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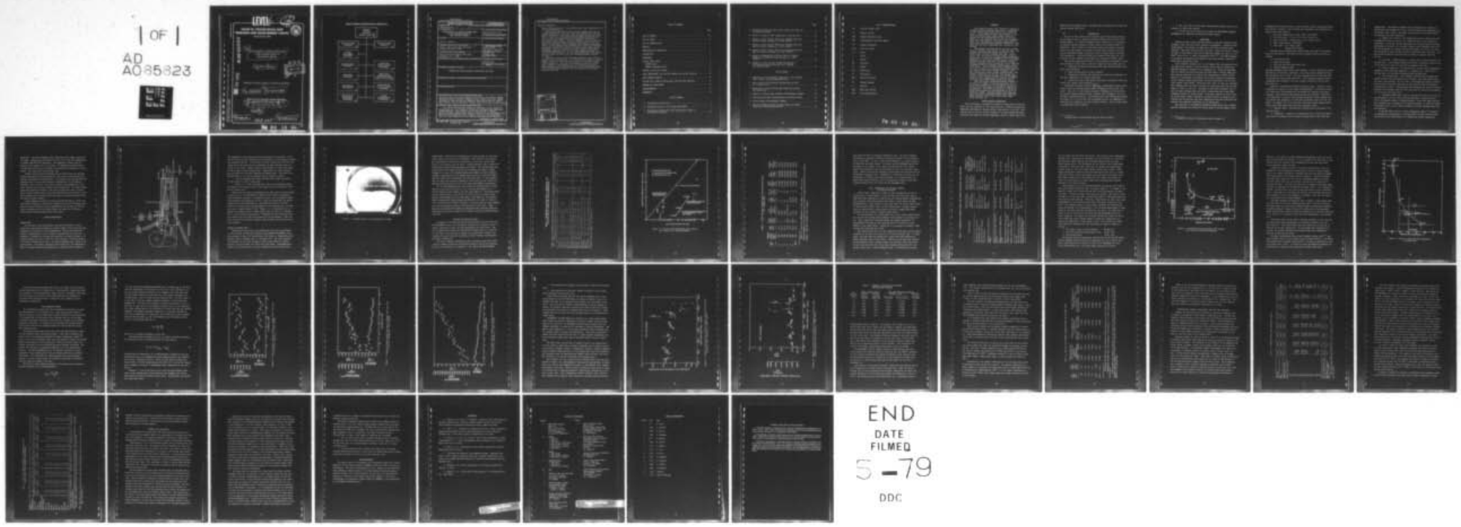

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FOR HEAT RECOVERY SYSTEMS

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FOULING EFFECTS OF TURBINE EXHAUST GASES ON HEAT EXCHANGER TUBES FOR HEAT RECOVERY SYSTEMS.

by

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PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT

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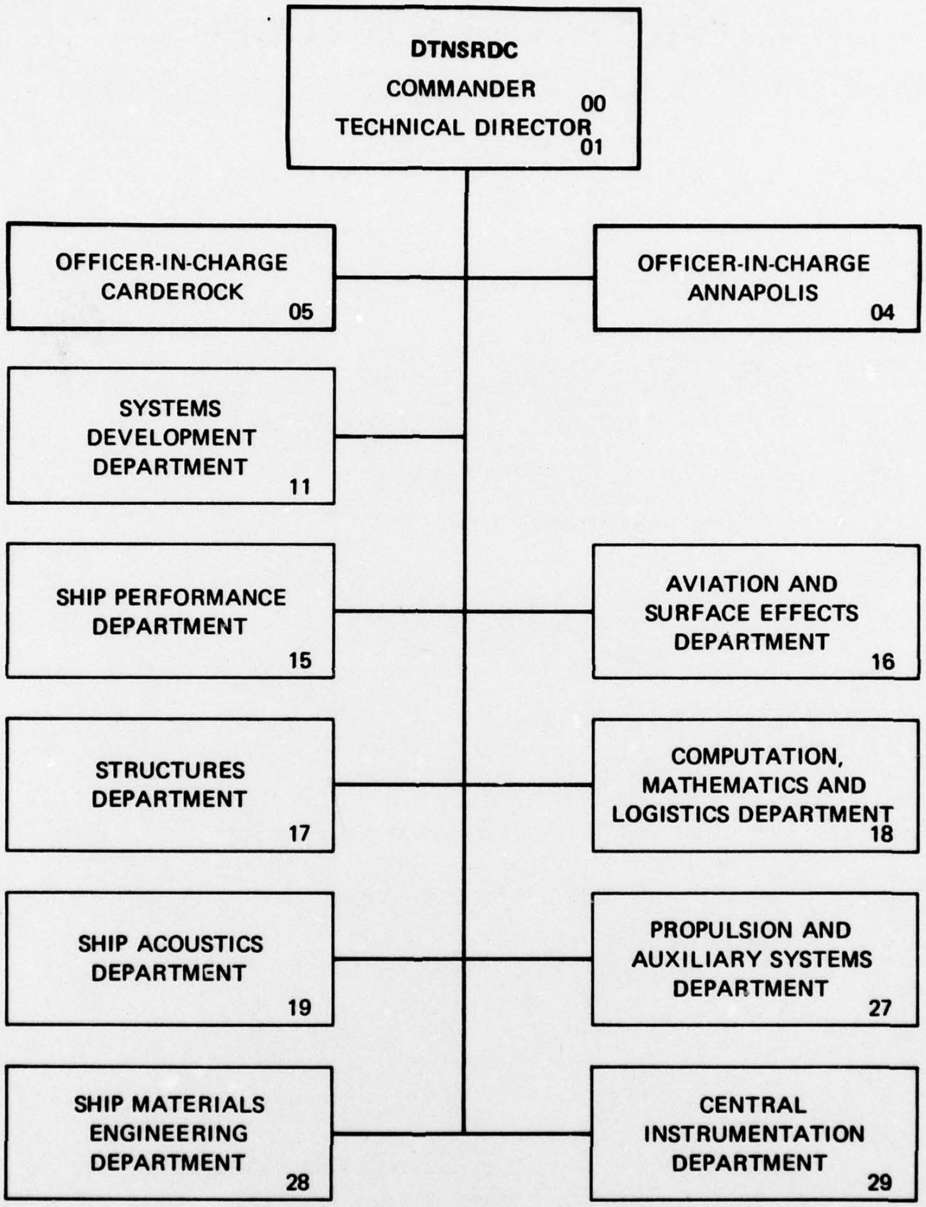

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC/PAS-79/5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FOULING EFFECTS OF TURBINE EXHAUST GASES ON HEAT EXCHANGER TUBES FOR HEAT RECOVERY SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED RDT&E thru March 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert D. Rogalski		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Element 62543N Task Area SF 43 432 301 Work Unit 1-2720-152
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command (SEA 0331G) Washington, D.C. 20064		12. REPORT DATE February 1979
		13. NUMBER OF PAGES 46
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Heat pipes, Heat flux probes, Exhaust fouling probes, Gas turbine engines, Exhaust particulate analysis, Shipboard tests, Fouling film rates, ADMIRAL CALLAGHAN LM 2500, Fouling film chemistry, Muse Solar Saturn gas turbine, Heat transfer, Thermal resistance, Thermal conductivity, Heat recovery systems		
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heat exchanger conditions. Film build-up rates were established for a variety of conditions.

The average film build-up rate and heat transfer rate are inversely proportional to the test time. The measured total hot-side thermal resistance of the fouled probe increased linearly with time. After a 5-hour test, the measured fouling thermal resistance factor was 1.5 times the recommended Tubular Exchangers Manufacturers' Association design factor. During the shipboard fouling probe test, the measured fouling thermal resistance factor reached up to four times the recommended Tubular Exchangers Manufacturers' Association factor. As the average surface temperature for the tests increased, the average fouling film build-up rate and the film sulfur content decreased. Lower wall temperatures produce thicker fouling films. The thermal conductivity of the test films ranged from 0.0204 to 0.0272 British thermal unit per hour-degree Fahrenheit-foot squared per foot (0.0353 to 0.0470 joule per second-Kelvin-meter squared per meter).

There was a good correlation between elements of the fuel and elements in the fouling films. Up to 30 percent by weight of the film samples consists of metals and sulfur present in the fuel as impurities or additives. The films are suspected to consist of alkali metal sulfates in concentrations of 10 to 30 percent by weight. Fouling deposits from shipboard waste heat boiler operation, unlike those from land-based operation, will be affected by more alkali metals in salty air.

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LIST OF ABBREVIATIONS

Btu	British thermal units
°C	Degrees Celsius
EDX	Energy dispersive X-ray
EPA	Environmental Protection Agency
°F	Degrees Fahrenheit
ft/s	Feet per second
hr	Hours
J	Joules
K	Kelvin
kg	Kilograms
m	Meters
mil	0.001 inch
μm	Micrometers
ppm	Parts per million
°R	Degrees Rankine
s	Seconds
WHB	Waste heat boiler
XRF	X-ray fluorescence

ABSTRACT

This report discusses test results of inserting a cooled cylindrical fouling probe unit in a shipboard LM 2500 and land-based Solar Saturn gas turbine exhausts. These probes are heat pipes exposed to sampled, particulate-laden exhaust gases, cooled by ambient air and instrumented such that the fouling probe test unit becomes a total heat flux measurement device for film chemistry and heat transfer experiments under simulated heat exchanger conditions. Film build-up rates were established for a variety of conditions.

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ADMINISTRATIVE INFORMATION

This investigation consists of analysis of tests done in 1976 thru March 1977 and completed in 1978 under Work Unit 1-2720-152 (Propulsion Technology Development), Element 62543N, Task Area SF 43 432 301. This work was done in the Gas Turbines Branch of the Power Systems Division, Propulsion and Auxiliary Systems Department, David W. Taylor Naval Ship

Research and Development Center, through support provided by the Naval Sea Systems Command (SEA 0331G).

INTRODUCTION

The use of heat recovery with shipboard gas turbine engine exhausts has generated a need to examine operational problem areas of waste heat boilers (WHB's). To ensure dependable boiler operation, it is necessary to minimize gas-side fouling of boiler tubes if the fouling cannot be eliminated. This fouling of a waste heat boiler will produce increased boiler core gas pressure drop which increases back pressure on the gas turbine propulsion engine, resulting in loss of power output and higher fuel consumption. Gas-side fouling also produces films which act as resistances to heat transfer and as media for corrosion of boiler tubes.

This report summarizes work done at this Center on the subject of gas-side fouling of boiler tubes. Some of the goals of this effort are to:

1. Establish fouling film build-up rates under simulated WHB* economizer tube conditions.
2. Study fouling effects on heat transfer.
3. Characterize fouling film chemistry in relation to properties of the fuel, combustion, and exhaust conditions.
4. Obtain data base of WHB design guidelines concerning fouling from several gas turbine engine exhausts.

These goals have been fully or partially accomplished through approximately 300 hr of turbine testing using cylindrical fouling probe test units. This unit is a bare heat pipe whose evaporator end is exposed to gas turbine exhaust gases and whose condenser end is cooled by air flow through a calibrated orifice. The fouling probe test unit is instrumented to convert it to a total heat flux measurement device for experiments of film build-up, chemistry, and heat transfer effects. This unit was tested in several gas turbine engines:

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*Definitions of abbreviations used are given on page v.

1. For up to 100 hr at the Center during short duration tests in an exhaust of a Saturn gas turbine.

2. For 84- and 114-hr tests at sea aboard the MTS ADMIRAL WILLIAM CALLAGHAN in its starboard LM 2500 gas turbine exhaust.

