8.39	100.0	199.50	0.02	0.13	100.0

*47 mm Nuclepore^R filter

Table B4

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE 85% RATED POWER
1 ml FILTERED* ON SITE, 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^7	Number Cumulative Frequency %	nd^3 μm^3 $x10^3$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	7	37	1.11×10^7	1.11	16.4	2.26	0.00	0.00	0.1
2	7	58	1.74×10^7	2.85	42.0	48.88	0.00	0.00	2.5
3	7	63	1.89×10^7	4.74	69.9	177.53	0.02	0.02	11.3
4	7	47	1.41×10^7	6.14	90.7	442.70	0.04	0.06	33.2
5	7	15	4.50×10^6	6.59	97.3	472.45	0.04	0.11	56.6
6	7	5	1.50×10^6	6.74	99.6	526.55	0.05	0.16	82.6
7	7	1	3.00×10^5	6.77	100.0	352.13	0.03	0.19	100.0

*25 mm Nuclepore^R filter

Table B5

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT 85% RATED POWER
10 ml FILTERED* AT IITRI 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^7	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	4	34	8.66×10^7	8.66	16.2	1.76	0.00	0.00	0.1
2	4	57	1.45×10^8	23.16	43.3	40.82	0.00	0.00	3.6
3	4	63	1.60×10^8	39.22	73.3	150.87	0.01	0.02	16.2
4	4	41	1.04×10^8	49.66	92.9	328.18	0.03	0.05	43.6
5	4	14	3.57×10^7	53.23	99.5	374.73	0.04	0.08	75.0
6	4	0	0.00	-	-	0.00	0.00	-	-
7	4	1	2.55×10^6	53.48	100.0	299.24	0.03	0.11	100.0

*47 mm Nuclepore^R Filter.

Table B6

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT 95% RATED POWER
1 ml FILTERED* ON SITE, 2/14/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^6	Number Cumulative Frequency %	nd^3 μm^3 $x10^3$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	9	30	6.99×10^6	6.99	7.2	1.42	0.00	0.00	0.0
2	9	74	1.72×10^7	24.24	25.1	48.50	0.00	0.00	0.7
3	9	118	2.75×10^7	51.75	53.5	258.62	0.02	0.03	4.3
4	9	96	2.24×10^7	74.12	76.6	703.29	0.07	0.10	14.2
5	9	59	1.38×10^7	87.87	90.8	1445.36	0.14	0.23	34.6
6	9	30	6.99×10^6	94.87	98.1	2457.22	0.23	0.46	69.2
7	9	8	1.86×10^6	96.73	100.0	2191.04	0.21	0.67	100.0

*25 mm Nuclepore^R Filter

Table B7

ELECTRON MICROSCOPY MASS AND SIZE DATA, CARBON PARTICLES, ENGINE AT 95% RATED POWER
10 ml FILTERED* AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^7	Number Cumulative Frequency %	nd^3 μm^3 $x10^3$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	6	21	3.57×10^7	3.57	7.4	7.26	0.00	0.00	0.0
2	6	23	3.91×10^7	7.47	15.6	109.81	0.00	0.00	0.2
3	6	71	1.21×10^8	19.53	40.8	1133.54	0.01	0.01	2.5
4	6	81	1.38×10^8	33.28	69.5	4322.56	0.04	0.05	11.3
5	6	62	1.05×10^8	43.81	91.5	11063.86	0.10	0.16	33.9
6	6	11	1.87×10^7	45.67	95.4	6563.06	0.06	0.22	47.2
7	6	13	2.21×10^7	47.88	100.0	25935.42	0.24	0.46	100.0

*47 mm Nuclepore^R Filter

Table B8

ELECTRON MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES*, ENGINE OFF, INLET PUMP
20 ml FILTERED† AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^8	Number Cumulative Frequency %	nd^3 μm^3 $x10^4$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	5	54	1.10×10^8	1.10	19.4	2.24	0.00	0.00	0.4
2	5	94	1.92×10^8	3.02	53.2	53.86	0.04	0.04	9.8
3	5	80	1.63×10^8	4.65	82.0	153.27	0.11	0.15	36.4
4	5	47	9.58×10^7	5.60	98.9	300.98	0.21	0.36	88.8
5	5	3	6.11×10^6	5.66	100.0	64.24	0.05	0.41	100.0
6	5	0	0.00	-	-	0.00	0.00	-	-
7	5	0	0.00	-	-	0.00	0.00	-	-

