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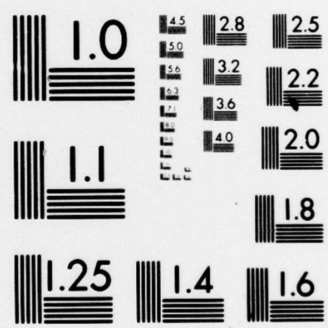

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Combined Cycle Steam Generator Gas Side Fouling Evaluation

PHASE 1 - FINAL REPORT
July 1979

Prepared Under Contract Number N0024-77-C-4366 for
Naval Sea Systems Command
Department of the Navy

Prepared by
P.B. Roberts
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Naval Sea Systems Command
Public Affairs-00D2
Cleared for public release.
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80-0032

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ABSTRACT

Liquid-fueled gas turbines can produce serious steam generator fouling in gas turbine combined cycle applications and other waste heat recovery systems as a result of combustion system generated soot particles. In addition, standard soot blowing practices are not always compatible with the advanced, compact matrix designs sometimes required for minimum package size applications. This report describes an experimental program conducted on both test rigs and engine hardware designed to evaluate the effects on gas side soot fouling rates of various operational parameters such as soot loading, temperature and velocity. Particular attention was given to the effectiveness of the self-cleaning concept where elevated steam generator metal temperatures are utilized to remove soot deposits.

The test results showed that a combustion rig can simulate the soot fouling rates and the type of soot encountered in a combined cycle gas turbine steam generator if duplication of the controlling parameters is achieved. In addition, self-cleaning by dry operation appears to be a viable alternative to air or steam blowing although further work is recommended in this area to see if the threshold temperature can be depressed or the rate of cleaning increased.

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INTRODUCTION AND PROGRAM OBJECTIVE

Potentially, one of the most difficult problems to solve on compact steam generators for combined cycle gas turbines is carbon or soot build-up on the heat transfer surfaces. This build-up reduces heat transfer and increases pressure drop, both factors that contribute to a reduction in overall cycle thermal efficiency. In addition, the presence of soot on the gas side surfaces may be a significant fire hazard and necessitate increased maintenance levels.

Air or steam soot blowing devices are not always fully effective and may not be compatible with the advanced, compact matrix designs that are called for in space-limited applications such as shipboard combined cycle installations.

Although there are considerable data published on soot fouling and the mechanisms of soot fouling (Ref. 1, 2 and 3), little information exists for *turbine exhaust* soot fouling of continuous circular finned tubes arranged in a staggered tube matrix; this configuration being one of the most effective heat transfer matrices.

Solar Turbines International (STI), an Operating Group of International Harvester Company is currently in the pre-production test phase of an advanced steam generator designed for combined cycle applications of gas turbines and some soot fouling data were generated from these tests. Representative engine data were also obtained from a fouling probe mounted in the exhaust duct of a General Electric LM-2500 gas turbine during a test run at the U.S. Naval Ship Engineering Center, Philadelphia. An experimental rig investigation has been carried out to study the effects of various combustor and steam generator parameters on soot fouling rates. In addition a study was made of the self-cleaning concept where soot deposits are removed by curtailing steam generator water flow and raising fin/tube temperatures to the prevailing gas turbine exhaust gas temperature.

The objective of the program was to determine whether a combustor rig test of a model steam generator could duplicate the fouling and cleaning characteristics that are met in a gas turbine exhaust environment. If such a simulation is available then the combustor rig becomes a very cost-effective method of predicting the combined cycle steam generator response to, for example, a change in fuel type or design configuration. Some attention was also paid to the mechanisms of soot fouling and self-cleaning but no effort was made to examine the basic mechanisms of soot formation within the combustor.

2

TEST EQUIPMENT

2.1 COMBUSTOR TEST RIG

The combustor rig used in this test program is shown in Figure 1 and schematically in Figure 2, where the main features of the system can be seen. The rig consists of an atmospheric combustor stacked vertically above a steam generator model used for studying the soot fouling and cleaning phenomena.

2.1.1 Combustor

The combustor is a self-contained unit with the air supplied by a variable-speed, electric motor-driven radial fan drawing air from ambient. A spinning cup fuel atomizer is mounted on the fan shaft and is used to inject a low pressure fuel into the combustor. Variable geometry is incorporated whereby an air slide controls the split of the total fan airflow to either a primary reaction air swirler or to a series of dilution ports located axially downstream of the combustor reaction zone. An alternate low pressure air supply is also available to augment the fan supplied air. Further control over the combustor exit gas temperature is afforded by a secondary dilution system separately fed by a shop air supply through a ring manifold as shown in Figure 3.

The assembled combustor with the electric motor drive and air valve actuator is shown in Figure 4. A view of the belt-driven fan inlet is shown in Figure 5. A view looking into the combustor showing the spinning cup fuel atomizer is given in Figure 6.

In addition to the capability of varying airflow and fuel spray quality by modulation of the fan/cup speed, the variable geometry feature of the combustor means that the operating point, in terms of outlet temperature, velocity, and emissions can be readily controlled.

2.1.2 Steam Generator Model

The steam generator mounted below the combustor consists of a matrix of finned tubing arranged in a rectangular array four rows deep and five tubes wide. Photographs of the model arranged in alternate staggered and in-line

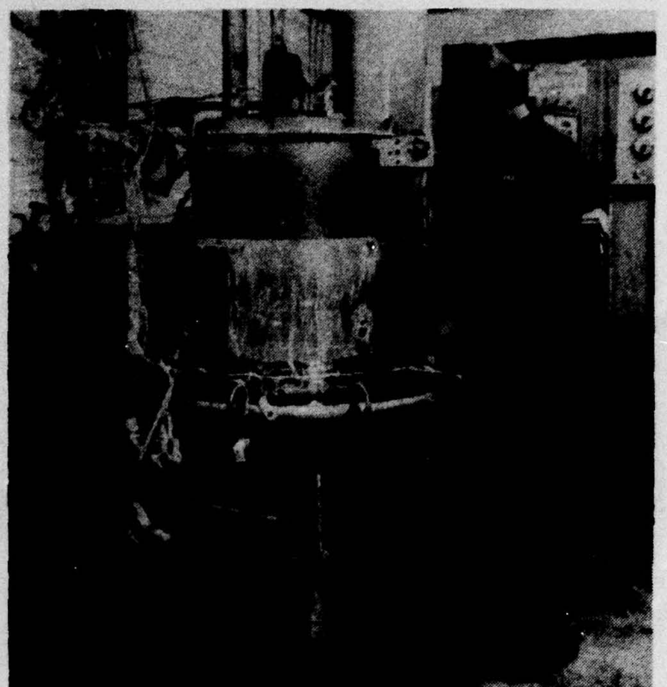

Figure 1. Combustor Rig

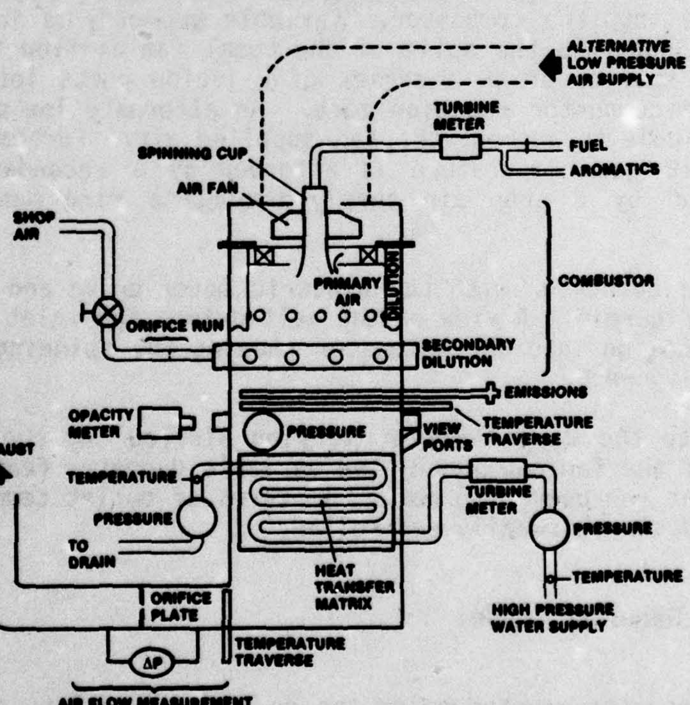

Figure 2. Combustor Rig Schematic

Figure 3.

Secondary Dilution Air Manifold

Figure 4.

Combustor Assembly

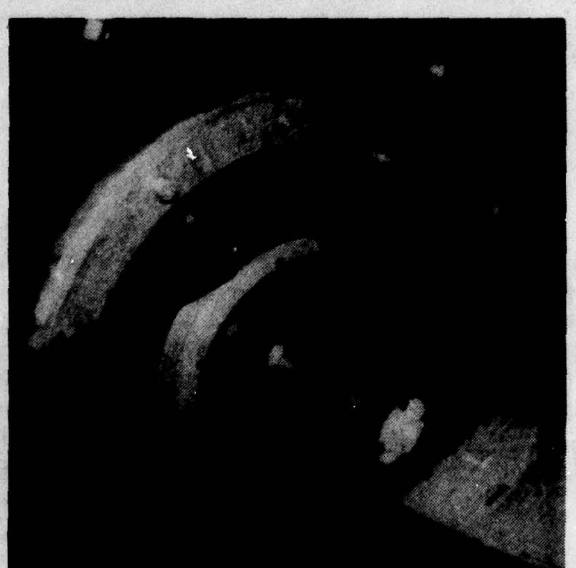

Figure 5.

Air Supply Fan Inlet

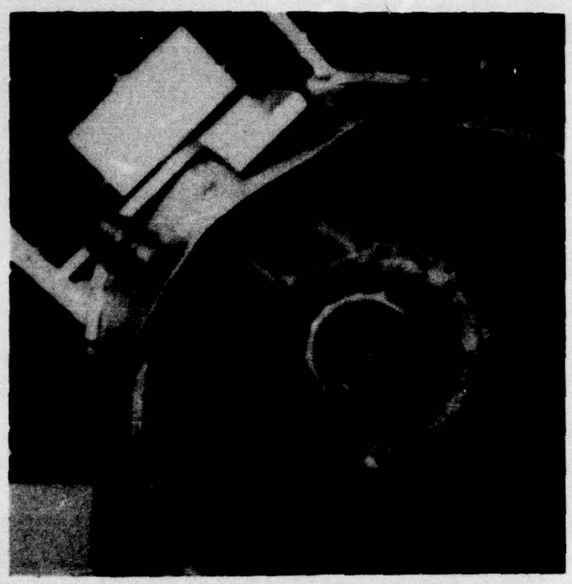

Figure 6.

Rotating Cup Fuel Injector

configurations are shown in Figures 7 and 8. Figure 7 also shows the headering system for supplying cooling air and/or water to the tubing.

The finned tubing is representative of the type used in a gas turbine combined cycle steam generator designed by Solar Turbines International and described in Section 3.2. The stainless steel tubes are either 1.59 cm (0.625 in.) or 1.91 cm (0.750 in.) diameter finned with helically wrapped 0.71 mm (0.028 in.) carbon steel strip to produce fin densities of 2.8 and 3.5 fins per cm (7 and 9 fins/inch) respectively. The fins are brazed to the tubing with Nicrobraze 50 which forms a continuous film over both the tubing and fin surfaces. Both water and air cooling were used during the rig testing to vary the range of metal temperatures obtainable.