BACKGROUND

Mention of some current and past efforts on gas-side fouling of heat exchanger tubes from gas turbine exhausts is meaningful. Current efforts beside those of the Center are under way at the Solar Turbines International[1*] under Navy Contract N-024-77-C-4366. Some past efforts, during the mid- to late-1960's, were done by Hamilton Standard for the U. S. Air Force[2] and by the U. S. Naval Postgraduate School.[3,4] The ASME Committee on Corrosion and Deposits from Combustion Gas has produced a reference[5] found useful during this study.

Solar Turbines International,[1] as of August 1978, has conducted fouling tests with a module of high continuous finned tubes of various fin spacings exposed to exhausts from a combustor rig. Tests for determination of fouling film build-up rates have been made at various smoke numbers and gas velocities for constant gas temperatures of 850°F (454°C). There is a relationship, noticeable in the Solar Turbines International effort, between exhaust smoke number and the film build-up rate for constant exhaust temperatures. During one Solar test, at high soot loadings, soot bridged across the entire fin gaps of a tube with nine fins per inch (gaps of 0.083 to 0.116 in.). Progress on this effort discusses the results of many cleaning tests and several energy dispersive X-ray (EDX) elemental analysis of fouling films. Film sulfur levels for Solar tests, as in this Center effort, represent a notable fraction by weight of the fouling film for gas-side tube wall temperatures both above and below the sulfuric acid dewpoint temperature of the exhaust gas.

The objective of the Hamilton Standard fouling study[2] was to experimentally determine the effects of exhaust gases on various types of heat

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*A complete listing of references is given on page 39.

exchangers which would be used in a heat recovery system including pressure drop and heat transfer. The following list represents test parameter variables used in the program:

1. Gas inlet temperatures: 600°, 1100°, and 1400°F.
2. Face velocities: 11, 20, 33, 40, 46, and 60 ft/s.
3. Fuel-air ratios: 0.009, 0.011, 0.015, 0.018, 0.020.
4. Metal temperatures: 250°-900°F.
5. Fuel types: JP-4 (MIL-J-5724)
   Combat (MIL-G-3056).

Seventeen heat exchangers were manufactured from AISI 347 stainless steel for the project. The types of heat exchanger modules used were as follows:

1. Plate-fin-ruffled.
2. Plate-fin-straight.
3. Coil tube with helically would fins.
4. Tubular-staggered bank.

The heat exchangers were placed in the exhaust of a JT-3 annular can burner modified to use low flow, commercial, oil burner nozzles compatible with the relatively low air flows. All heat exchangers were run with and without barriers in the gas-side flow area. Tests employing various surface roughnesses and coatings of the heat transfer surfaces on the gas side were also run.

Results of the Hamilton Standard program are many. Effects of some parameters of interest to this report are summarized. It should be noted that these early test programs did not measure the exhaust particulate loadings. Well developed instrumentation was not available. Therefore, it is impossible to say how these exhaust particulate levels compare with the present test programs or if they were consistent within the test programs. In general, it can be said that early gas turbine exhaust particulate levels were higher than presently acceptable levels.

1. Fuel-air ratio - Fouling rates increase with an increase in the fuel-air ratio.

2. Temperature - Exhaust gas temperatures have a relatively significant effect on fouling, with the larger fouling rates at the lower gas

temperatures. The Hamilton Standard study concluded that, contrary to expectations and findings by others, the wall temperatures themselves did not produce such a trend. The Center study produced a noticeable effect on fouling by the wall temperature.

3. Exhaust gas velocity - The exhaust gas velocity through the heat exchanger was found to have the most dominant effect of all parameters considered. As the gas velocity decreases, the fouling deposits increase. Decreasing the velocity of a straight plate-fin heat exchanger from 60 to 20 ft/s increased the pressure drop by 250 percent in 25 hr of test time and decreased the gas-side heat transfer coefficient (hA) 40 percent. The most rapid increases of fouling rates occurred at velocity less than 30 ft/s.

4. Fuel type - Combat gasoline, a leaded fuel, produces greater fouling than JP-4. Lead deposits adhere more firmly to the metal surfaces and do not blow off or burn off as easily as deposits from JP-4.

5. Surface roughness - Two tubular units, with surfaces mechanically roughened, were tested and compared to a standard unit. After a 25-hr fouling test, the resultant differences were insignificant.

6. Core configuration - The straight plate-fin units produced the highest pressure drop increases due to fouling. Then came ruffled plate-fin units, tube bundles, and coil tubes. No significant trends or differences existed concerning reductions in heat transfer (hA) for different configurations tested. Lower pressure drop increases (by about 30 percent) resulted from straight plate-fin test units with 24 fins per inch compared to 18 fins per inch test units.

7. Extended running time - Most of the test runs were 25 hr, but one was extended to 78 hr at severe fouling conditions. During the first 20 hr, the highest degree of fouling occurred. After that time, the general condition was to stabilize or actually decrease. It cannot be stated conclusively that a run of several hundred or several thousand hours will act similarly.

In the mid-1960's the U. S. Naval Postgraduate School[3,4] conducted an experimental investigation of fouling effects on heat transfer rates and pressure drop characteristics in compact gas turbine regenerator geometries. The heat exchanger units tested were very compact plate and fin units. Exhaust gas velocities to 55 ft/s (16.8 m/s) and temperatures to 1050°F (565.6°C) were generated. The regenerator modules were installed in the exhaust of a gas turbine. By changing the engine bleed, and therefore the load on the engine, the exhaust gas temperature could be varied. The engine used marine diesel fuel.

Primary factors affecting fouling and its effects were the gas-side surface temperature and gas composition. The lower the average gas temperature the greater the fouling rate. The pressure drop through the heat exchanger unit is very nearly inversely proportional to the hydraulic diameter to the 4.5 power. This was concluded[3] from examination of the usual friction factor versus pressure drop relationship. Any small change in gas-side hydraulic diameter, such as by fouling, will have a radical effect on unit pressure drop. This work concluded that the effect of fouling on pressure drop characteristics was found to be more pronounced than the effect on heat transfer.

A wall temperature effect was noted from the NPS effort. After running similar modules at constant gas temperatures but with different cooling air and heat transfer surface temperatures, the increase in friction factor was greatest for the coolest module and least for the hottest. Fouled surface cleaning methods were also tested.

FOULING PROBE TESTS

CENTER TESTS

At the Center, the fouling probe test unit was tested in a Solar Saturn gas turbine engine exhaust at several ranges of gas velocities, gas temperatures, and probe hot wall temperatures. Center test times were limited to approximately 5 hr of turbine operating time per test day. A drawing of a cylindrical fouling probe test unit is shown in Figure 1. A stainless steel heat pipe is used for rapid transfer of exhaust gas heat at the bare cylindrical hot end to the finned condenser end, cooled by air from a blower. The blower, supplying probe cooling air, was regulated so that, for a given exhaust gas temperature, a desired range of probe hot

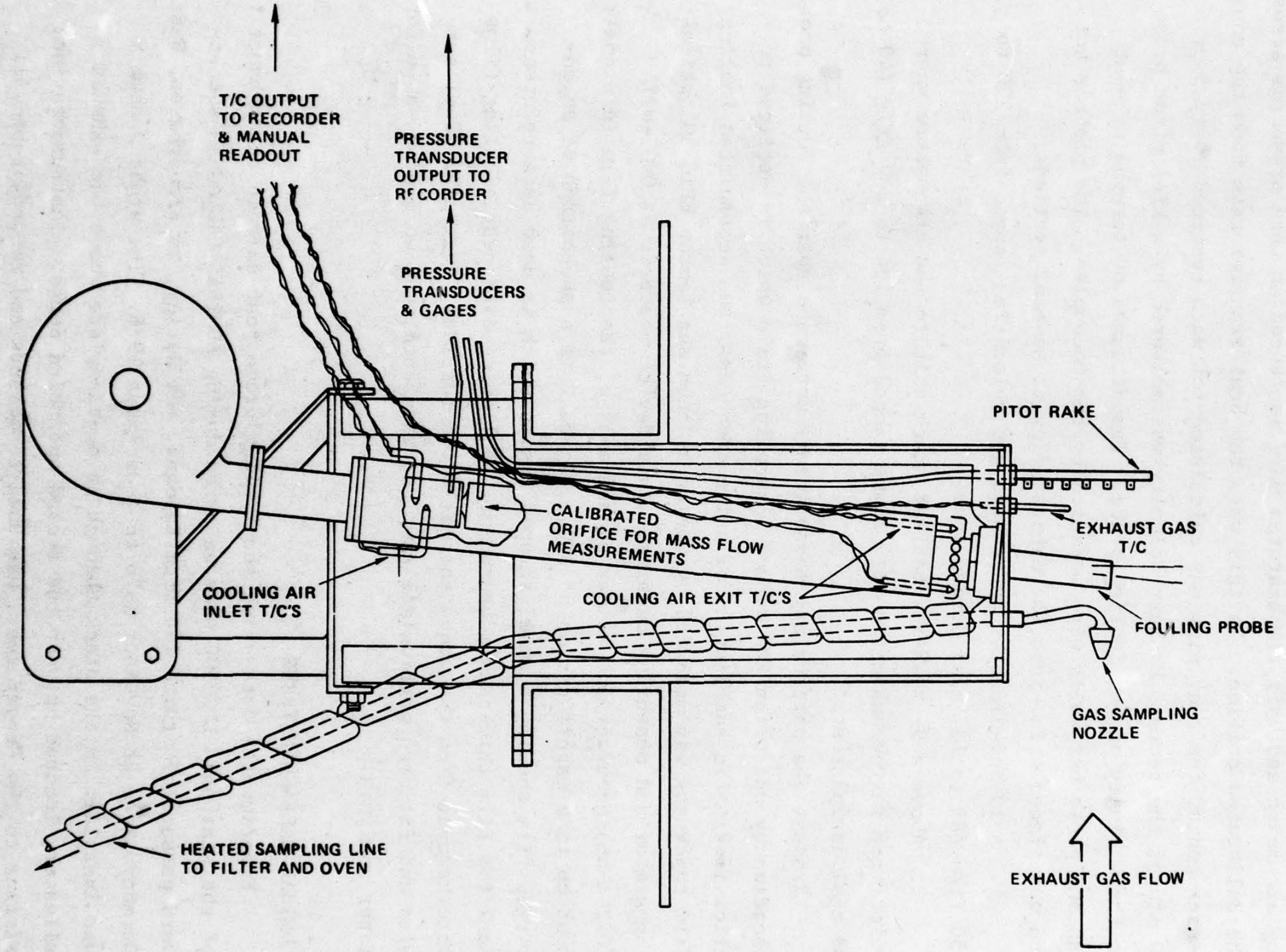

Figure 1 - Cylindrical Fouling Probe

wall temperatures was reached on the fouled portion of the probe. Cooling air inlet and exit temperatures were monitored as were pressures across the calibrated orifice. In this way, the heat transfer rate from the condenser end of the heat pipe was calculated for data recorded every 5 or 10 min of the tests. Exhaust velocity was measured by a kiel pitot probe in the vicinity of the fouling probe. Temperatures of turbine exhaust gas and probe hot walls were measured by thermocouples. The probe's hot end was placed 4 in. into the exhaust flow at several sections:

1. A 19-in.-diameter duct where gas velocities ranged from 290 to 450 ft/s (88 to 137 m/s) during test.

2. Above a 9- x 48-in. baffled stack exit to the atmosphere where velocities in the exhaust outlet plume ranged from 134 to 289 ft/s (40 to 88 m/s) during tests.