*All particles are assumed mineral

†47 mm Nuclepore^R filter

Table B9

ELECTRON MICROSCOPY MASS AND SIZE DATA, MINERAL PARTICLES, ENGINE OFF, SPRAY RING #1,
20 ml FILTERED* AT IITRI, 2/21/79

Size Category	Number of Fields Counted	Number of Particles Counted	Total Particles on Filter n	Number Cumulative Frequency 10^7	Number Cumulative Frequency %	nd^3 μm^3 $x10^3$	Mass Distribution mg/ℓ	Mass Cumulative Frequency mg/ℓ	Mass Cumulative Frequency %
1	5	16	3.26×10^7	3.26	5.4	6.64	0.00	0.00	0.0
2	5	56	1.14×10^8	14.67	24.3	320.85	0.02	0.02	1.0
3	5	79	1.61×10^8	30.77	51.0	1513.52	0.11	0.13	5.8
4	5	81	1.65×10^8	47.27	78.4	5187.08	0.37	0.50	22.1
5	5	52	1.06×10^8	57.86	95.9	11135.24	0.79	1.28	57.1
6	5	9	1.83×10^7	59.70	99.0	6443.73	0.46	1.74	77.4
7	5	3	6.11×10^6	60.31	100.0	7182.12	0.51	2.25	100.0

*47 mm Nuclepore^R filter.

APPENDIX C

PHOTOMICROGRAPHS

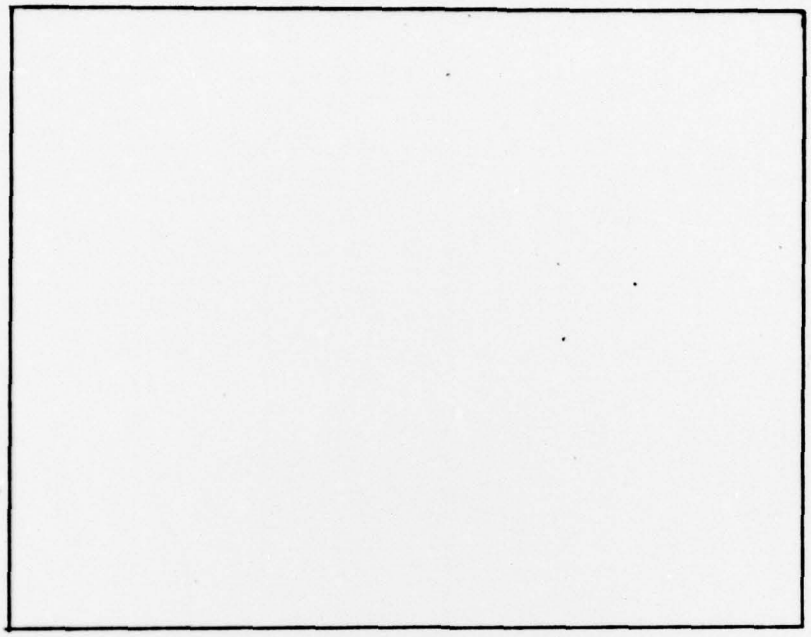


Figure C1. Pump inlet scrubber water sample, 63X slightly uncrossed polars.



Figure C2. Spray Ring #1 inlet scrubber water sample, 63X slightly uncrossed polars.



Figure C3. Idle outlet scrubber water sample, 63X slightly uncrossed polars.



Figure C4. 85% rated power outlet scrubber water sample, 63X slightly uncrossed polars.



Figure C5. 95% rated power outlet scrubber water sample, 63X slightly uncrossed polars.