2.1.3 Instrumentation

Instrumentation includes thermocouples to monitor the gas temperatures at the combustor outlet and after the addition of the secondary cooling air. A turbine meter is used to measure fuel flow rates. Air flow rates are calculated indirectly from an exhaust emissions carbon balance. The exhaust emissions instrumentation includes a Beckman 315A NDIR for carbon monoxide (CO) and carbon dioxide (CO_2), a Teco Model 10A chemiluminescent monitor for nitrogen oxides (NOx) and a Beckman 402 Hydrocarbon Analyzer. The operation and maintenance of the gaseous emissions equipment is per the provisions of SAE ARP 1256. Smoke loadings are indicated using a Von Brand smokemeter in conjunction with an Andersen sampler.

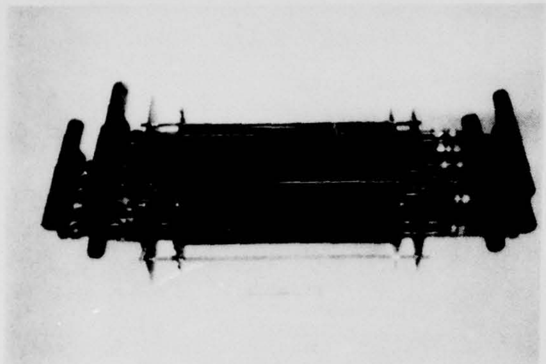

Figure 7.

Steam Generator Test Model
Staggered Tubing Configuration

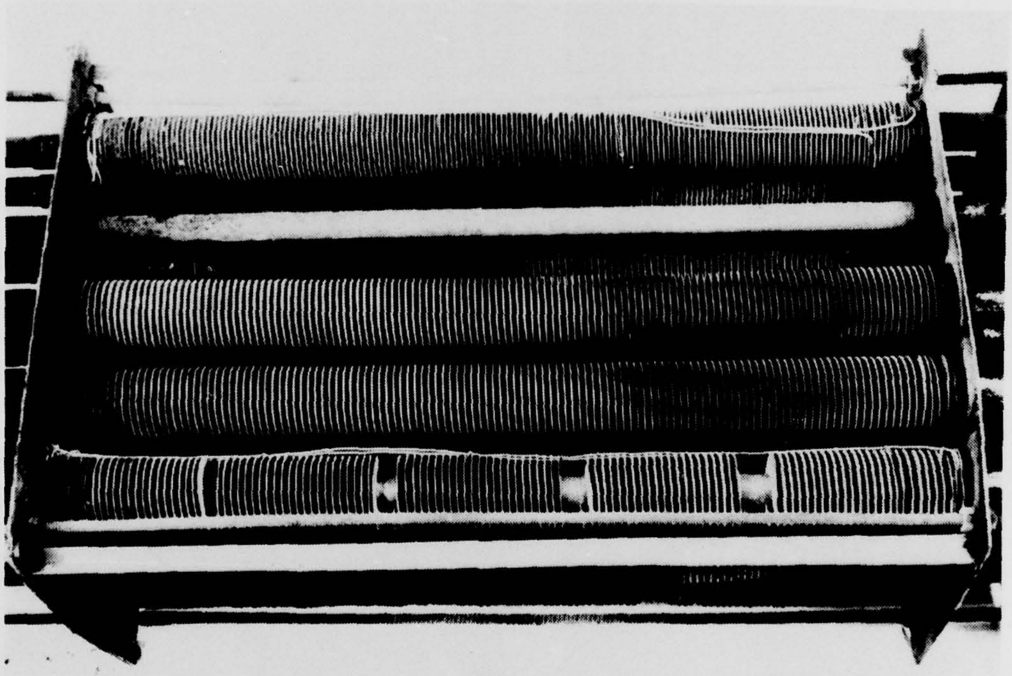

Figure 8. Combustor Rig In-Line Tubing Configuration

Thermocouples are used to monitor fin, tube metal and gas temperatures within the steam generator model.

2.2 CENTAUR STEAM GENERATOR MODULE

Solar Turbines International has designed an advanced, compact, finned-tube steam generator for use in combined cycle gas turbine applications.

The steam generator is a once-through, parallel circiut dual pressure design with the turbine exhaust gas and steam in counterflow (see Figs. 9 and 10). The finned-tubing design and arrangement has been previously described in connection with the combustor test rig.

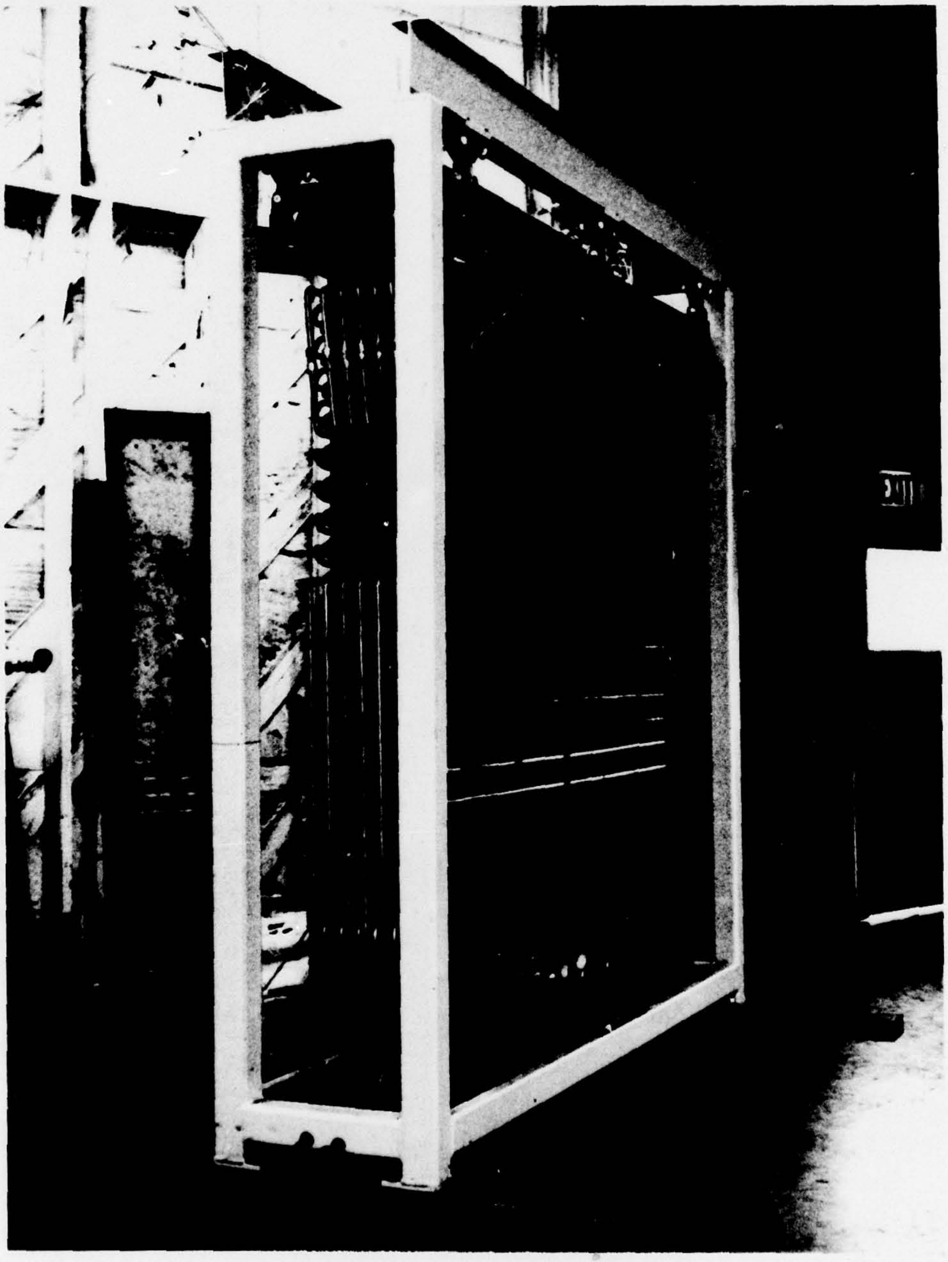

Figure 9. Solar Centaur Combined Cycle Steam Generator Model Figure

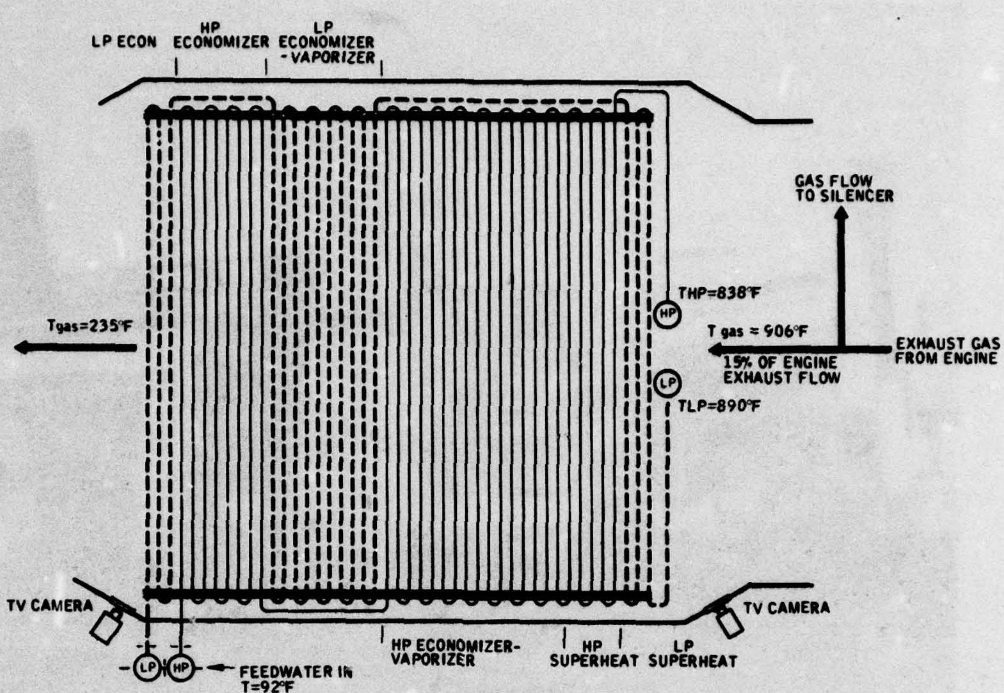

Figure 10. Flow Diagram Combined Cycle Steam Generator Test Module (45 Tubes 7 ft x 7 ft per Circuit, 6 Circuits Total)

A module comprised of six full size parallel circuits rather than the forty required for a complete unit, was mounted in the exhaust of an experimental gas turbine generator set for performance and fouling tests. The arrangement is shown in Figure 11 with the gas turbine generator set on the right and the steam generator module on the left. Because of the sizing of the module, only one sixth of the total exhaust flow was required to drive the steam generator, the remainder bypassing the unit through the main engine stack.