Exhaust gas particulate measurements were made near the fouling probe location by use of an EPA Method 5 sampling train which is designed to allow isokinetic sampling. Following each test, the accumulated fouling film thickness was measured by use of a Jones and Lamson EPIC 30 optical comparator and measuring machine. This device measures at 0.01-mil (0.254-μm) accuracy and allows photography of the fouling film in a small spot up to a magnification of 200. Figure 2 is a photograph of an enlarged film showing a small scraped region which is used as a reference mark for film thickness measurement. Following each test, fouling films were removed from the probe and collected for later analysis. Fuel samples and filtered particulate samples, when obtained, were also saved for later analysis.

ADMIRAL CALLAGHAN TESTS

Experimental data using the fouling probe test unit in the exhaust of the starboard LM 2500 were gathered during ADMIRAL CALLAGHAN's eastward passage of Cruise 148 from Bayonne, New Jersey, to Bremerhaven, West Germany, from 28 November 1976 to 7 December 1976. The probe assembly was installed in the stack through an access plate above the exhaust silencer, located between the second and third decks. Instrumentation, similar to the Center test, was used to measure and record probe wall

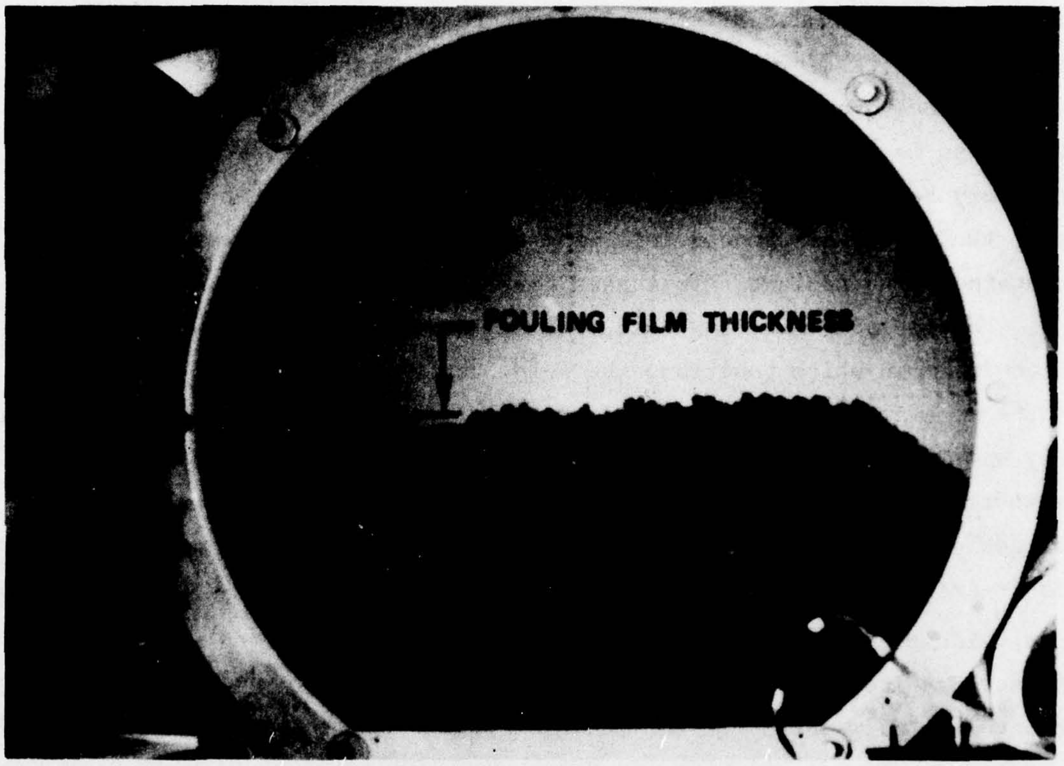

Figure 2 - Enlarged Portion of the Fouling Film (100X)

temperatures, pressures for determination of probe cooling air mass flow rates, exhaust gas velocity and isokinetic stack sampling rate, exhaust gas temperatures, particulate concentration, sulfur gas, and moisture levels of the exhaust near the probe. During shipboard tests, engine conditions were periodically monitored and recorded. The fouling probe was used for two test periods of 84 and 114 hr during the voyage. Midway through the voyage, the starboard engine was stopped for probe removal, thickness measurements of the foulant film on the tube, and film sample recovery before probe reinsertion for the second test. At the voyage's end, the probe was removed following the 114-hr test and was stored in a container with foulant film intact for later measurements and analysis.

For the ADM CALLAGHAN test, the cylindrical fouling probe is assembled in a can which positions the 4-in. active probe length 24 in. (0.61 m) away from the exhaust duct wall (see Figure 1). The probe assembly was inserted into a port of the 9- x 13-ft (2.74- x 3.96-m) stack almost at the midpoint of the stack width. The baffles of the silencer directly beneath the probe reduced the effective flow area of this 9- x 13-ft cross section by almost 50 percent. At this location, local exhaust gas velocities ranged from 60 to 94 ft/s (18.3 to 28.7 m/s). These measured velocities were checked by comparisons with expected engine exhaust mass flow rates for many sets of engine conditions recorded during the tests.

FOULING FILM BUILD-UP RATES

A summary of fouling build-up and fouling rates from the Center and ADM CALLAGHAN tests of the cylindrical fouling unit is given in Table 1. Exhaust velocities, probe, and gas temperatures are also listed. Figure 3 graphically presents the fouling film build-up data as a function of test time. Also included in Figure 3 and summarized in Table 2 are fouling film data from tests performed by Solar Turbines International, San Diego, California.[1]

The Solar Turbines International data is obtained from tests which utilize a module constructed from finned tubing of various fin spacings and run in the exhaust of a combustor. The Center and ADM CALLAGHAN

TABLE 1 - COMPARISON OF FOULING RATES, TEMPERATURE, AND VELOCITY DATA OF CENTER AND ADM CALLAGHAN TESTS

Test Date	Test Duration, Hours	Film Thickness, mils			Film Build-up Rate, mils/hr			Range of Probe Hotwall Temperature [°F] T_{WH}	Range of Exhaust Gas Temperature [°F] T_G	Range of Exhaust Gas Velocity (ft/s)
		Max	Avg	Min	Max	Avg	Min			
7-21-76	5.3	-	0.7	-	-	0.132	-	715 - 320	916 - 675	264 - 181
7-22-76	3.33	0.6	0.55	0.5	0.180	0.165	0.150	622 - 340	896 - 615	251 - 43
7-26-76	4.5	0.6	0.55	0.5	0.133	0.122	0.111	700 - 308	921 - 661	265 - 87
7-29-76	4.47	-	0.9	-	-	0.201	-	591 - 359	763 - 740	173 - 135
7-30-76	5.217	-	0.9	-	-	0.173	-	439 - 362	792 - 741	189 - 164
8-2-76	5.5	1.4	0.9	0.4	0.255	0.164	0.0727	660 - 298	922 - 635	258 - 68
9-23-76	3.783	1.6	0.9	0.4	0.423	0.238	0.106	299 - 266	615 - 572	288 - 265
10-18-76	5.083	5.2	4.39	3.5	1.023	0.864	0.689	215 - 186	611 - 588	290 - 281
9-28-76	3.08	3.5	3.1	2.2	1.154	1.022	0.725	235 - 203	619 - 571	290 - 267
10-4-76	2.883	2.8	2.5	2.2	0.971	0.867	0.763	202 - 187	617 - 588	288 - 264
11-28 to 12-2-76	84.	7.0	6.0	5.0	0.0833	0.0714	0.0595	239 - 214	754 - 659	86 - 64
12-2 to 12-7-76	114.	15.9	10.9	6.7	0.139	0.0956	0.0587	229 - 145	756 - 522	90 - 61

Conversion Factors: 25.4 μm/mil; (m/s) = 0.3048 (ft/s).

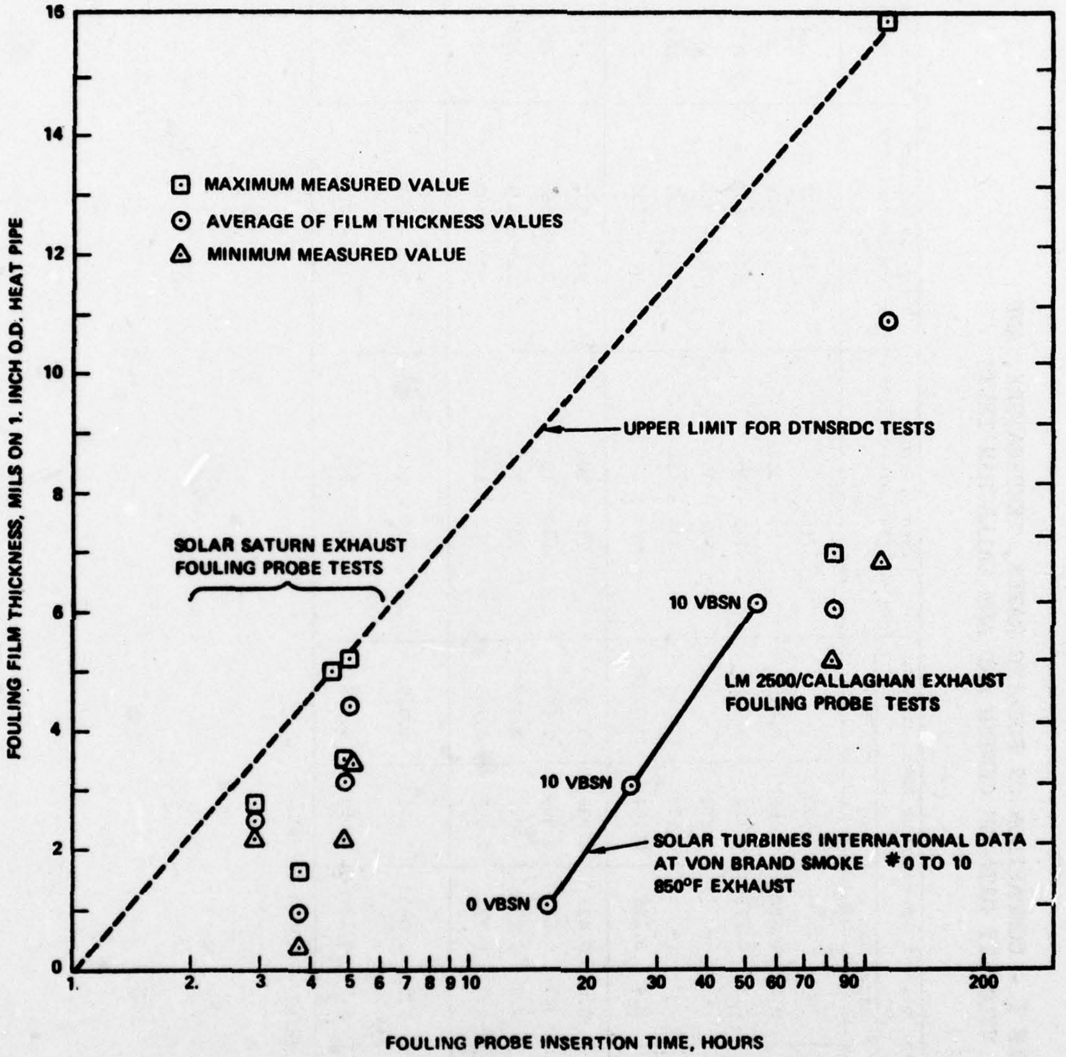

Figure 3 - Fouling Film Thicknesses after Various Test Times in Gas Turbine Exhausts

TABLE 2 - SOLAR TURBINES INTERNATIONAL FOULING BUILD-UP DATA
NO. 2 DIESEL FUEL

Test No.	Exhaust Gas Temperature (^oF)	Test Time (hr)	Film Thickness (mils)	Film Build-up Rate (mils/hr)	Von Brand Smoke No.	No. of Start/Stop Cycles	Tube Wall Temperature (^oF)	Fin Temperature (^oF)*	Exhaust Gas Velocity (ft/s)
1	850	17.0	1	0.059	0	8	70-300	300-600	20-25
2	850	26.0	3	0.115	10	8	70-300	300-600	20-25
3	850	52.0	6	0.115	10	18	70-300	300-600	20-25
4	850	52.0	6-10	0.115-0.192	21	20	70-300	300-600	20-25
5	850	8.0	20	2.5	35-40	2	70-300	300-600	30-40
6	850	12.0	40**	3.33	35-40	4	70-300	300-600	30-40
7***	850	19.0	30	1.58	55-60	6	70-300	300-600	30-40

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*More of a mean fin temperature in some cases, i.e., close to tip.