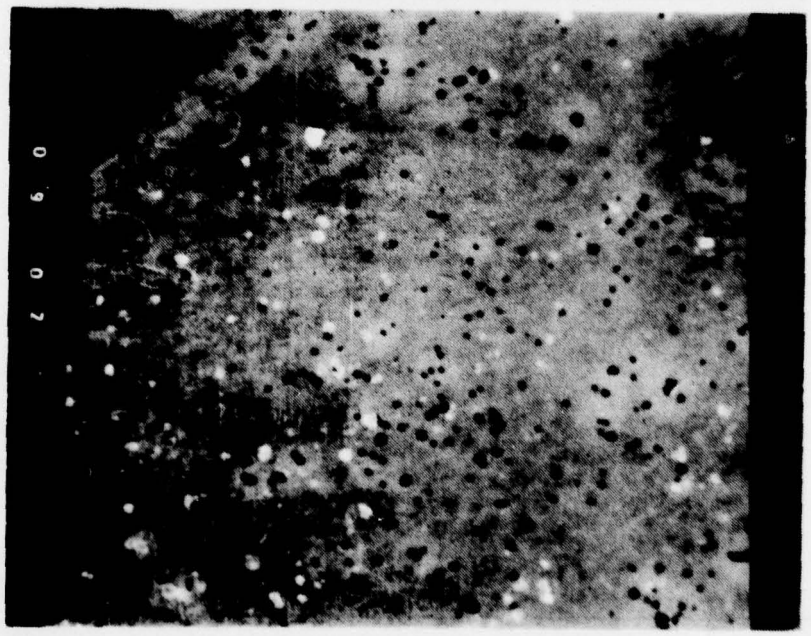


Figure C6. Pump inlet scrubber water, 6000X

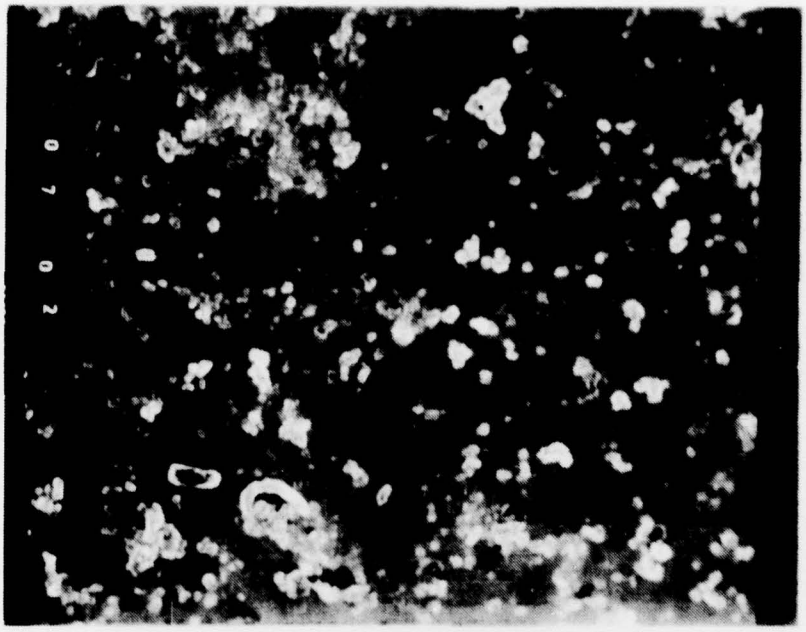


Figure C7. Spray Ring #1 scrubber water, 6000X.



Figure C8. Idle outlet scrubber water sample, 6000X.



Figure C9. 85% rated power outlet scrubber water sample, 6000x.