2.3 LM-2500 SOOT FOULING PROBE

A soot fouling probe was constructed for mounting in the exhaust duct of a General Electric LM-2500 gas turbine. This was done in order to observe the nature of and the buildup rates of soot deposits on steam generator surfaces under actual exhaust conditions. A photograph of the probe subassembly is shown in Figure 12. Two independent finned-tube circuits are used which include bare and finned sections with both 2.8 fins per cm (7 fins per inch) and 1.2 fins per cm (3 fins per inch). Full gas velocity and temperature instrumentation is included. The tube circuits are installed within a square-section tube (Fig. 13) which forms both a rigid support and a velocity control volume, reducing the local flow velocities from the main exhaust duct

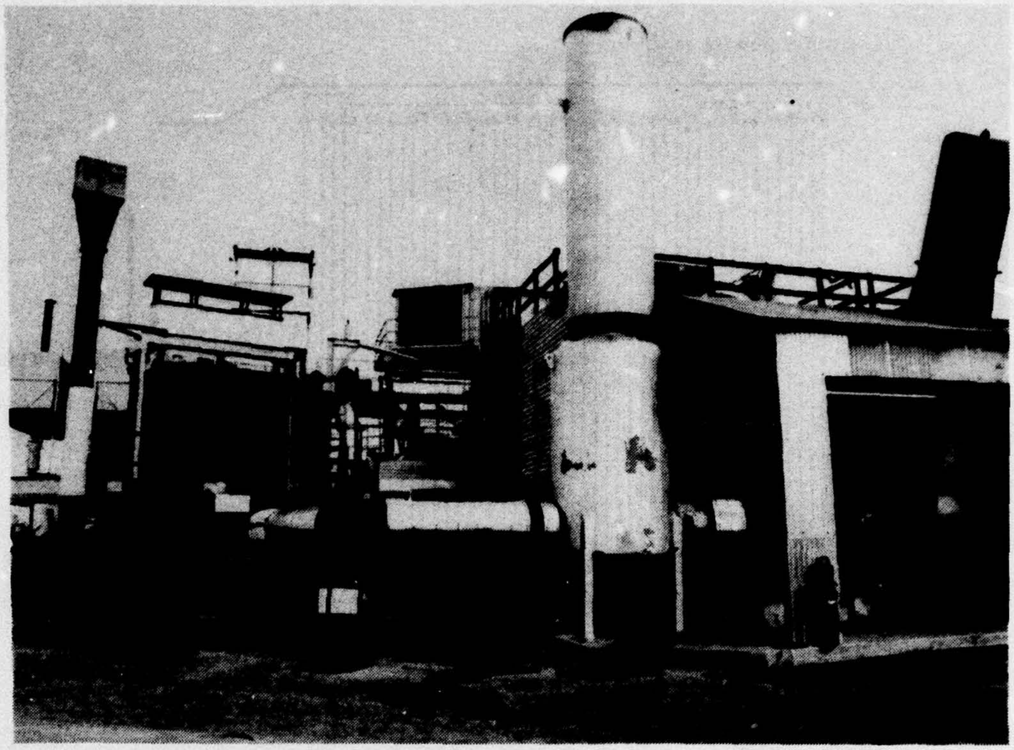

Figure 11. Combined Cycle Steam Generator Module - Test Arrangement

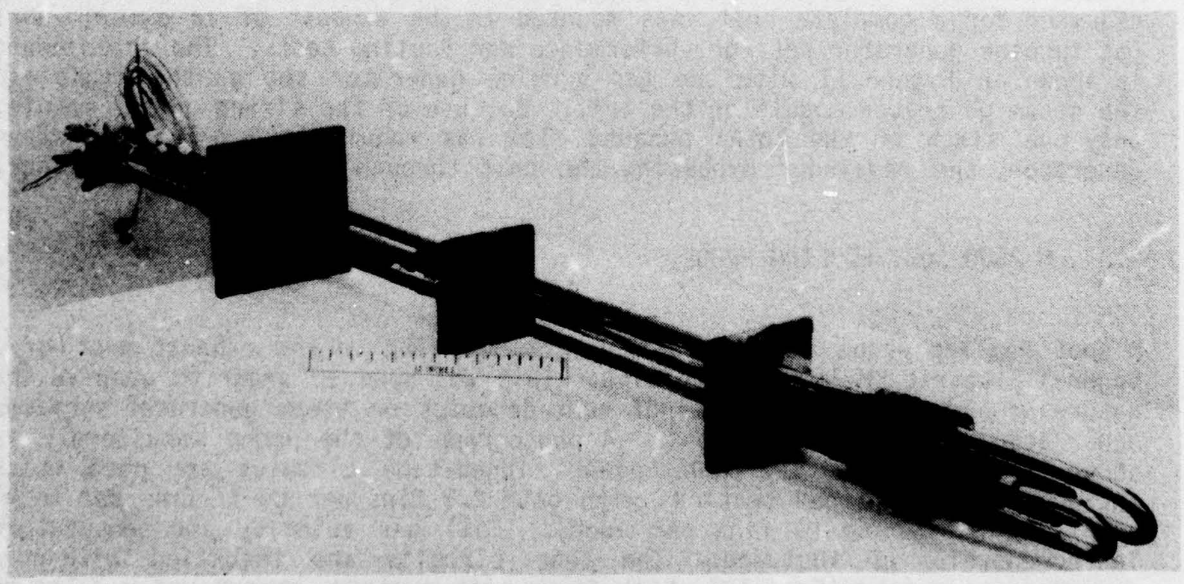

Figure 12. LM-2500 Soot Fouling Specimen Finned Tube Element Subassembly

Figure 13. LM-2500 Soot Fouling Specimen Assembly

value of about 107 m/sec (350 ft/sec) to a level more representative of those in a steam generator matrix.

Cooling of the two circuits was independent: the one circuit was cooled with 276 kPa (40 psi) saturated steam; the other with ambient river water.

3

RESULTS AND DISCUSSION

3.1 SOOT FOULING

Soot fouling data were obtained both from the combustor rig from and the engine module. Both series of tests were conducted using #2 Diesel as the primary fuel in order to aid comparison.

3.1.1 Combustor Rig

The approach used during the combustor rig testing was to vary each operating parameter independently and to assess the separate effects. The range of interest corresponds to the operating conditions of the engine module.

Soot Loading

The exhaust smoke characteristic obtained from the engine module tests is shown in Figure 14 showing the normal trend of increasing smoke with increasing engine load. The technique used on the combustor rig was to set the operating conditions to reproduce the smoke number at several points along the characteristic and to perform a test run at each point. The test points and the resulting soot fouling levels are also shown in Figure 14. A more complete tabulation of the operating parameters and fouling rates is given in Table 1. As might be expected, the soot film buildup rate increases as the smoke loading in the combustor exhaust is increased. The buildup rates on the bare tube sections appeared to be identical to those on the standard finned tubes.

In general, the deposits appeared to be "fluffy" in nature and only loosely adhered to the tubes and fins; air blast or water washing easily removed the bulk of the deposits.

A correlation between soot loading and smoke number, Von Brand and SAE, for the combustor rig is shown in Figure 15. This data was obtained by operating the combustor at a specific smoke number while simultaneously taking a soot loading measurement using a 0.015 micron filter. Also displayed is the data taken from a paper by Shaffernocher, et al, from which the correlation between Von Brand and SAE smoke number was obtained. For a given smoke

Table 1

Combustor Rig Test Fouling Data

Exhaust Gas Temperature K (F)	Test Time (Hours)	Film Thickness mm (mils)	Film Build-up Rate mm/hr (mils/hr)	Von Brand Smoke No.	No. of Start/Stop Cycles	Tube Wall Temperature K (F)	Fin Temperature K (F)	Exhaust Gas Velocity m/s (ft/sec)
728 (850)	17.0	<0.025 (<1.0)	<0.0015 (<0.059)	0	8	294-422 (70-300)	422-844 (300-600)	6.10-7.62 (20-25)
↓	26.0	0.076 (3.0)	0.0029 (0.115)	10	8	↓	↓	↓
↓	52.0	0.152 (6.0)	0.0029 (0.115)	10	18	↓	↓	↓
↓	52.0	0.152-0.254 (6.0-10.0)	0.0029-0.0049 (0.115-0.192)	21	20	↓	↓	↓
↓	8.0	0.508 (20.0)	0.064 (2.5)	35-40	2	↓	↓	9.14-12.20 (30-40)
↓	12.0	1.016* (40.0)*	0.085 (3.33)	35-40	4	↓	↓	9.14-12.20 (30-40)

*Also bridging of soot build-up across entire fingaps 2.11-2.95 mm (0.083-0.115 inches) occurred.