**Also bridging of soot build-up across entire fin gaps (0.083-0.116 in.) occurred.

***Test 7 used JP-5 instead of No. 2 diesel.

tests were run with an isolated cylindrical tube. The Solar Turbines International combustor's exhaust particulate loading could be adjusted over a wide range. In fact, tests were performed up to a smoke number of 60 using the von Brand method. The Center and ADM CALLAGHAN tests were performed in the exhaust of an actual gas turbine where the exhaust particulate loading can only be influenced by the fuel and engine operations. Exhaust particulate loadings in these tests were measured with an EPA Method 5 sampling train. Although it is difficult to relate the two measurements of exhaust particulate loading, it is expected that von Brand smoke numbers between 5 and 20 correspond to exhaust particulate loadings obtained with the Center and ADM CALLAGHAN tests.

TIME, TEMPERATURE, AND VELOCITY EFFECTS ON FOULING BUILD-UP

Center tests, summarized in Table 3, were accomplished in two sequences over a 4-month period. First fouling probe tests were run at high probe wall temperatures, high Saturn gas turbine exhaust temperatures, and at exhaust velocities greater than those of later Center and ADM CALLAGHAN tests. Some thermal cycling tests were done in the first series of Saturn engine exhaust tests of the fouling probe. Thermal cycling refers to operating the fouling probe at various cooling loads while operating the gas turbine at various power levels.

The second period of fouling probe tests in the Saturn engine exhaust was run with the fouling probe assembly in the exhaust at the stack outlet. This location was selected because the exhaust temperature is approximately the same at both locations while the velocity is much smaller at the stack outlet. During the second period of testing, larger fouling film build-ups were noted.

The fouling probe tests, in the shipboard LM 2500 gas turbine exhaust, consisted of two runs of 84 and 114 hr of probe insertion time. In these tests, the probe film thicknesses were larger than those produced by shorter duration tests at the Center. Because of the long test duration during shipboard tests, average fouling film build-up rates were lowest for all tests but were near those rates obtained during the first test series of the probe. During shipboard tests, the exhaust gas velocity

TABLE 3 - COMPARISON OF CENTER FOULING TEST SERIES FOR VARIOUS TEST CONDITIONS

Test Condition	First Test Series	Second Test Series	Shipboard Test Series
	Summer 1976 in Saturn Gas Turbine	Summer and Fall 1976 in Saturn Gas Turbine Exhaust	Winter 1976 on ADM CALLAGHAN in Starboard LM 2500 Exhaust
Test Duration (hr per test)	Short (3-5)	Short (3-5)	Long (84-114)
Film Build-up (mils)	Small (less than 2)	Larger (2-6)	Largest (6-16)
Film Build-up Rate (mils/hr)	Small (0.1-0.2)	Larger (0.68-1.15)	Smaller (0.06-0.14)
Film Consistency	Soft and porous, powdery	Soft and porous, powdery	Hard, porous, flaky
Film Total Sulfur Content (% by weight)	2.89-7.13	6.27-12.52	11.9
Range of Probe Hot Wall Temperature, T_{WH} (^{O}F)	High (300-715)	Low (186-235)	Low (145-239)
Range of Exhaust Gas Temperature, T_G (^{O}F)	High (635-916)	Low (571-619)	Low (522-756)
Range of Exhaust Gas Velocity (ft/s)	High (290-450)	Medium (134-289)	Low (60-94)
Temperature Ratio, T_{WH}/T_G ($^{O}F/^{O}F$)	High (0.781-0.466)	Low (0.381-0.308)	Low (0.331-0.276)
Exhaust Gas Thermal Cycling	Varying load	Constant load	Constant load
Fuel Type	No. 2-D	No. 2-D	No. 2-D
Fuel Sulfur Content (% by weight)	0.11	0.11	0.8
Particulate Mass Emission (gram particulate/kg fuel burned)	0.61-1.09	0.61-1.09	0.416-0.705

was the lowest for the three test series. The probe hot wall temperature was kept low. Conditions of shipboard tests were similar to those which produced the largest fouling film thickness obtained from the short Saturn engine tests. The consistency of the fouling films formed seems influenced by insertion time, probe wall and exhaust gas temperatures, exhaust velocity, and fuel sulfur content, among other factors. Films formed during short duration tests were more porous and easier to remove than those harder, denser films which were found after the longer tests. The probe's exposure to a hot exhaust gas for a long test may have an effect on film formation to some steady-state thickness which becomes hardened on the tube's surface.

There appears to be a relationship between the average film build-up rate and the probe insertion time, as shown in Figure 4. In Figure 4, the range of a given test's film build-up rate is plotted against its insertion time. Average or single rate values are encased. The vertical lines in Figure 4, at any test time, indicate the range of fouling film build-up rate over the time interval. There is a range since, for some tests, many measurements of film thickness were made at different locations on the probe. The encased values, in these cases, represent the build-up rate using the average of all measurements. The von Brand smoke number is also shown for the Solar Turbines International test data. All other data in Figure 4 are for Center tests in Saturn and ADM CALLAGHAN LM 2500 engines' exhausts. The dotted line is drawn through the points for Center tests which have nearly similar ranges of probe wall temperature and exhaust gas temperature. From Tables 1 and 2, it is noted that predominant local gas velocities for the tests shown in Figure 4 ranged as follows:

1. For Center tests in Saturn exhausts	250-290 ft/s
2. For Solar Turbines International tests	20-40 ft/s
3. For LM 2500 tests	61-90 ft/s

The General Electric Company has supplied data on the LM 2500 engine exhaust smoking characteristics from combustion of a No. 2 diesel fuel with a distillation curve similar to that of the CALLAGHAN test fuel. The LM 2500 exhaust has a low smoke number during its operation

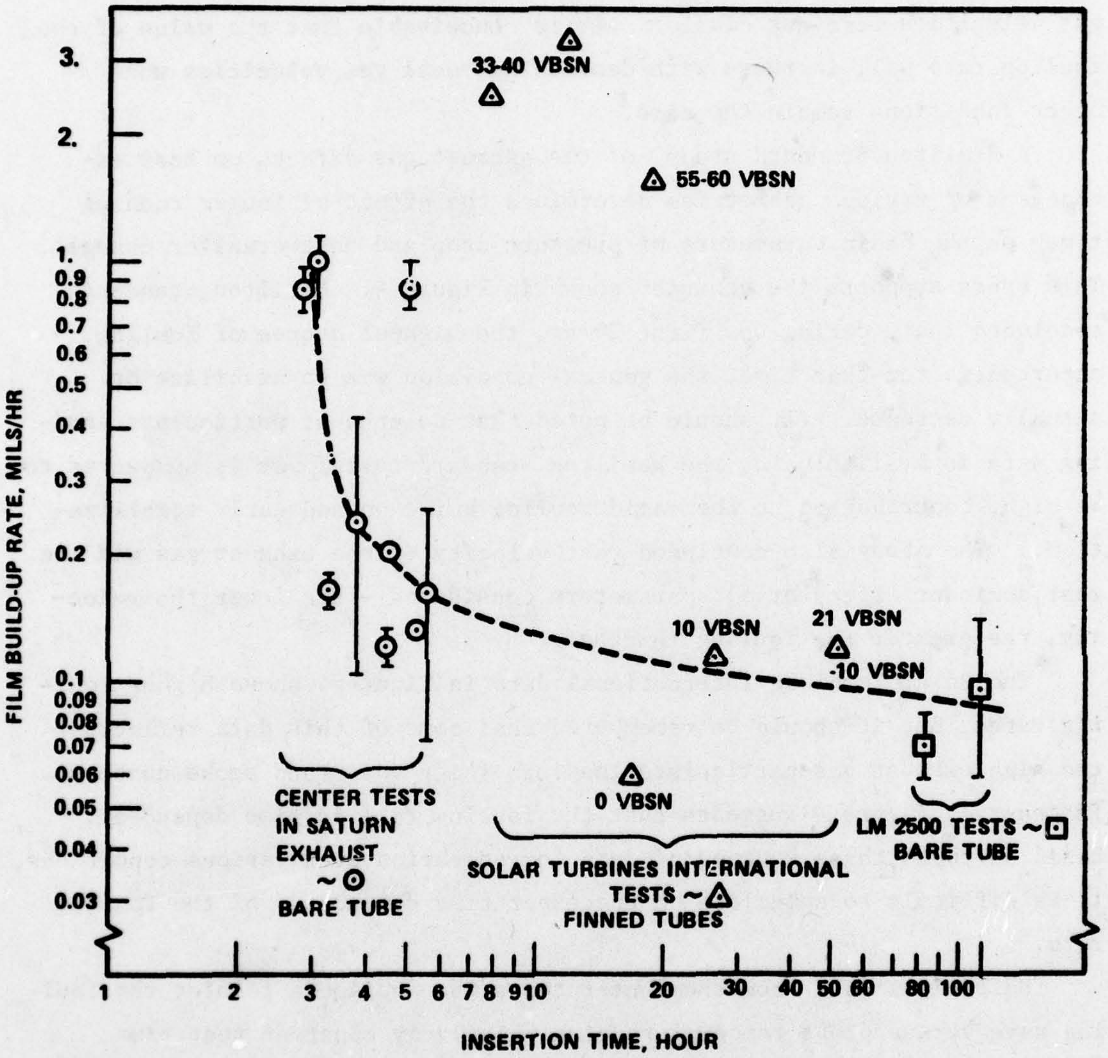

Figure 4 - Fouling Film Build-up Rates after Various Test Times in Gas Turbine Exhausts

(SAE 5.4 to 18) similar to Solar Turbines International tests, but local gas velocities were not similar. It is conceivable that the value of the fouling rate will increase with decreasing local gas velocities when other conditions remain the same.

A Hamilton Standard study[2] of the exhaust gas effects on heat exchangers of various geometries determined the effect of longer running times on the basic parameters of pressure drop and heat transfer changes. This study supports the behavior shown in Figure 4. Hamilton Standard concluded that, during the first 20 hr, the highest degree of fouling occurred; after that time, the general condition was to stabilize or actually decrease. (It should be noted that no exhaust particulate loading data is available for the Hamilton Standard tests. It is suspected to be high, contributing to the rapid fouling build-up and early stabilization.) The study also concluded that velocity of the exhaust gas was the most dominant effect of all parameters considered - the lower the velocity, the greater the fouling thickness.