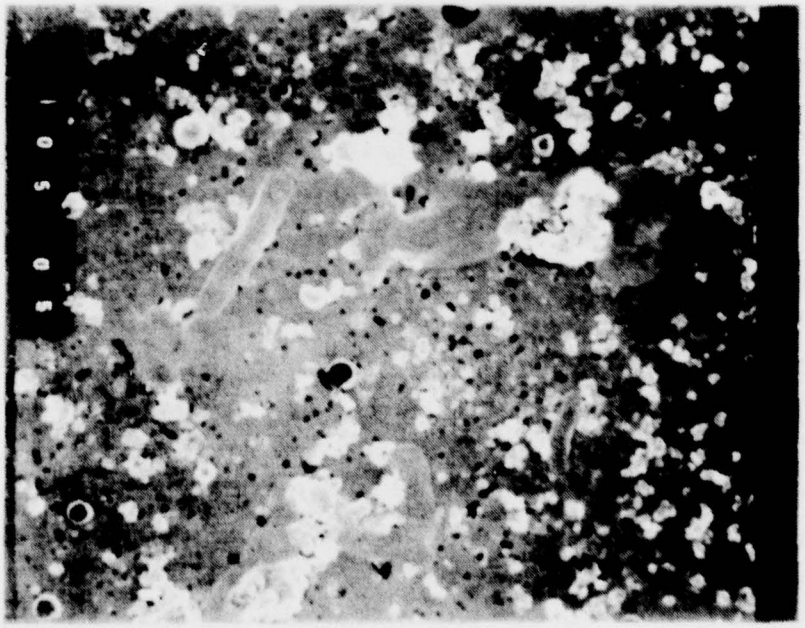


Figure C10. 95% rated power outlet scrubber water sample, 6000x.

INITIAL DISTRIBUTION

OASD/(I&L)EES	1
OUSDR&E	1
OSAF/MIQ	2
DDC/DDA	2
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AFMSC/SGPA	1
HQ AFSC/DLWM	1
HQ AFSC/SD	1
HQ AFSC/DEV	1
HQ AFSC/SGB	1
AMD/RDV	1
AMD/RDB	1
AMRL/THE	1
OEHL/CC	4
USAFSAM/EDE	2
USAFSAM/VNL	1
USAFSAM/CC	1
AFOSR/CC	1
AFOSR/NA	1
AFOSR/NC	1
AFRPL/Library	1
ADTC/DLODL (Tech Library)	1
FTD/LGM	1
AFWL/SUL (Tech Library)	1
AFTEC/SG	1
HQ SAC/DEPA	1
HQ SAC/SGPA	1
HQ TAC/SGPA	1
HQ TAC/DEEV	1
35 CSG/DEV	1
HQ AFLC/DE	1
HQ AFLC/DEEPV	3
HQ AFLC/MAXF	3
2852D ABG/DEV	1
SHALC/MA	1
USAF HOSP/SGB	1
HQ MAC/SGPE	1
HQ MAC/DEEV	1
HQ ADCOM/SGPAP	1
HQ ADCOM/DEEV	1
HQ ATC/SGPAP	1
HQ ATC/DEEV	3
HQ PACAF/SGPE	1
HQ PACAF/DEEV	1
1 Med Service Wg/SGB	1
HQ AFISC/SG	2
HQ AAC/SGB	1
HQ AAC/DEEV	1
HQ USAFE/SGB	1
HQ USAFE/DEVS	1
HQ USAFE/DEPV	1
USAF Hospital/SGB-Wiesbaden	3
HQ AUL/LSE 71-249	1
HQ USAFA/Library	1
AFIT/Library	1
AFIT/DE	1
AFRES/SGB	1
USAFRCE/WR/DEEV	3
USAFRCE/CR/DEEV	3
USAFRCE/ER/DEEV	3
Ch, Environmental Chem Div/ USAEHA	1
US Army Med Bioengrg R&D Lab	2
Ch, Industrial Hyg Div/USAEHA	2
Dept of the Army/DARD-ARE-E	1
Naval Ship R&D Center	1
NAVFAC Code 111	1
NAPC/Code PE71:AFK	1
NESO	1
Commandant/GDD US Coast Guard	1
NASA Lewis Research Center (MS60-6)	1
FAA/AEE-300	1
FAA/ARD-550	1
EPA/ORD	1
EPA/MD-46	1
Federal Laboratory Program	1
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Toxic Matls Information Ctr	1
HQ AFESC/DEV	4
HQ AFESC/TST	1
HQ AFESC/RDVC	15