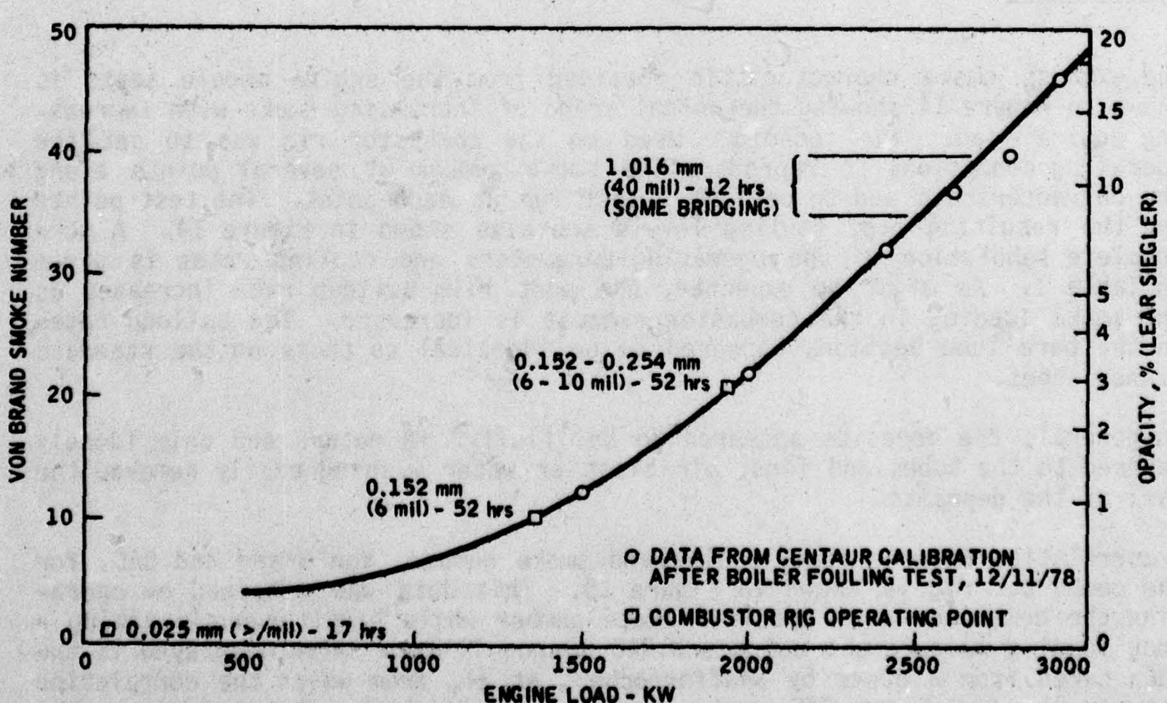

Figure 14. Cenatur Soot Characteristic - #2 Diesel Fuel

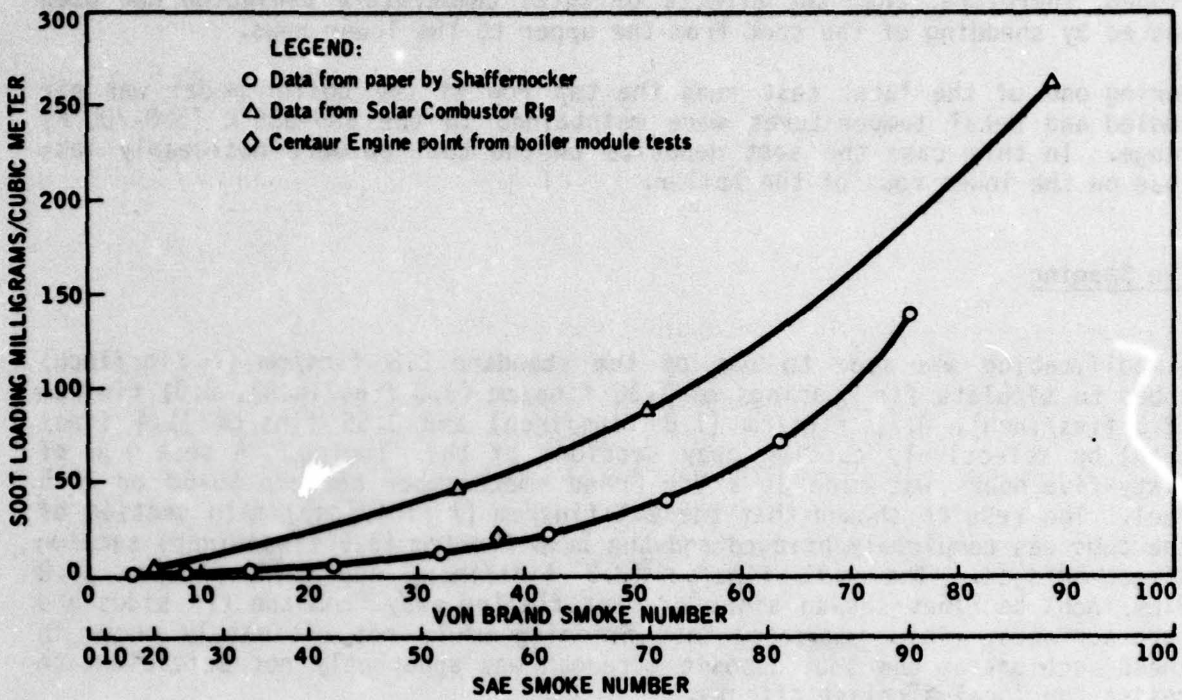

Figure 15. Soot Loading Vs. Smoke Number

number, data from the combustor rig indicates a slightly higher loading than that presented by Shaffernocker.

Surface Finish

Three of the finned tubes in the boiler model were replaced by units partially coated with Solaramic S5-8A, a lead silicate/chromium oxide coating fired on at 811°K (1000°F). A test run was made at a Von Brand smoke number = 21 to investigate the effects of surface finish and type of substrate on soot adhesion and inorganic composition. After completion of a 52 hour test, an inspection and measurement showed no apparent difference in soot build-up between the coated and uncoated sections of the tubes.

Metal Temperature

The bulk of the combustor rig testing was performed with separate water cooling flows to each of the four rows in the boiler maintaining a sufficiently high rate of flow to prevent steam generation. In this mode, tube and fin temperatures varied over the range 294-478°K (70-400°F) throughout the boiler. Under these conditions there appeared to be heavier soot deposits on the lower (colder) rows of the model than on the upper (hotter) rows. The deposits on each row, however, were uniform from tube to tube even though significant variations in tube metal temperature were indicated. It was concluded, therefore, that the effects of metal temperature variation had been masked by shedding of the soot from the upper to the lower rows.

During one of the later test runs the top row of the boiler model was air cooled and metal temperatures were maintained in the 589-655°K (600-700°F) range. In this case the soot deposits on the top row were noticeably less than on the lower rows of the boiler.

Fin Spacing

A modification was made to one of the standard 2.8 fins/cm (7 fins/inch) tubes to simulate fin spacings of 1.38 fins/cm (3.5 fins/inch), 0.91 fins/cm (2.3 fins/inch), 0.71 fins/cm (1.8 fins/inch) and 0.55 fins/cm (1.4 fins/inch) by selectively cutting away sections of the finning. A test run of sixty-five hours was made at a Von Brand smokenumber between 55-60 on JP-5 fuel. The results showed that the 2.8 fins/cm (7 fins/inch) main section of the tube was completely bridged and the 1.38 fins/cm (3.5 fins/ inch) section almost bridged. The 0.91 fins/cm (2.3 fins/inch) and 0.71 fins/cm (1.8 fins/inch) sections showed signs of soot flaking away from the fin sides and tube surfaces. This indicated that bridging would not ultimately occur in these sections as the soot deposit strength was apparently not sufficient to resist the local airblast effects.

Fuel Type

In order to determine the effect of fuel type on soot fouling rates a test run was made firing the combustor on JP-5 fuel and compared with a test under similar operating conditions using the standard #2 Diesel fuel. The combustor was fired with JP-5 fuel at a Von Brand smoke number in the range of 50-60 for a period of nineteen hours. The fouling results are shown in Figures 16 and 17 which are an overall view of the steam generator model and a view of the bottom row, respectively. The generator model was water cooled throughout except for the top row, which was air cooled. The air cooling was adjusted to maintain a maximum fin tip temperature of 655°K (700°F) with an incoming mean gas temperature of 728°K (850°F). Fouling was generally in the 0.76-1.016 mm (30-40 mil) thickness range throughout the water cooled sections.

In comparison, when the combustor rig was run on No. 2 Diesel fuel for 12 hours at a Von Brand smoke number of 35-40, the resulting soot buildup was in the 1.016 mm (40 mil) thickness range. It would therefore appear that fuel type does have an effect on the rate of soot buildup. However, two important points should be taken into account in connection with these results: first, the level of hydrocarbons in the combustor exhaust was lower for the JP-5 fuel than for the No. 2 Diesel; and second, a higher Von Brand smoke number may not necessarily indicate a higher soot mass loading with two different fuel types.

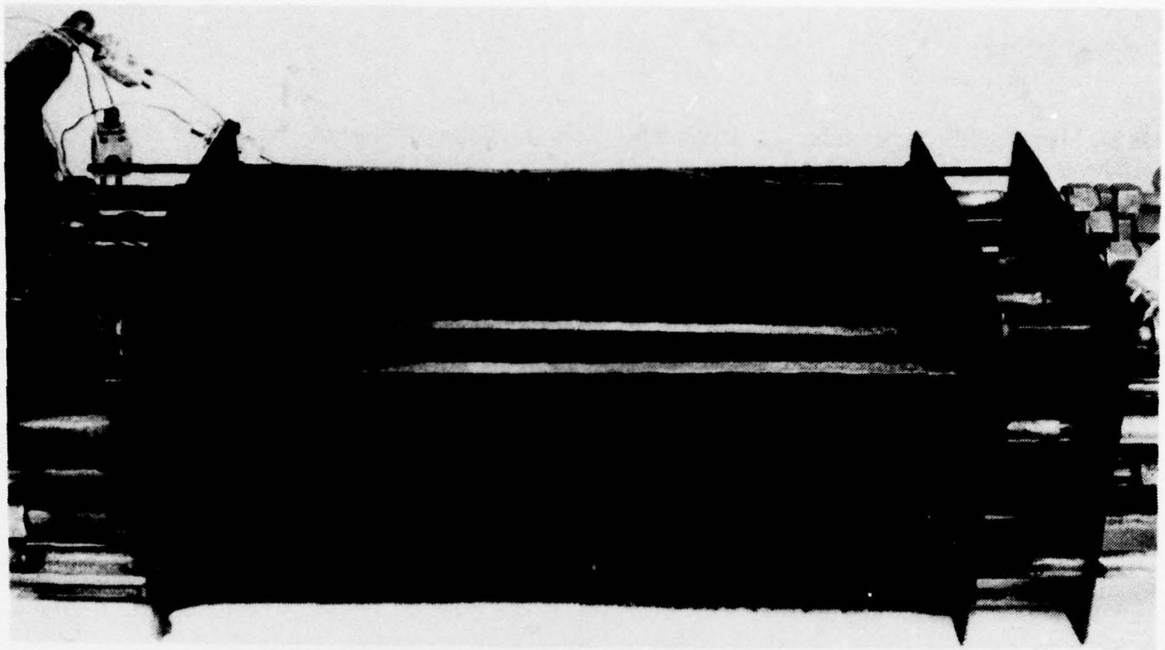

Figure 16. Boiler Model After 19 Hours on JP-5
Von Brand Smoke Number = 55-60

Figure 17. Boiler Model - Bottom Row After 19 Hours in JP-5
Von Brand Smokenumber - 55-60

Configuration

The boiler model was rebuilt with the finned-tube elements modified from the standard staggered configuration to an in-line configuration. A 38 hour test run at a Von Brand smoke number = 33 showed that there was no appreciable effect on the fouling buildup rate and the deposits were uniformly distributed around the finned tube sections.

3.1.2 Combined Cycle Steam Generator

Because the engine test of the combined cycle steam generator was not totally dedicated to the study of fouling characteristics, it is difficult to abstract definitive results for the soot buildup rates. The total engine running time of 105.2 hours was on No. 2 Diesel fuel at loads varying between 2800-2900 kW (due to variations in engine inlet temperature). Three start cycles were included to encompass an initial 0.4 hour checkout run and a subsequent 2.0 hour run which was curtailed for a fuel tank switch. The final 102.8 hours were continuous. Some general observations can be made, however:

Fouling Rates

The total deterioration in the boiler module effectiveness over the length of the test was approximately 7.0 percent, as shown in Figure 18. The tests began with a deterioration of 1.4 percent from the "as built" condition. This is thought to be due mainly to fin oxidation. The test was conducted at constant boiler gas side mass flow and the pressure drop increased from a starting value of 11.7 cm (4.6 inches) of water to approximately 14.7 cm (5.8 inches) at the completion of the test. This rate of fouling was accomplished at an exhaust stack opacity of 8-10 percent which corresponds to a Von Brand smoke number = 35-40.

The most heavily fouled rows occurred in the preheater and although no fin bridging occurred the deposits were approximately 0.51-0.76 cm (20-30 mils) thick and thus filled approximately one half of the inter-fin spaces 2.8 fins/cm (7 fins/inch). Experience on the combustor rig at similar smoke numbers and metal temperatures indicated some bridging of the fin gaps on the 2.8 fins/cm (7 fin/inch) sections after only 12 hours of operation. This indicates a much higher fouling rate than the engine run and may be a function of the higher unburned hydrocarbon level in the combustor rig. The engine exhaust hydrocarbon levels were typically close to ambient background levels in the less than 10 ppm range while the combustor rig operated at a level of 40-60 ppm.