The Solar Turbines International data in Figure 4 shows higher fouling rates, but it should be remembered that some of this data reflects the high exhaust gas particulate loadings (high von Brand smoke numbers). In general, Figure 4 suggests that the fouling rate is time dependent. Based on these three sources of data for operation over various conditions, it is difficult to speculate on the exact time dependency of the fouling rate.

Sufficient data from the Center tests was available to plot the fouling rate versus probe temperature at a relatively constant test time (see Figure 5). This figure shows that the fouling rate is greatly influenced by the wall temperature. As the average wall temperature increased, the average fouling rate decreased (lower wall temperatures produced thicker fouling films).

The Naval Postgraduate School heat exchanger fouling study[3,4] indicated similar effects of wall temperature on fouling build-up. The Hamilton Standard heat exchanger fouling study,[2] contrary to expectations, did not produce such a trend. It should be noted that Hamilton Standard had difficulties in measuring wall temperatures during their tests.

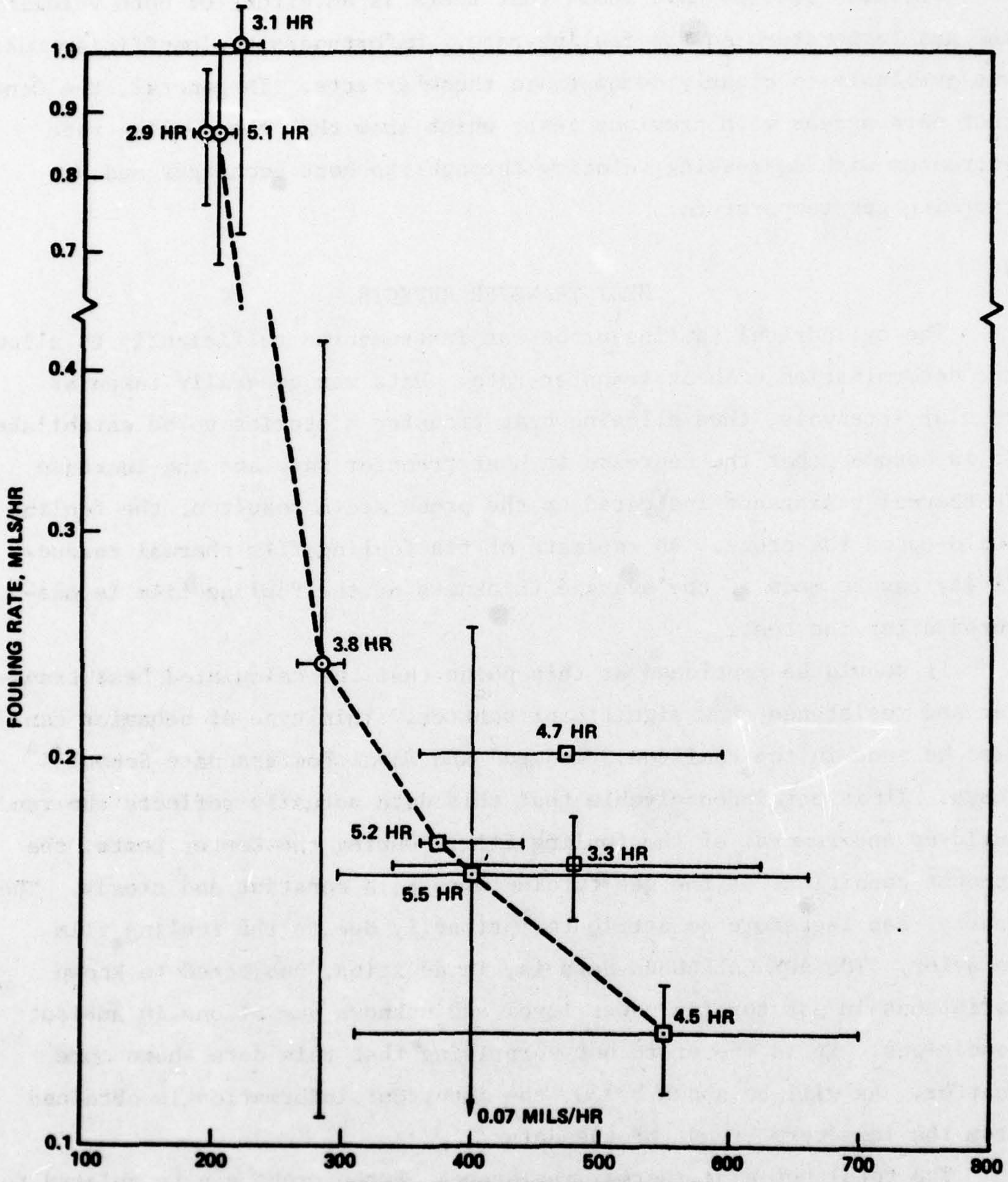

Figure 5 - Effect of Probe Hot Wall Temperature on Fouling Rate

Previous studies have shown that there is an effect of both velocity and gas temperature on the fouling rate. Unfortunately, insufficient data was available to clearly demonstrate these effects. In general, the Center test data agrees with previous tests which show that the fouling rate increases with decreasing velocity through the heat exchanger and decreasing gas temperature.

HEAT TRANSFER EFFECTS

The cylindrical fouling probe was instrumented sufficiently to allow the determination of heat transfer rate. Data was generally taken at regular intervals, thus allowing heat transfer histories to be established. It is assumed that the decrease in heat transfer rate and the increase in thermal resistance indicated by the probe are a result of the fouling build-up on the probe. An estimate of the fouling film thermal conductivity can be made if the average thickness of the fouling film is measured after the test.

It should be mentioned at this point that the calculated heat transfer and resistance show significant scatter. This type of behavior can also be seen in the Hamilton Standard[2] and Naval Postgraduate School[3,4] tests. It is not inconceivable that this data actually reflects the random build-up and removal of the fouling film. During the Center tests, the exhaust conditions of the gas turbine were held constant and steady. The scatter can therefore be attributed primarily due to the fouling film behavior. The ADM CALLAGHAN data is, in addition, subjected to known variations in gas turbine power level and unknown variations in ambient conditions. It is therefore not surprising that this data shows more scatter. As will be shown below, the important information is obtained from the long term trends of the data.

The total hot-side thermal resistance of the probe can be related to the heat transfer in the following manner:

$$R_{TOT} = \frac{T_G - T_{WH}}{Q_C} \qquad (1)$$

where T_G is the gas temperature measured near the probe, T_{WH} is the average wall temperature of the portion of the probe in the gas stream, and Q_C is the heat transfer measured at the condenser end of the heat pipe. At clean probe conditions, near time zero, the thermal resistance calculated above is due to convection and radiation only. At later times or at the end of the test, another thermal resistance is calculated from Equation (1). The difference between the thermal resistance at time, t, and that at time, zero, is the thermal resistance due to film conduction. For a bare cylinder with a film thickness, FT, much less than the cylinder diameter, the thermal resistance change due to conduction through the film, ΔR, is expressed as a function of the surface area of the cylinder with the fouling film, A_f, the film thickness, and the thermal conductivity of the fouling film, K_f, as

$$\Delta R = \frac{C \cdot FT}{K_f \cdot A_f} \qquad (2)$$

where C is a constant depending on units used.

The measured heat transfer rate, Q_C, is based on the heat removed by the cooling air from the condenser end of the heat pipe as

$$Q_C = \dot{m}\, cp\, (T_{CA_{OUT}} - T_{CA_{IN}}) \qquad (3)$$

The mass flow of cooling air, $\dot{m}$, is calculated as a function of the measured blower inlet air temperature, static pressure before, and pressure drop across a calibrated orifice. Since the heat pipe is a high efficiency device, the heat transferred to the pipe's hot end from the exhaust gas is assumed to be equal to the measured heat transferred to the cooling air.

Figures 6, 7, and 8 are plots of the total hot-side thermal resistance of the fouling probe and the measured heat transfer rate versus probe insertion time for selected Center tests. In each test, the following trends were noted:

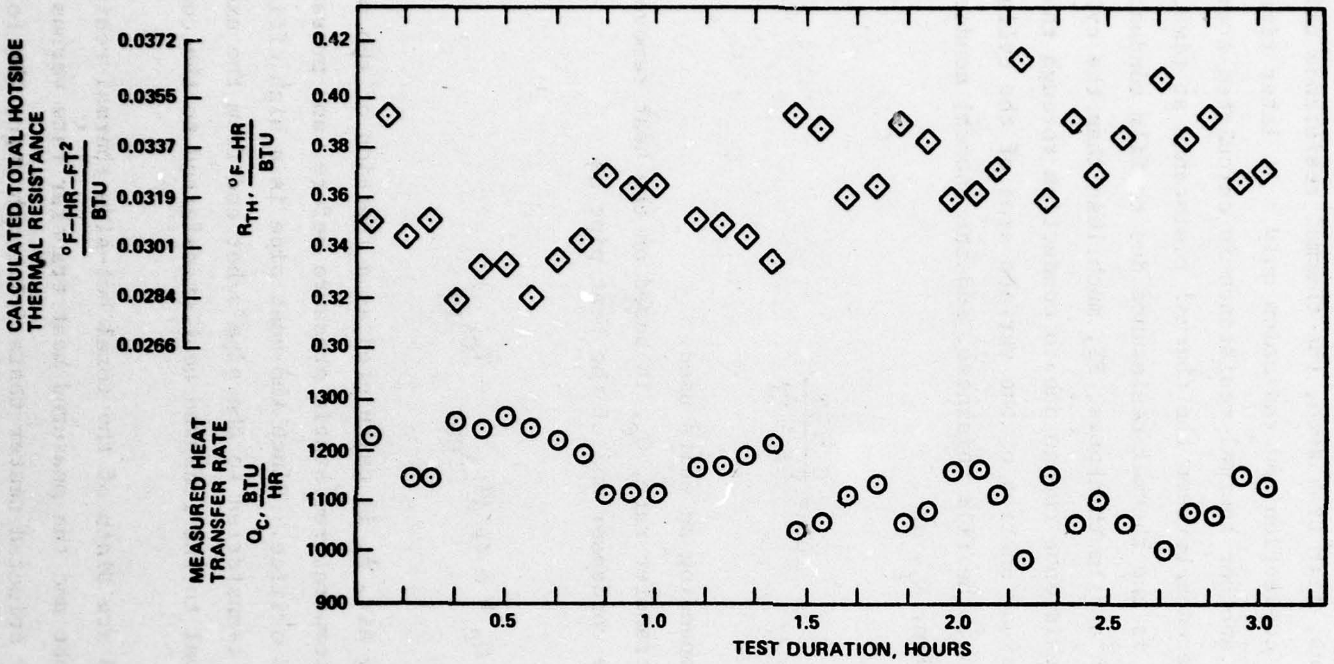

Figure 6 - Summary of Heat Transfer Results of Fouling Probe Test Data of 9-28-76, Average T_G = 316°C (600°F)