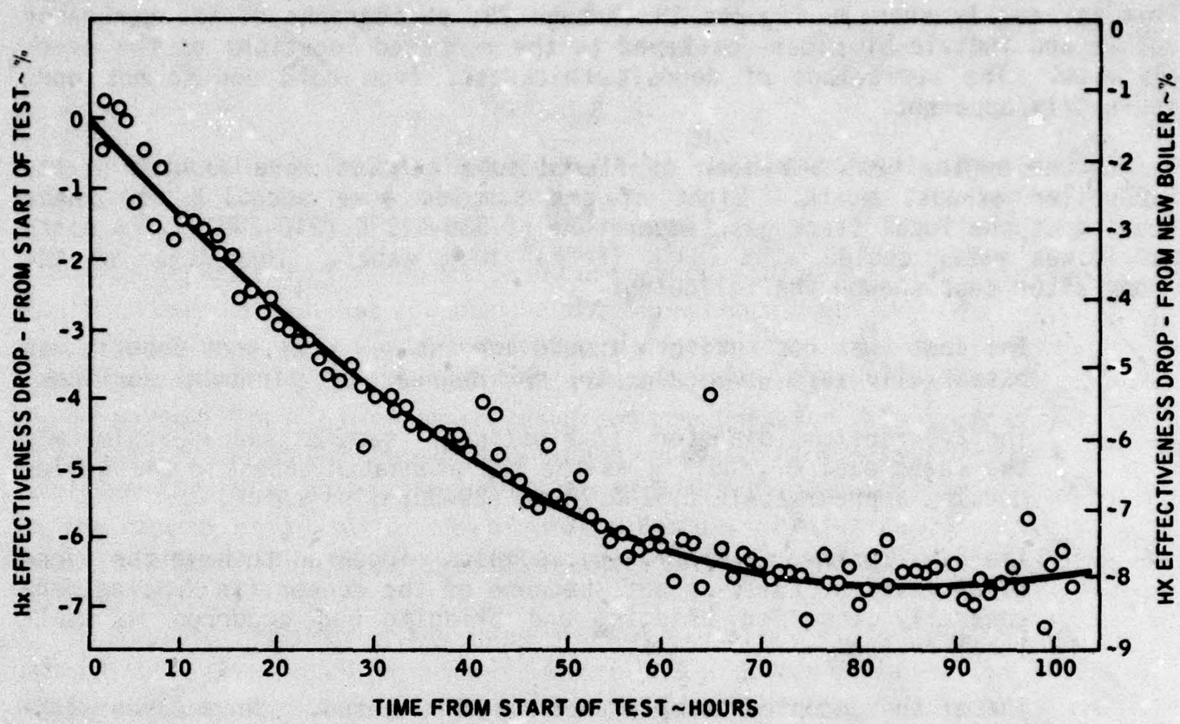

Figure 18. Centaur Steam Generator Module Fouling Rate

Fouling Factors

At the greatest degradation experienced during the engine test a fouling coefficient of approximately 127.9 watt/m^2°K (22.5 Btu/hr ft^2°F) was calculated. This figure is an average over the module as the fouling coefficient varied throughout due to the varying deposit thickness.

In terms of a fouling factor, the point of greatest performance degradation gave a fouling factor of 0.93. The fouling factor is defined as the multiplier of the clean boiler heat transfer. It should be noted that these fouling coefficients and fouling factors are the worst obtained from the limited engine test data and are a function of time and operating conditions. It appears from the data that longer run times could produce lower coefficients and fouling factors. The numbers presented here are only an indication of the worst case experienced and in no way reflect the limits which the fouling, fouling coefficient, or fouling factor could attain if tests had been run for longer period of time.

Metal Temperature

Upon final inspection of the steam generator the soot deposition was seen to occur in the heaviest concentrations in the cooler preheat section (gas outlet) and decrease to essentially zero in the hot superheater (gas inlet). This is readily seen in Figures 19 through 29; photographs of the generator module and individual close-ups keyed to the numbered locations on the overall view. The variations of deposit thickness, from cold end to hot end, is readily apparent.

During the engine test a number of finned tube samples were mounted across the boiler exhaust stack. Eight of the samples were uncooled and hence running at the local stack gas temperature of 389-411°K (240-280°F). A ninth sample was water cooled with 294°K (70°F) inlet water. Inspection of the tubes after test showed the following:

- The soot was not uniform around the tubes. The soot deposit was essentially zero over the top 90 degrees of fin/tube surfaces.
- The 2.8 fins/cm diameter (7 fins/inch) samples had approximately the same level of fouling as the top preheater tubes in the boiler module, approximately 0.51-0.76 mm (20-30 mils) thick.
- The 3.5 fins/mm (9 fins/inch) samples appeared to have the identical level of build-up but, because of the denser fin spacing were generally closer to bridging and bridging had occurred in small local regions.
- One of the uncooled samples was ceramic coated. No apparent differences in soot type or build-up thickness was noted.
- A metal shroud was removed from one of the uncooled samples. The fin and tube surfaces in the shrouded region were completely clean of soot deposits.
- The appearance of the soot on the water-cooled sample was distinctly different from that on the uncooled samples, appearing to be "wetter" and more granular.

Soot Characterization

The soot deposits collected during testing were "fluffy" in nature and could be brushed easily away down to the bare metal surface. These deposits were uniformly deposited around the finned tubes with no signs of shedding.

Some flaking of the soot away from the U-bends in the high pressure evaporator section was noted, see Figure 30. This action could possibly be due to the result of raw fuel and/or water/sulfuric acid condensation and subsequent drying.

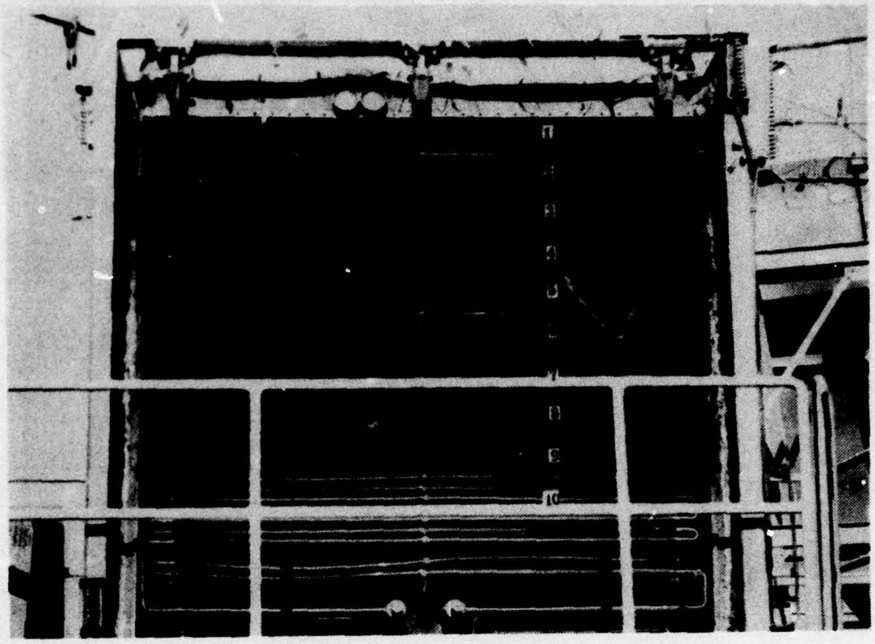

Figure 19. Centaur Steam Generator Module - After 105.2 Hour Test

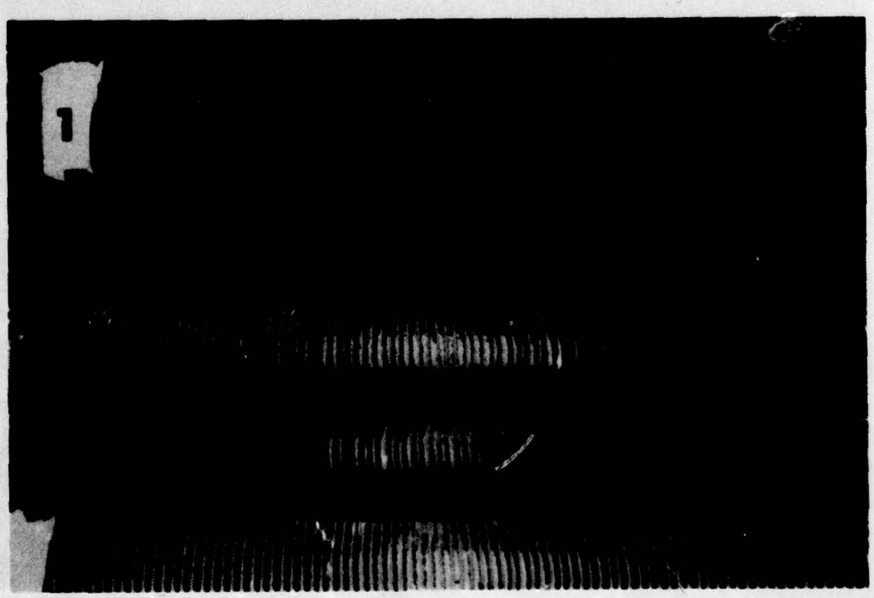

Figure 20. Centaur Module Tube Location Number 1
Water 370°K (206°F) - Gas 389°K (240°F)

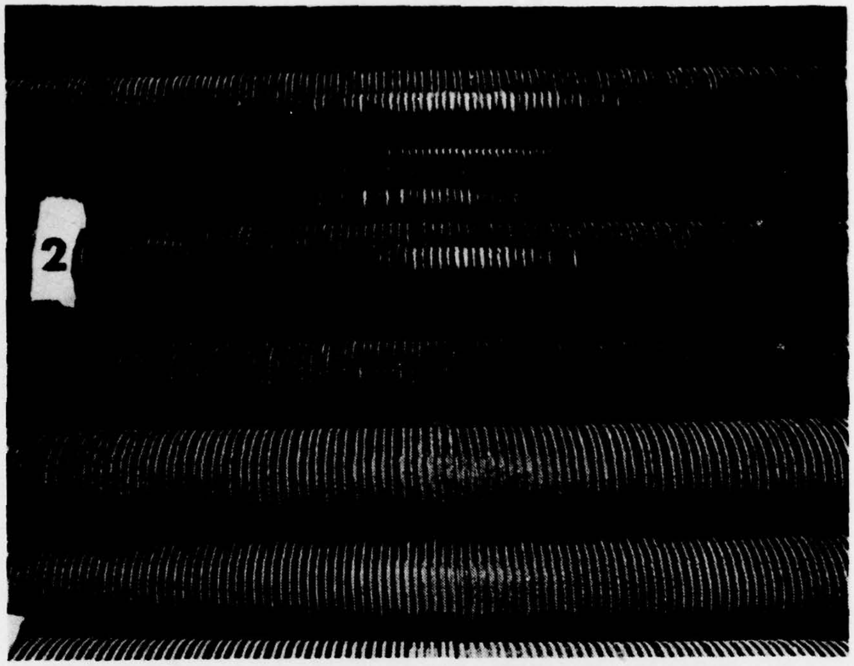

Figure 21. Centaur Module Tube Location Number 2

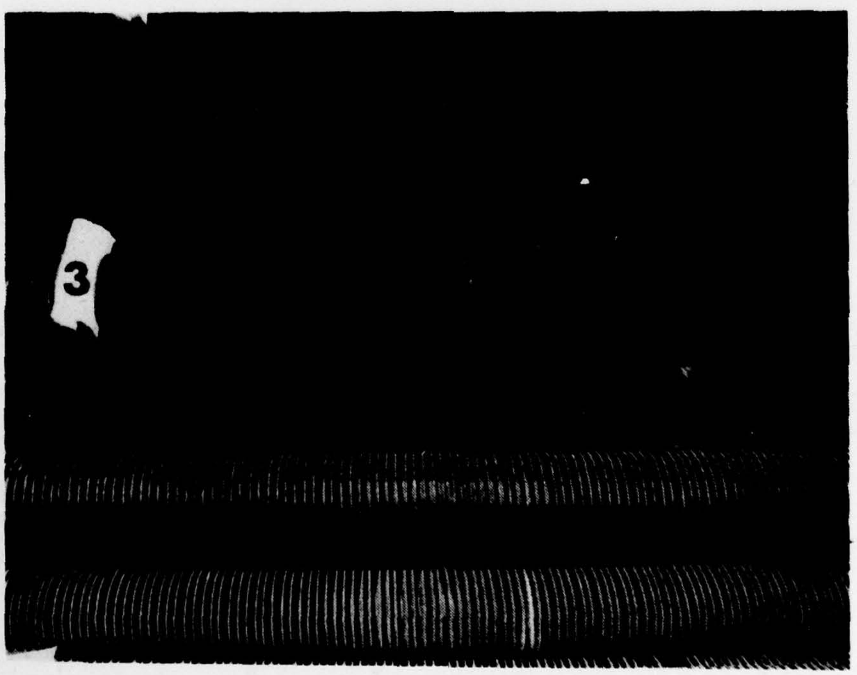

Figure 22. Centaur Module Tube Location Number 3

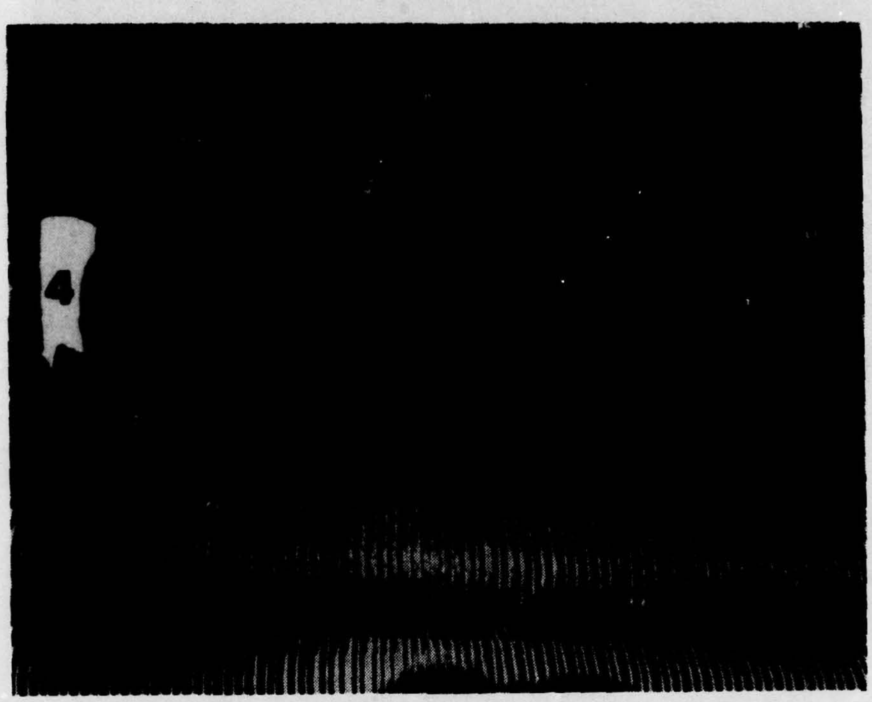

Figure 23. Centaur Module Tube Location Number 4

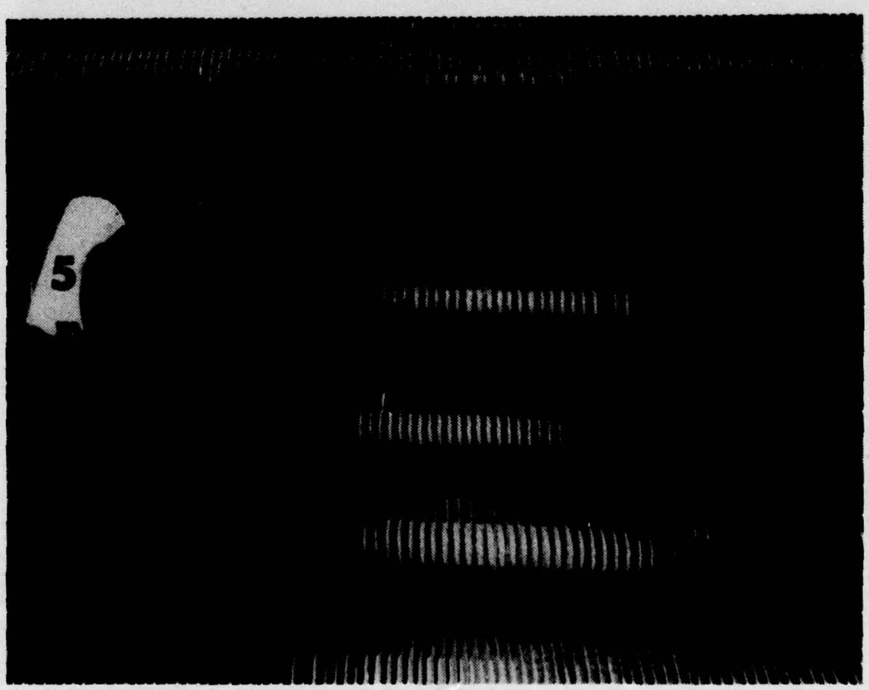

Figure 24. Centaur Module Tube Location Number 5

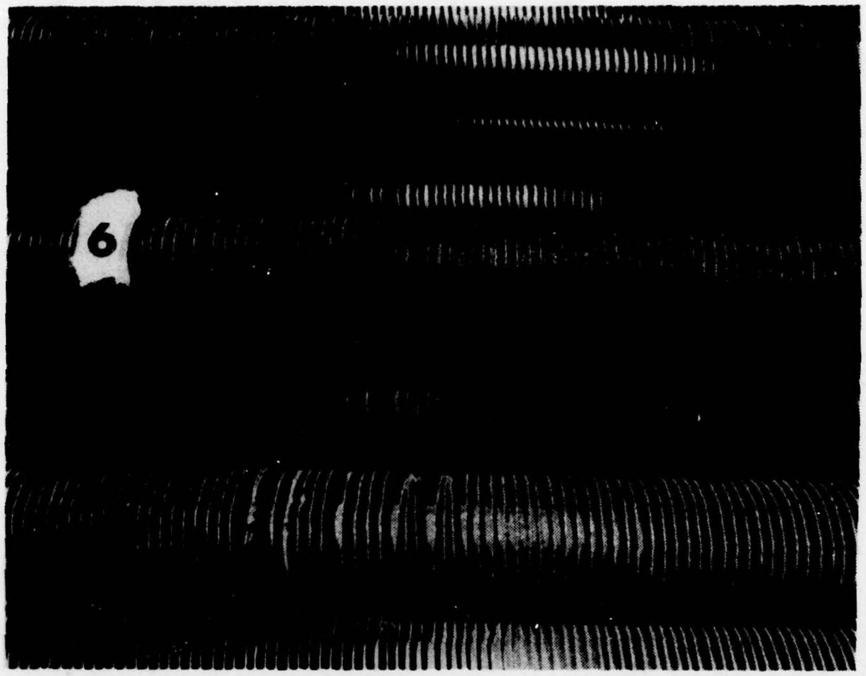

Figure 25. Centaur Module Tube Location Number 6

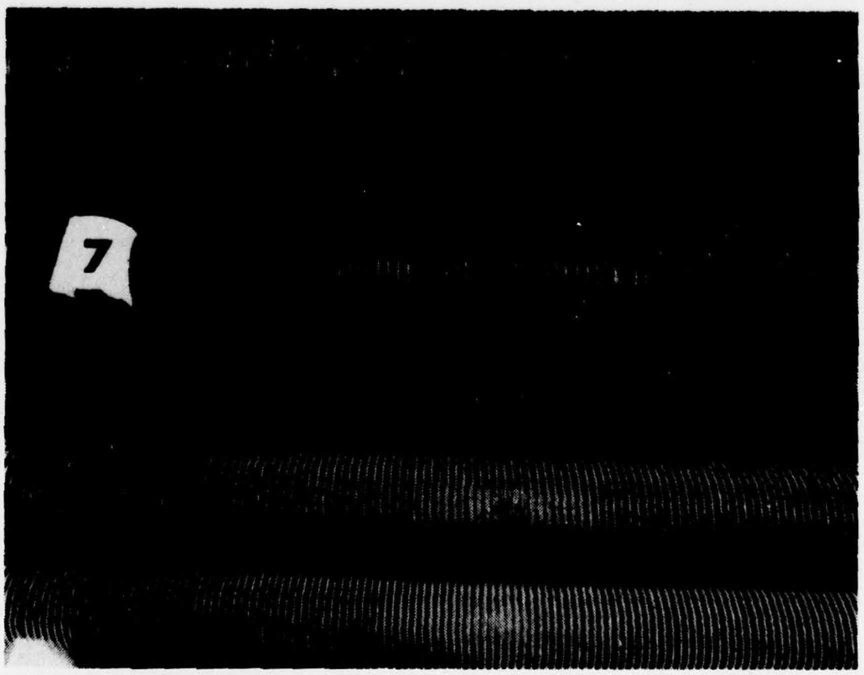

Figure 26. Centaur Module Tube Location Number 7

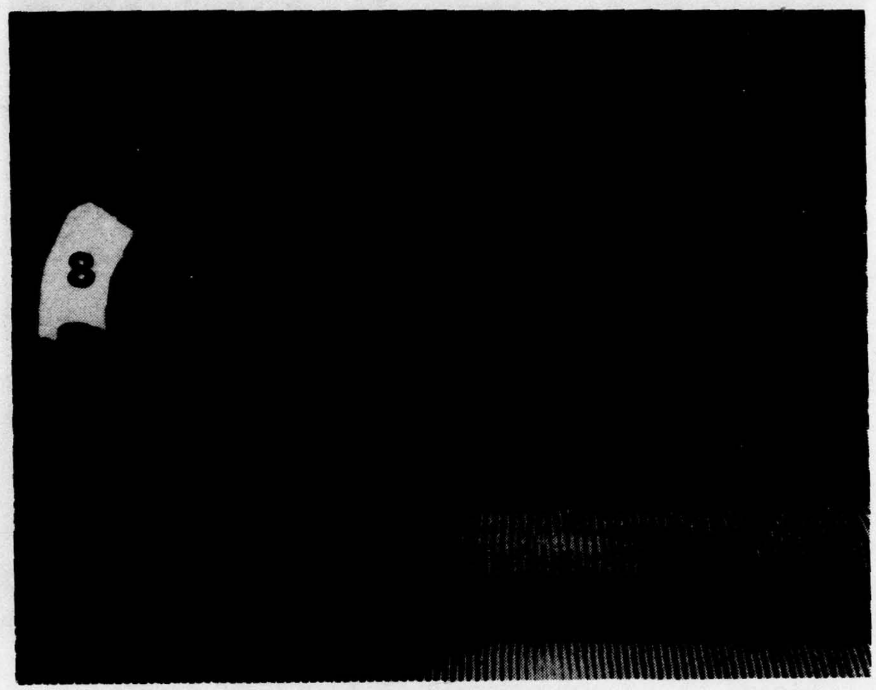

Figure 27. Centaur Module Tube Location Number 8

Figure 28. Centaur Module Tube Location Number 9

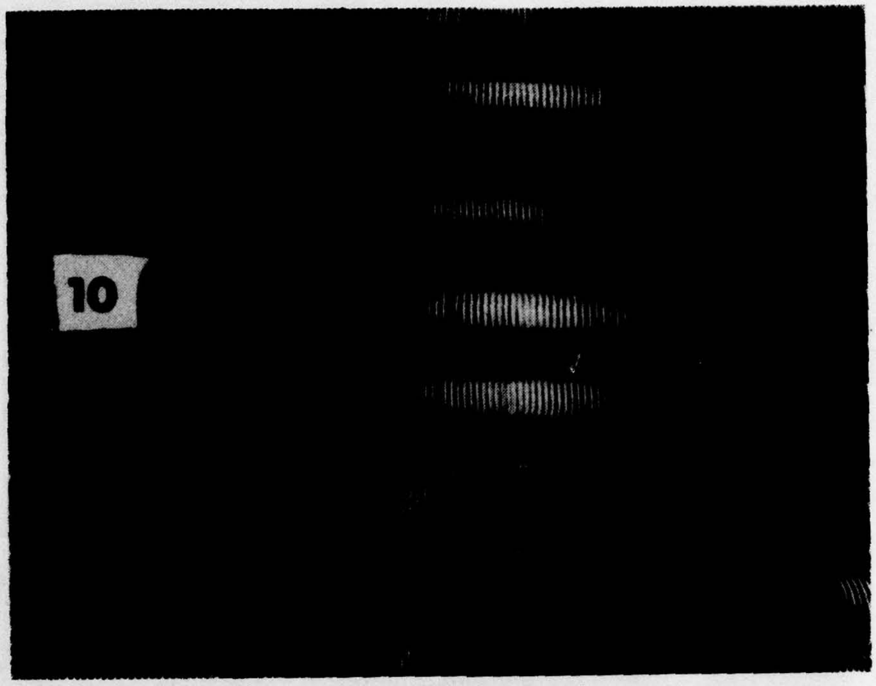

Figure 29. Centaur Module Tube Location Number 10
Steam 731°K (856°F) - Gas 772°K (930°F)

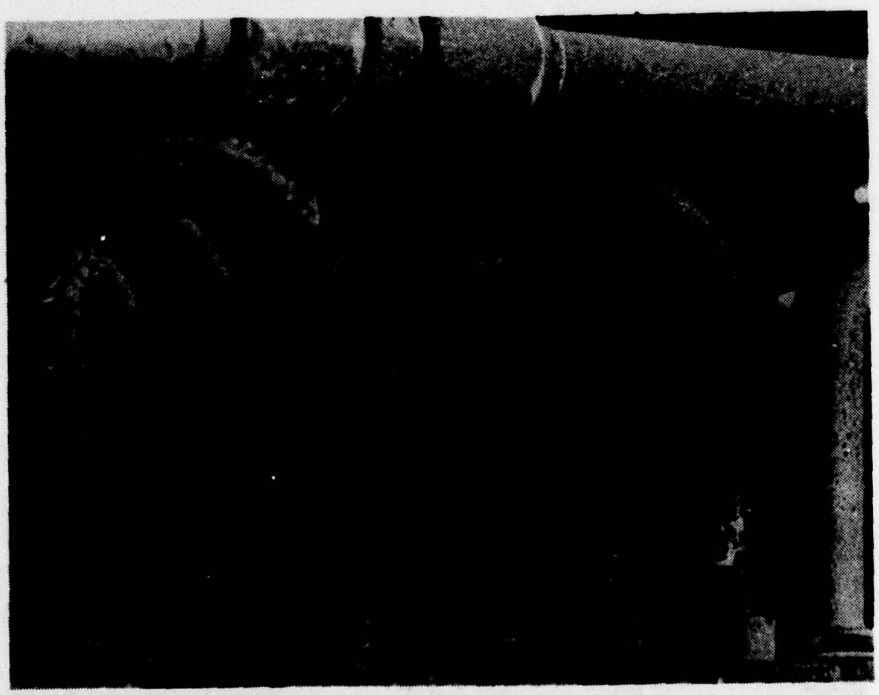

Figure 30. Centaur Generator Module U-Bend

3.1.3 LM-2500 Soot Fouling Probe

The soot fouling probe shown in Figure 13 was installed in the engine exhaust of a General Electric LM-2500 gas turbine engine for a test run using Marine Diesel fuel. The test covered a total