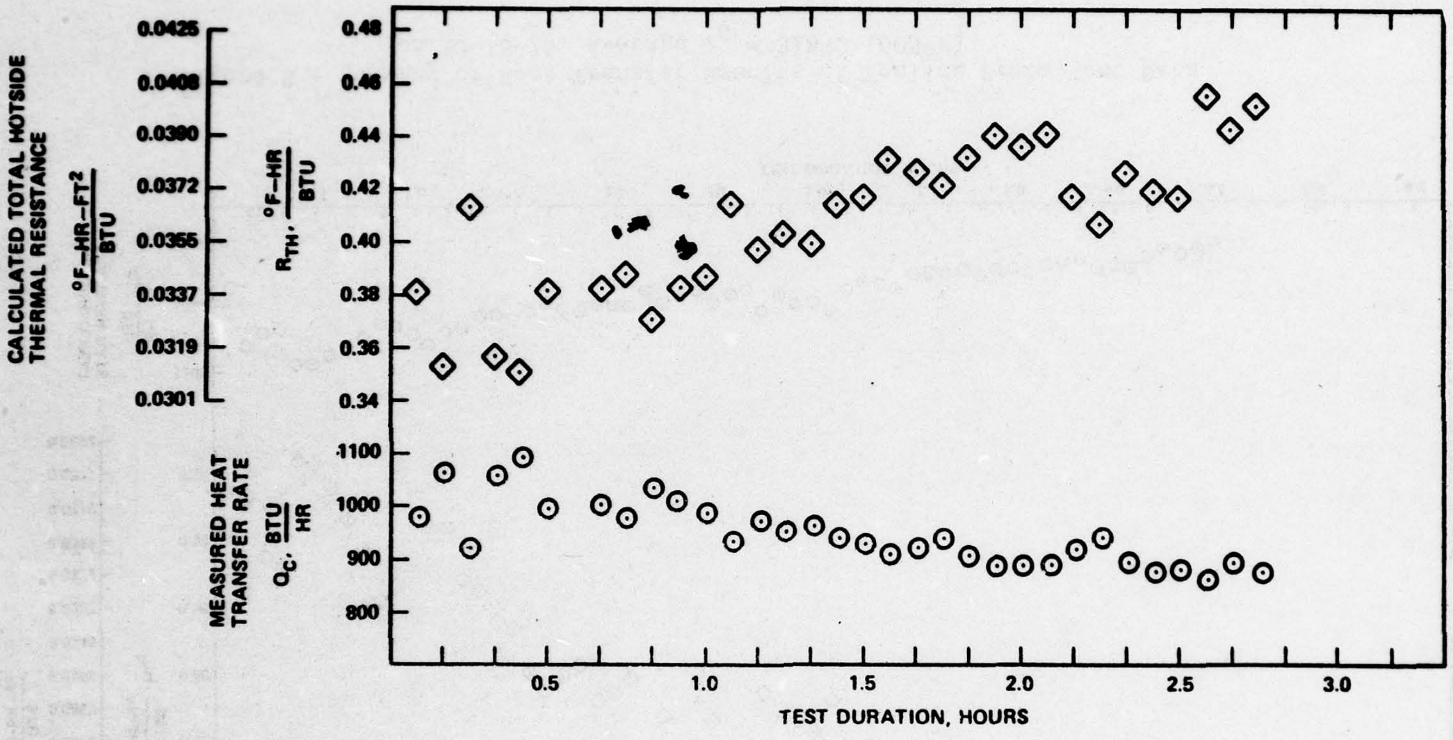

Figure 7 - Summary of Heat Transfer Results of Fouling Probe Test Data of 10-4-76, Average T_G = 321°C (610°F)

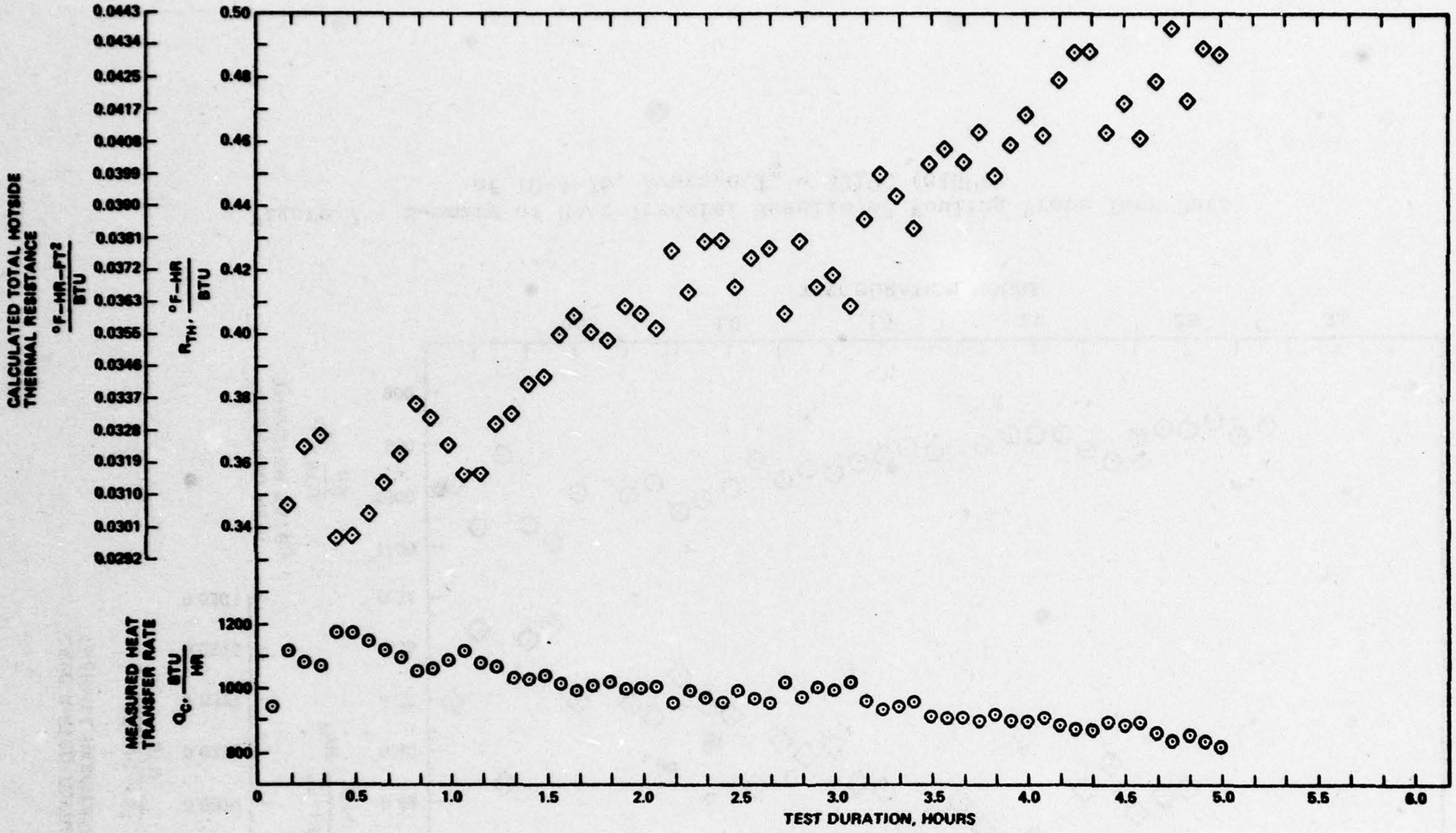

Figure 8 - Summary of Heat Transfer Results of Fouling Probe Test Data of 10-18-76, Average T_G = 318°C (605°F)

1. The measured heat transfer rate decreased linearly with fouling time.

2. The measured total hot-side thermal resistance of the fouled probe increased linearly with time.

Plots of heat transfer data for the 114-hr shipboard test of the probe exposed to the LM 2500 exhaust are shown in Figures 9 and 10 for changes with time of the measured heat transfer rate and thermal resistance. As in the shorter tests of probes exposed to Saturn engine exhausts, the thermal resistance increased with time and the heat transfer rate decreased with time for a constant mass flow of cooling air. These changes were not as linear with time as were those for the short Saturn engine tests.

CALLAGHAN's LM 2500 engines are operated on a daily power profile which causes the exhaust conditions to vary with respect to time of day. Some of the scatter of the CALLAGHAN test data heat transfer rate and thermal resistance is caused by the variation of exhaust conditions. The Center tests (Figures 6, 7, and 8) were operated at nearly constant load in a narrow range of exhaust gas temperatures. This type of operation caused the more uniform film build-up at a given exhaust temperature and more consistent changes with time of the heat transfer data for Center tests.

The sharp rises and declines of Figures 9 and 10 are characteristic of those noted in other data on thermal resistance due to fouling deposition on heat exchanger surfaces. Temperature, velocity, surface roughness, surface adhesion characteristics of particulate film, and flow turbulence will determine both the deposition and removal rates and hence the rises and declines of the thermal resistance with operating time.

Heat transfer data for several selected fouling tests have been summarized in Table 4 for time-dependent reductions in measured heat transfer rates, Q_C, and for time-dependent increases in the measured total thermal resistance of the probe. This data does not show any clear trend in terms of a variation of a measured parameter's reduction or increase as a function of test time. Time, temperature, exhaust velocity, fuel, particulate loading of the exhaust, probe operation, and other effects cause the

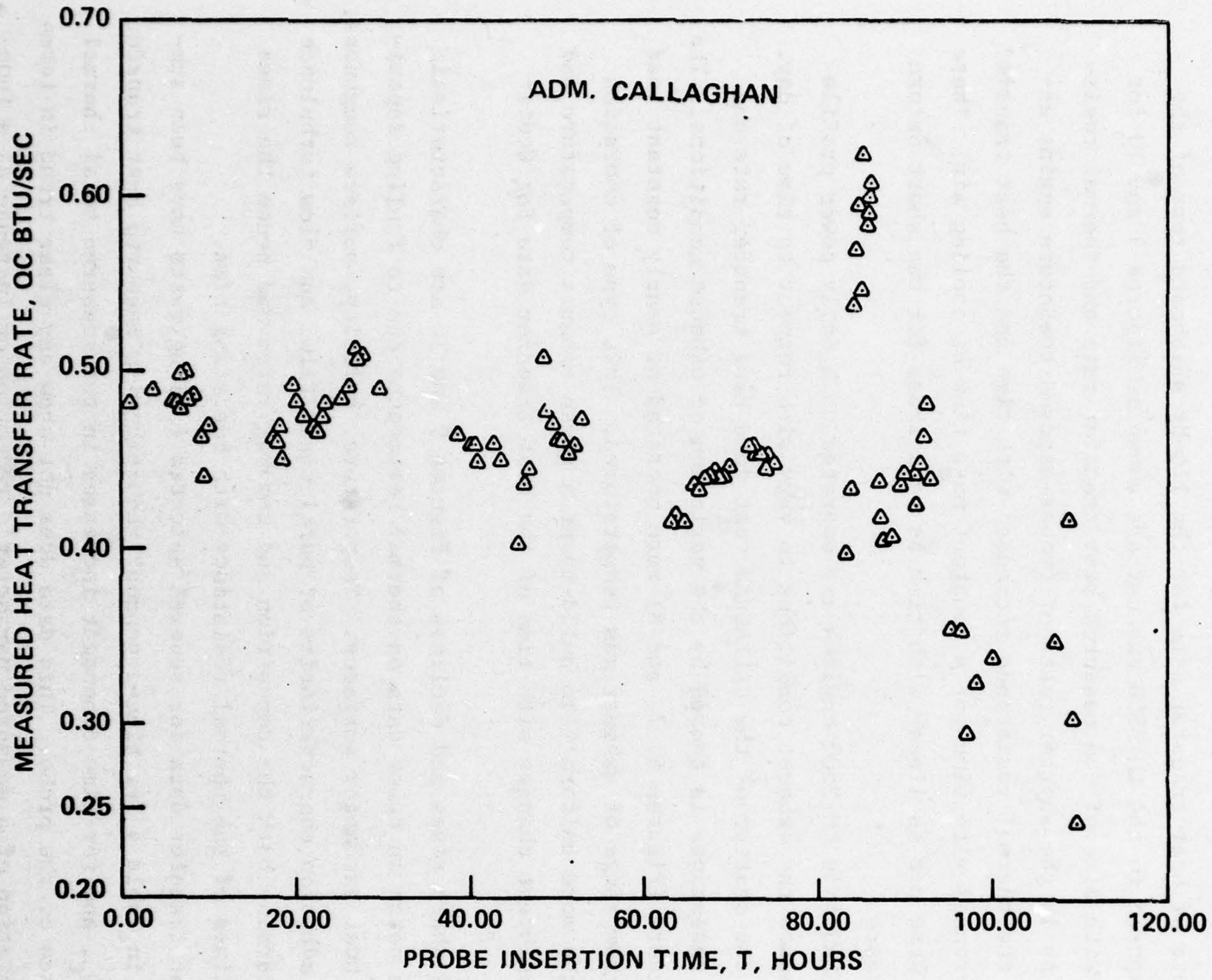

Figure 9 - Summary of Measured Heat Transfer Rates of Fouling Probe during Shipboard Tests, Average $T_G = 338^oC$ (640^oF)