elapsed time of 279 hours apportioned at various horsepower levels as shown in Table 2. One of the two finned-tube circuits was cooled with saturated steam, the other with river water. Photographs of the soot fouled probe are shown in Figures 31 and 32.

Table 2

Operation Log and LM-2500 Soot Fouling Probe
NAVSEC-Philadelphia Engine Test

Horsepower Range, HP	Operating Time, hrs
IDLE - 3000	95
4000 - 7000	91
8000 - 14000	60
15000 - 19000	13
Transient	20

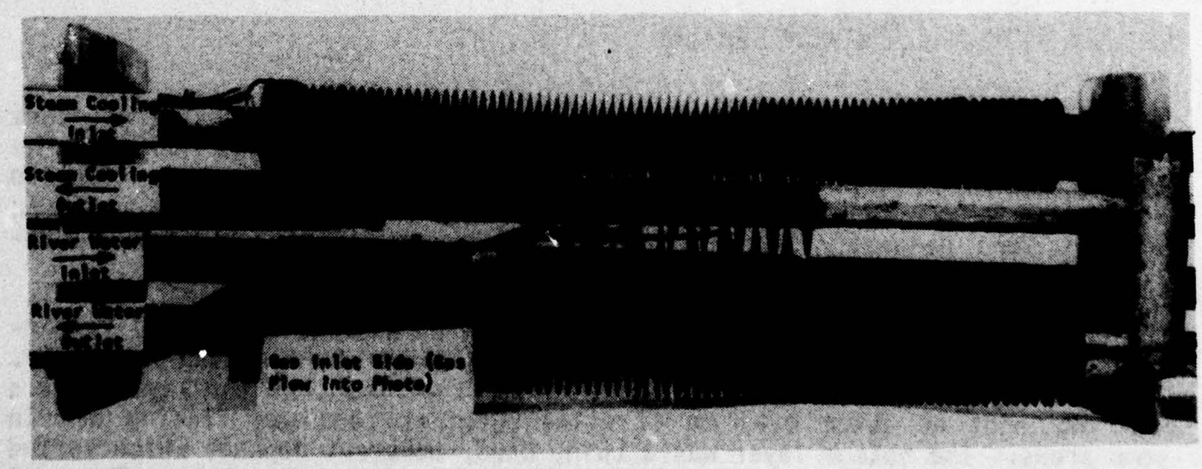

Figure 31. Deposits on LM-2500 Soot Probe After NAVSEC Testing - Gas Inlet Side

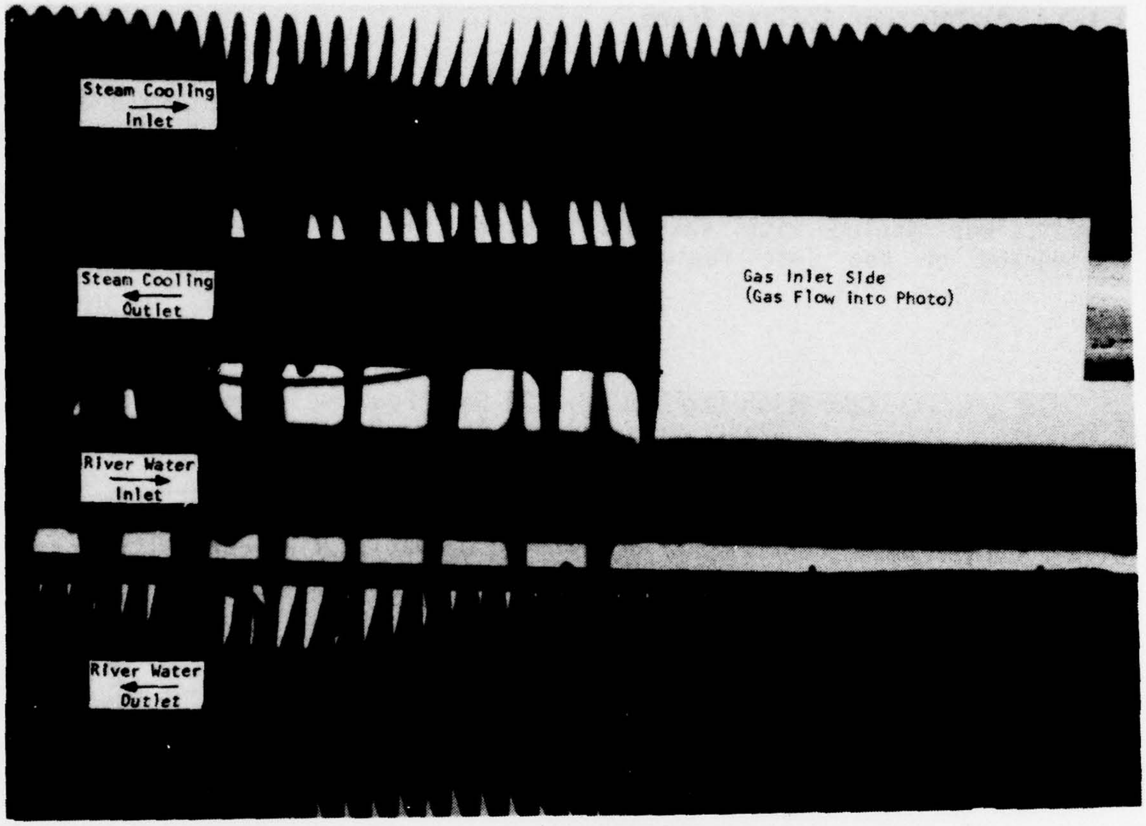

Figure 32. Deposits on LM-2500 Soot Probe After NAVSEC Testing - Gas Outlet Side

Fouling Rates and Characterization

The loop cooled with saturated steam ran at an average tube metal temperature of 436°K (325°F) and an average fin tip temperature of 550°K (530°F). The deposit was soft, dry, and distributed evenly over the bare tube surface to a depth of 0.15-0.20 mm (6-8 mils). The deposits on and between all finned surfaces were generally lighter, having a thickness of approximately 0.025-0.05 mm (1-2 mils).