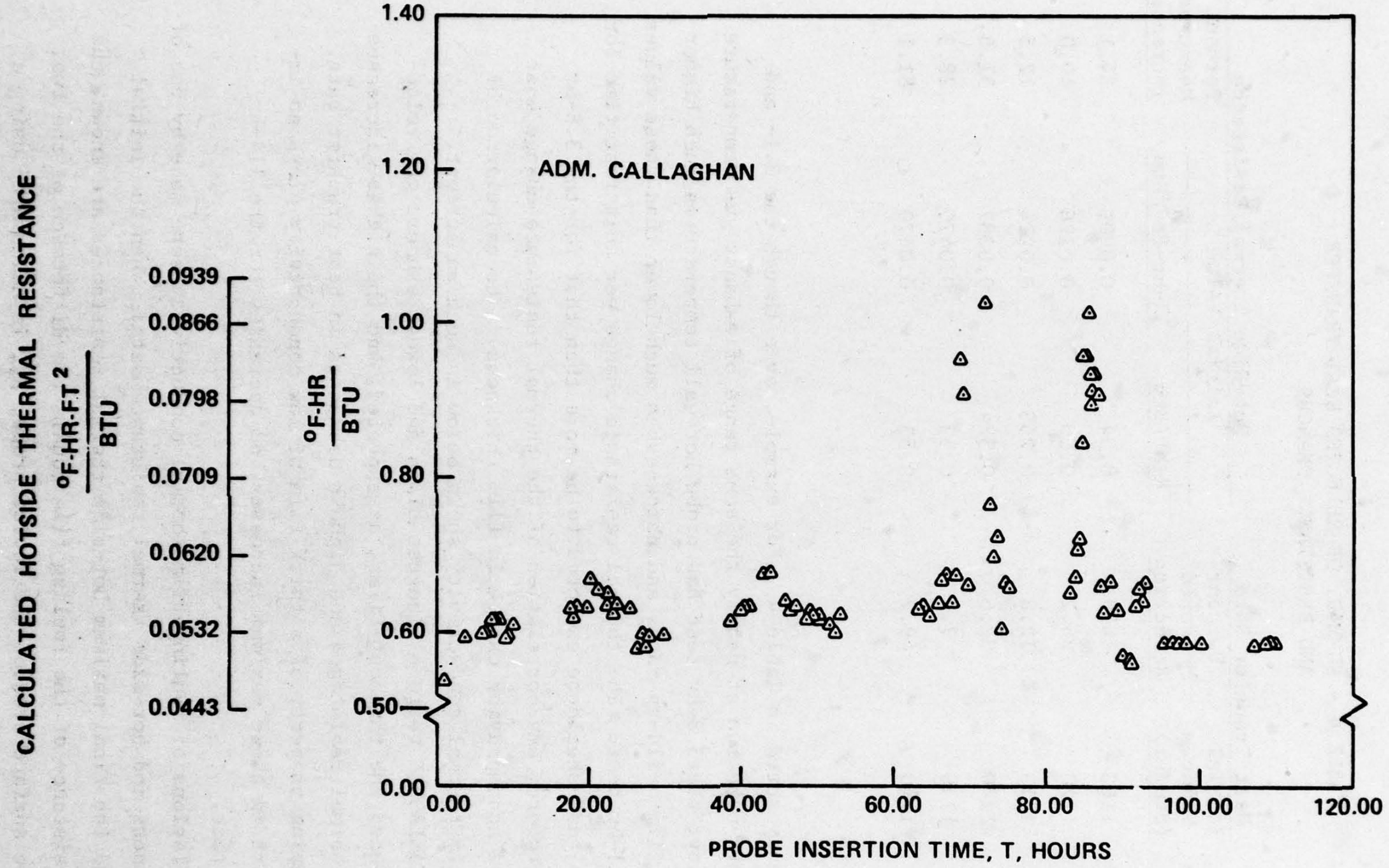

Figure 10 - Summary of Total Hot-Side Thermal Resistances of Fouling Probe during Shipboard Tests, Average T_G = 338°C (640°F)

TABLE 4 - SUMMARY OF SELECTED HEAT TRANSFER AND RESISTANCE CHANGES

Test Duration (hr)	Heat Transfer Rate		Hot-Side Thermal Resistance		
	Initial Value (Btu/hr)	Percent Measured Reduction	Initial Value		Percent Measured Increase
			^oR-hr/Btu	^oR-hr-ft^2/Btu	
2.9	1163	26.9	0.34	0.0301	34.1
3.1	1220	26.2	0.30	0.0226	40.0
3.8	1213	12.8	0.253	0.0224	12.5
5.1	1200	32.6	0.324	0.0287	51.8
44.0	1740	7.2	0.53	0.0470	28.3
114.0	1740	49.7	0.53	0.0470	81.1

inconsistency noted in Table 4. For example, even though the 3.1- and 3.8-hr tests were run at nearly the same range of exhaust gas temperature and velocity, the 3.8-hr test had probe hot wall temperatures much higher and hence film build-up rates and thicknesses much lower than those values for the 3.1-hr test. The thermal resistance change per unit test time for the 3.1-hr test should be expected to be more than that for the 3.8-hr test. Therefore, any correlation of the thermal resistance change must include the accompanying change in film thickness. The calculation of fouling film thermal conductivity shown below is such an attempt.

The CALLAGHAN tests of longest times and lowest exhaust gas velocities produced the thickest films, as expected, and the highest increases in total thermal resistance and highest decreases in heat transfer rate. The insulating property of a thick film of low conductivity plays an important part in these maximum increases and decreases for the 114-hr CALLAGHAN test.

Calculations of fouling film thermal conductivity were made by use of film thickness and hot-side thermal resistance data. When the initial minimum and the final maximum hot-side thermal resistances are known, the thermal resistance of the fouling film equals the difference of the two, or ΔR. The surface area of the fouled probe, A_f, is calculated using a total diameter which includes probe diameter and two film thicknesses, 2 FT. The thermal conductivity of the fouling film, K_f, can be calculated from Equation (2).

Table 5 shows fouling film thermal conductivities for selected tests. In the six cases analyzed, the film thermal conductivity ranges from 0.0204 to 0.0272 Btu/hr-^{o}F-ft^{2}/ft (0.0353 to 0.0470 J/s-K-m^{2}/m).

This is a notable correlation considering that the data covers two different series of tests with significantly different time frames. Also, the fouling films of the two test series were significantly different in thicknesses and consistencies. As mentioned before, the fouling films observed in the Center tests were light and sooty, while those from the ADM CALLAGHAN tests were more adherent and harder.

It is expected that this fouling film thermal conductivity can be related to thermal conductivities of the gas components of the exhaust gas and the solid constituents of the fouling film.

When trying to relate the calculated thermal conductivity to these gas and solid constituents, it becomes apparent that this fouling film is an excellent insulator, especially at the film temperature it is subjected to. Some high-temperature insulating materials have thermal conductivity values which are almost twice as large as was calculated for the fouling film.

The thermal conductivity of typical gas constituents of the exhaust gas agrees rather well with the calculated fouling film thermal conductivity. Air[6] has a thermal conductivity of 0.0266 Btu/hr-^{o}F-ft^{2}/ft at the typical exhaust gas temperature of 600^{o}F and 0.0225 at the typical film temperature of 400^{o}F. Combustion products[7] of fuel oil have a somewhat lower thermal conductivity range: 0.0233 at 600^{o}F and 0.0193 at 400^{o}F.

Information on the thermal conductivity of the fouling film's solid constituents is more difficult to obtain. The thermal conductivity of carbon powders or lamp black can range from 0.012 to 0.038 Btu/hr-^{o}F-ft^{2}/ft at temperatures of approximately 100^{o}F.[2] At the higher temperatures of interest to the fouling film, these values for thermal conductivity would be even higher.

TABLE 5 - FOULING FILM THERMAL CONDUCTIVITIES FOR SELECTED TESTS

Test Time (hr)	Film Thickness (mils)	Fouling Probe Hot-Side Thermal Resistance (°R/Btu/hr)		Thermal Resistance Due to Fouling ***		Thermal Conductivity of Fouling Film, K_f	
		Final	Initial	°R-hr/Btu	°R-hr-ft^2/Btu	Btu/hr-°R-ft^2/ft	J/s-K-m^2/m
2.9	2.5	0.456	0.34	0.116	0.0103	0.0204	0.0353
3.1	3.1	0.42	0.30	0.12	0.0106	0.0245	0.0424
3.8	0.9	0.285	0.253	0.0316	0.0028	0.0272	0.0470
5.1	4.4	0.492	0.324	0.168	0.0149	0.0248	0.0429
44.0	4.2**	0.68	0.53	0.15	0.0133	0.0265	0.0459
144.0	10.9	0.96*	0.53	0.43	0.0381	0.0236	0.0408

***Shipboard LM 2500 test, near maximum thermal resistance is final value used.**

****Shipboard LM 2500 test, film thickness = (44/114)10.9 = 4.2 mils estimated at 44 hr during 114-hr test.**

*****To convert all thermal resistances in this document from units of °R/Btu/hr to °R-hr-ft^2/Btu, multiply them by 0.08863 ft^2 which is the surface area of the clean portion of the fouling probe exposed to the exhaust gas.**

Based on the limited information on thermal conductivity which was obtained from the heat transfer data, it is difficult to propose a model of the fouling film; additional data is needed as to the density of the film, and the structure of the film layer must be examined in more detail. Even the assumptions need to be reexamined. It was assumed here that the entire increase in resistance is attributable to the fouling film. Actually the roughness of the probe surface changes with the film build-up which will affect the convective resistance of the probe.

FOULING FILM, EXHAUST PARTICULATE, AND TEST FUEL ANALYSIS

Exhaust gas particulates were sampled at isokinetic sampling rates according to procedures for EPA Method 5 sampling trains. Foulant film samples, taken following each fouling test, and filtered particulate samples were analyzed using X-ray fluorescence (XRF). The XRF method produces an elemental analysis of the sample. Fuels, burned during film formation and particulate sampling tests, were sampled following each test. These fuel samples were analyzed in a variety of ways by several sources. Results of these sample analyses are now discussed in reference to elements of the fuel found in the foulant films.

Analysis results are given in Table 6. From 10 to 30 percent by weight of the soot and foulant film samples are sulfur and metals, suspected to be mostly metal sulfates. The remaining 70 to 90 percent of the samples were mostly carbon, hydrogen, oxygen, and nitrogen, which are not identified by the XRF analysis. In the Center foulant film samples, the larger concentrations of elements existed for sulfur, barium, copper, iron, and zinc. Sulfur had the highest concentration in samples with an average value of 7.07 percent by weight. There were 15 elements found by XRF analysis of the fouling probe film samples but not found by XRF analysis of the filtered particulate samples from the Center tests. These elements are: bromine, silica, aluminum, magnesium, potassium, zinc, copper, nickel, cobalt, iron, vanadium, titanium, barium, calcium, and tin. This data suggests that elemental analysis of filtered particulate samples alone is not a good indicator of foulant film elemental composition.

TABLE 6 - CENTER FOULANT FILM ELEMENTAL SUMMARY

Test Date	8-2-76	8-27-76	9-28-76	9-23-76	10-18-76	10-4-76	12-2 to 12-7-76	
Type	Center	Center	Center	Center	Center	Center	Shipboard	CALLAGHAN
Sample Mass, μg/cm^2	22.43	51.83	38.90	25.06	52.13	30.11	113.01	36.2
Element (% by weight)								
Cr	-	-	-	-	-	-	0.74	0.81
Mn	-	-	-	-	-	-	0.07	-
Br	-	0.097	0.154	0.319	0.077	-	-	-
Si	0.401	0.405	0.257	1.157	0.249	0.764	0.33	1.36
Al	0.178	0.154	0.103	0.359	0.077	0.100	0.091	0.13
S	7.133	2.894	7.352	7.54	6.272	12.52	11.9	7.75
Na	-	-	-	-	-	-	-	0.66
Mg	0.045	0.058	0.051	0.160	0.038	0.133	0.046	-
K	0.178	0.058	0.051	0.120	0.077	0.100	0.044	0.098
Zn	0.446	0.579	0.206	0.439	0.192	0.365	0.10	-
Cu	6.687	1.447	3.419	6.185	1.688	3.72	0.16	0.40
Ni	-	0.058	0.129	-	0.211	0.266	0.70	0.60
Co	-	-	0.206	0.918	-	-	-	0.06
Fe	-	0.926	2.622	3.232	1.822	4.351	3.1	3.30
V	-	0.058	0.179	-	0.096	0.166	-	-
Ti	-	0.559	0.077	0.080	0.013	0.100	0.017	0.064
Ba	11.59	2.122	1.439	4.91	-	2.092	-	-
Ca	0.669	0.251	0.334	0.918	-	0.465	0.184	0.20
Sn	-	-	-	0.120	-	-	0.18	-
Total % Indicated by XRF	27.33	9.67	16.58	26.46	10.81	25.14	17.01	15.36
Remaining % (suspected UHC, N, & oxides)*	72.67	90.33	83.42	73.54	89.19	74.86	82.99	84.64

***All film samples were analyzed for and found to contain none of the following elements:** F, As, Se, P, Cd, **Sb, Hg, and Pb.**

Test fuel samples were analyzed for metals by an Atomic Baird fluid analysis spectrometer. Each fuel sample was analyzed for 20 elements by these tests. Table 7 gives a summary of this analysis. The Center and ADM CALLAGHAN test fuels were found to contain the following elements: calcium, aluminum, copper, zinc, lead, chromium, and iron. The No. 2-D Center test fuels contained, on the average, 10.4 ppm barium but no boron. The No. 2-D ADM CALLAGHAN test fuel contained, on the average, 10.6 ppm boron but no barium. Boron and barium are elements not normally found in petroleum and are probably the result of fuel additives. All metals found in test fuel samples were found to be present in the foulant film and filter particulate samples. Elements found present in foulant film and filter particulate samples, but not found present in test fuels, are: bromine, silica, magnesium, potassium, nickel, cobalt, vanadium, titanium, and manganese. Their presence can be due to factors such as engine wear and lube oil deterioration, impurities in engine inlet air, soot deposit removal from stack walls upstream of fouling probe, and coalescer residue carry-over. The levels of sulfur in the foulant films are due to metal sulfates deposited on the probe and sulfuric acid build-up due to the probe wall temperature being at or near the dewpoint temperature. All fuels were analyzed for, but did not contain, detectable concentrations of the following elements: magnesium, vanadium, sodium, potassium, silver, silicon, titanium, molybdenum, tin, and nickel.

The sulfur content of films varied somewhat as a function of probe hot wall temperature; lower temperature surfaces collected films with higher sulfur contents than those for films collected during tests at higher probe temperatures. For example, a film with a 2.9-percent sulfur content was obtained from a test when the range of probe hot wall temperature was 423° to 457°F. From another test, when the range of probe hot wall temperatures was 187° to 202°F, a film with a 12.5-percent sulfur content was collected. From the shipboard test, when the range of probe hot wall temperatures was 145° to 229°F, a film with an 11.9-percent sulfur content was collected.

A number of studies[5] on analysis of deposition from combustion gases in boilers has indicated that alkali metal sulfates represented a major

TABLE 7 - TEST FUEL SAMPLE ANALYSIS BY ATOMIC BAIRD* FOR METALS USING FLUID ANALYSIS SPECTROMETRY

Sample Designation	A	B	C	D	E	F	G	H	I
Test Date	10/21/76	10/18/76	9/28/76	9/23/76	12/7/76	12/4/76	12/7/76	12/5/76	12/7/76
Engine	Solar	Solar	Solar	Solar	LM2500	LM2500	LM2500	LM2500	LM2500
Elemental Concentration PPM; Element**									
Calcium	0.2	0.3	0.2	0.2	0.0	0.0	0.1	0.0	0.0
Aluminum	0.5	0.6	0.9	0.9	0.4	0.8	0.6	0.5	0.6
Copper	0.0	0.0	0.2	0.7	0.0	0.4	0.0	0.0	0.0
Boron	0.0	0.0	0.1	0.0	11.9	11.1	9.5	10.4	11.1
Barium	11.8	10.4	9.0	10.1	0.0	0.0	0.0	0.0	0.0
Zinc	0.4	0.7	0.6	0.7	0.4	0.0	0.3	0.3	0.2
Lead	0.4	1.1	1.1	1.0	0.3	0.0	0.5	0.5	0.6
Chromium	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.3	0.1
Iron	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.2

***Tests were conducted in September 1977. Instrument used is the military designation A/E35 U-3 manufactured to Mil Spec S-83129A.**

****All fuels were also analyzed and found to contain no concentration of the following elements: magnesium, vanadium, sodium, potassium, silver, silicon, titanium, molybdenum, tin, and nickel.**

NOTE: EPA XRF Analysis of particulate and foulant film samples exists for all but 10/21/76 Solar tests (test Fuel A).

portion of boiler economizer tube deposits produced from combustion of a variety of coals and oils. Even studies of fouling of tubes in waste heat boilers backfitted to incinerators indicate predominantly alkali metal sulfates in fouling samples.

SUMMARY AND CONCLUSIONS

The cylindrical fouling probe test units have proved effective as total heat flux measurement devices for experiments of fouling film build-up, film chemistry, film thermal resistance, and thermal conductivity. Fouling rates have been established for a variety of operating conditions.

There appears to be a relationship between the film build-up rate and the probe insertion time. The general trend is initially for high film build-up rates which drop off quickly with time. For tests of near equal times and exhaust gas temperature and velocity, the fouling rate tended to be influenced by the probe surface temperature. As the average surface temperature for the tests increased, the average fouling film build-up rate and film sulfur content decreased. Lower wall temperatures produce thicker fouling films. For comparison of tests of similar times and gas velocities, the fouling rate was found to decrease with increased local exhaust gas temperatures.

The instrumented fouling probes provided data for determination of probe heat transfer rate from exhaust gas, the thermal resistance build-up due to the fouling film, and the thermal conductivity of the fouling film. When the probe is constantly cooled during the Center test, the measured probe heat transfer rate decreased (and the associated total thermal resistance increased) as fouling test time increased. The same trends for the heat transfer rate and the total hot-side thermal resistance were noted for the long shipboard tests, except the trends were not as regular with time as in shorter Center tests. The thermal conductivity of the test films ranged from 0.0204 to 0.0272 Btu/hr-^{o}F-ft^{2}/ft (0.0353 to 0.0470 J/s-K-m^{2}/m). The fouling film thermal conductivity seems insensitive to time, and it agrees with published values for components of the exhaust gas thermal conductivity at test gas temperatures.

Analysis of the fuel for metals and analysis of the fouling film by X-ray fluorescence indicate that up to 30 percent of Center test film samples consisted of non-hydrogen/carbon elements, most of which were present as fuel impurities. For soot deposits from combustion of a No. 2 fuel with 0.11-percent sulfur, on the average, 7.07 percent by weight of the fouling films consisted of sulfur. The films are suspected to consist of alkali metal sulfates in concentrations between 10 to 30 percent be weight. This indicates that fouling deposits from shipboard waste heat boiler operation will be affected by more alkali metals in salty air. Analysis of filtered particulate samples by X-ray fluorescence has shown that the filtered particulate sample is not a good indication of elemental concentrations or existence of elements in the fouling films. There was a good correlation between elements of the fuel and elements in the fouling films, but this was not true for elements in the filtered particulate samples compared to those found in the films or the fuel. Barium, zinc, copper, iron, and sulfur were the largest concentrations of non-carbon/hydrogen/oxygen elements found in film samples from the Center tests. Barium and iron in metallorganic compounds are vary effective turbine engine smoke reduction fuel additives and are suspected to be sources for these elements found in fouling film samples.

The reader must be cuationed that these data from Center and ADM CALLAGHAN tests are for fouling of a bare tubular surface and that data from Solar Turbines International are for a finned tubular surface for various fin pitches. Solar Turbines International measured a von Brand smoke number to define the exhaust particulate loading, while for the Center and ADM CALLAGHAN tests, particulate concentrations were measured with an EPA Method 5 instrument. It is impossible and can be misleading to relate the two measures of exhaust particulate loading, but it can be said that the Solar Turbines International data up to a von Brand number of 20 is equivalent to the exhaust particulate loading during the Center and ADM CALLAGHAN tests. Fouling data for Solar Turbines International tests at von Brand smoke numbers higher than 20 is representative of fouling produced by combustion processes, causing high exhaust particulate concentrations such as might be encountered with heavy fuels or under off-design operating conditions.

The Tubular Exchangers Manufacturers' Association (TEMA) indicates a fouling factor of 0.01 for diesel engine exhaust streams (none so stated for gas turbine engine exhausts). Assuming that this factor may be the same which the TEMA would recommend for a gas turbine engine exhaust fouling resistance factor, a comparison of fouling resistance factors, ^oR-hr-ft^2/Btu, in Table 5 and Figure 10 indicates the following:

1. For the short Center tests, thermal resistances due to gas-side fouling were the same as the TEMA design factor for test times up to 3 hr. For the 5-hr test, the fouling thermal resistance factor was 1.5 times the TEMA factor.

2. For the shipboard tests, thermal resistances due to gas-side fouling reached maximum values of four times the TEMA design factor during time periods between 70 and 90 hr of probe insertion time.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions made by Mr. Rolf K. Muench of the Gas Turbines Branch, DTNSRDC, during the course of this investigation. The author acknowledges Mr. Roy L. Bennett of the Stationary Source Emission Research Branch of the Environmental Protection Agency, Research Triangle Park, North Carolina, for the free X-ray spectrometric analysis of foulant film and engine particulate samples. The author acknowledges the assistance of Harry Tongue of DTNSRDC for his assistance in the ADMIRAL CALLAGHAN tests.

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