The other loop, cooled with river water, ran at an average tube metal temperature of 380°K (225°F) and an average fin tip temperature of 527°K (490°F). The tube deposit was composed of two layers: the first, or top layer, was a soft dry soot of about 0.18 mm (7 mils) thickness and was flaking off in some areas. The bottom layer was a thin, hard, adherent deposit which varied in thickness from 0.05 mm (2 mils) to 0.13 mm (5 mils). The fin surfaces of this circuit appeared to have only a single layer of soot deposited which was of a soft, light nature.

Velocity

In addition to the controlled velocity section of the probe, other sections of the probe shown in Figures 33 and 34 were exposed to either a stagnant, zero velocity environment, or to the full exhaust duct velocity of 106.7 m/sec (350 ft/sec). The deposits were identical to those in the controlled velocity section of the probe.

3.1.4 LM-2500 Soot Fouling Probe in Combustor Rig

The 4 x 5 tube boiler model was removed from the combustor rig which was then modified to accept installation of the LM-2500 soot fouling probe. One circuit was provided with water cooling and the other with compressed air cooling. The combustor rig was then fired on marine diesel fuel for a period of 49 hours at a Von Brand smoke number = 2-3. The intent during this test was to operate with exhaust gas characteristics similar to those of a LM-2500 General Electric engine burning marine diesel fuel. The conditions during the test were adjusted to duplicate as close as possible those conditions present during the LM-2500 engine test.

An inspection of the probe after the 49 hour period revealed the following:

- The air cooled circuit had a soft, dry, easily removable deposit of about 0.05-0.075 mm (2-3 mils) in thickness.
- The water cooled circuit seemed to have a two layer deposit; a soft somewhat greasy top layer about 0.05 mm (2 mils) in thickness and a hard, adherent underlayer about 0.025 mm (1 mil) in thickness.

Although the variation in power levels during the engine test precluded making any meaningful comparison of soot buildup rates, it does appear that the mechanism of soot deposition is identical as the two layer deposit was observed in both the LM-2500 engine and combustor rig tests.

3.2 SOOT ANALYSIS

Some attention was devoted to the chemical analysis of the soot deposits from the combustor rig, engine tests, and LM-2500 probe in an attempt to gain an understanding of the soot buildup mechanisms and to characterize the deposits in terms of organic and inorganic constituents.

3.2.1 Combustion Rig

Soot samples, formed on the combustor rig tube bundle by firing JP-5 fuel, were removed and subjected to pyrolysis gas chromatography to determine what hydrocarbons might be adsorbed by the carbon in the soot. This analysis

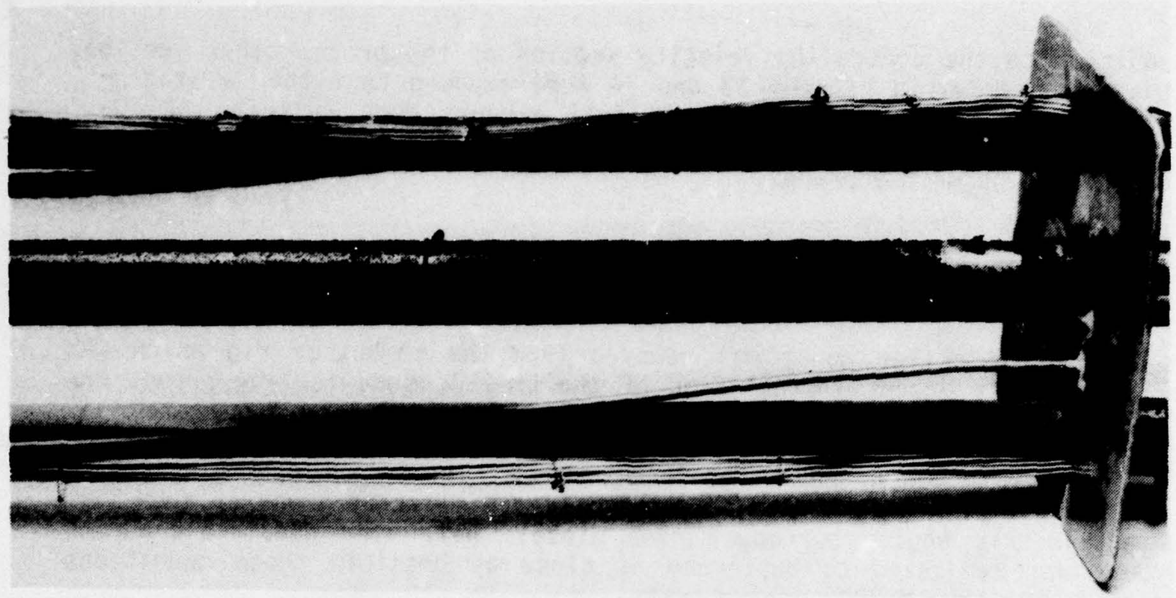

Figure 33. Portion of LM-2500 Probe Exposed to Stagnant Environment

Figure 34. Portion of LM-2500 Probe Exposed to Maximum Duct Velocity of 106.7 m/sec (350 ft/sec)

technique involves placing a small quantity of soot in a tube through which heated helium is passed carrying the adsorbed gases to the chromatograph. The helium is heated to a temperature a few degrees higher than the soot experienced during the test run. In the absence of any temperature data, the helium was heated to 533°K (500°F).

The results of these analyses for three samples taken from the combustor rig are shown in Table 3. These results may tend to support the mechanism of soot buildup in which trace quantities of heavy hydrocarbons condense onto the heat transfer surface resulting in a thin coating of an adhesive nature. Soot then becomes attached or entrapped by this coating.

Table 3

Analysis of Adsorbed Gases From Soot Samples Taken From Combustor Rig Firing JP-5

Species	% by Weight		
	Sample #1*	Sample #2	Sample #3
CO_2	0.29	0.0016	0.00055
Air	0.25	0.030	1.20
H_2O	0.54	--	--
CH_4	0.00019	0.000053	0.00029
C_5H_{12}+	>0.48	0.90	0.50

*This soot sample was analyzed and found to contain 75% carbon by weight.

An Anderson air sampler was used to characterize the particle size of the soot resulting from the firing of diesel fuel. These results are presented in Table 4. This table reveals that the particle size for the greater fraction of the soot is one micron or less.

Inorganic analyses of soot deposits obtained from the combustion rig were also performed. Table 5 shows the analyses of soot deposits formed by firing No. 2 Diesel fuel. As expected the soot is found to be composed of primarily carbon with a fair amount of sulfur also present. Also in evidence are nickel and iron which are believed to be the products of corrosion of the fin and brazing materials.

Table 4

Andersen Air Sampler Results
No. 2 Diesel Firing in Combustor Rig

Particle Size Range	% by Weight			
	Sample #1	Sample #2	Sample #3	Sample #4
7.5 μ and above	15.0	34.7	4.2	2.9
4.7 μ - 7.5 μ	1.1	6.3	1.0	5.0
3.2 μ - 4.7 μ	4.3	3.5	3.1	1.7
2.2 μ - 3.2 μ	3.4	5.6	1.0	4.6
1.4 μ - 2.2 μ	6.5	7.0	2.1	5.0
0.75 μ - 1.4 μ	15.7	1.4	7.3	6.6
0.44 μ - 0.75 μ	23.1	3.5	9.4	7.5
0.29 μ - 0.44 μ	20.1	21.7	10.4	6.6
0.29 μ - 0.015 μ	10.8	16.3	61.5	60.1

Table 5

Inorganic Analysis of Soot Deposits From Combustion Rig - No. 2 Diesel Fuel (X-Ray Florescence Analysis)

Element (%)	Sample #1	Sample #2
Aluminum	0.3	0.3
Carbon	71.5	67.3
Calcium	0.3	0.4
Chlorine	0.1	0.3
Chromium	0.6	0.7
Copper	0.4	0.1
Iron	3.3	6.2
Potassium	0.1	0.1
Molybdenum	0.1	0.1
Nickel	1.0	1.3
Phosphorus		0.1
Lead	0.4	0.5
Sulfur	20.5	21.6
Silicon	1.3	0.9
Zinc	0.1	0.1

3.2.2 LM-2500 Soot Fouling Probe

After testing, the probe, which had been installed in the exhaust of a LM-2500 General Electric gas turbine, was returned to Solar where deposit samples were taken and analyzed. The results of these analyses for five samples are shown in Table 6. Samples 1, 2, 5 and 6 were taken from the water cooled portion of the tubing and samples 3 and 4 were taken from the steam cooled areas. Sample Nos. 1 and 6 are characteristic of the hard, crusty bottom layer found on the water cooled sections of the probe. The data, however, shows no particular trends as far as the difference in hydrocarbon concentration between the various samples.

One point to be noted is the rather large difference between the concentration of the C_5+ hydrocarbons for this group of samples and those discussed previously in connection with the combustion rig (Table 3). A possible explanation for this lies in the fact that the soot generated in the combustor rig may have been exposed to raw fuel as a result of aborted starts.

Carbon analyses of the soot samples were also performed and are reported in Table 7. The average composition is seen to be about 60 percent by weight carbon. This compares to 75 percent carbon for the soot sample generated by the combustion rig firing JP-5 fuel.

Inorganic analysis by energy dispersive X-ray (EDX) analysis was performed on deposits removed from the probe. These results are presented in Table 8. The EDX technique is unable to detect elements whose atomic number is less than 13, this excludes carbon from detection. Sample No. 1 is characteristic of the hard, crusty material adjacent to the water cooled tube while Sample No. 5 represents the total sample, top and bottom layer. There may be a trend for more sulfur to be found in the hard, crusty material. This is to be expected as the sulfuric acid would tend to condense and concentrate there. In comparing Sample #2 from fins in the water cooled circuit, versus Sample #3, from fins in the steam cooled circuit, there is a trend for the sulfur concentration to be higher in the cooler regions.

3.2.3 Centaur Steam Generator Module

As mentioned previously, a test was conducted on the Solar steam generator module using a Centaur gas turbine to study soot fouling and self-cleaning characteristics. A total of 105.2 hours of operation were run using #2 Diesel fuel. At the completion of the testing a number of soot samples were taken from the tubing at various locations in the module. The first set of samples, reported in Table 9, were taken from tubing which was an integral part of the generator module as opposed to the second set of samples, see Table 10, which came from tubing which had been mounted across the module exhaust stack. These particular samples were analyzed by the EDX technique.

Table 6

Analysis of Adsorbed Gases on Soot Samples Taken From LM-2500 Probe After NAVSEC Tests

Sample No. 1
Taken from bare tubing, Loop #2, gas outlet side, water cooled tubing, hard under layer deposit. This sample prepared by selecting hard particles from Sample #5

Species	% by Weight
CO	0.009
Air	7.0
H_2O	2.4
C_5 + higher	0.003

Sample No. 2
Taken from fins at 3 fins/inch, Loop #2, gas outlet side, water cooled tubing. This sample includes both top and bottom layers

Species	% by Weight
CO_2	0.06
CO	2.0
C_2H_6	0.0004
C_3H_8	0.0007
Air	1.0
H_2O	3.0
C_4's	0.0006
C_5 + higher	0.004

Sample No. 3
Taken from fins @ 3 fpi, Loop #2 gas inlet side, steam cooled tubing

Species	% by Weight
CO_2	0.024
CH_4	0.00045
H_2O	0.16
CH_4H_{10}	0.0021
C_5 + higher	0.022

Sample No. 4
Taken from bare tubing, Loop #2, gas inlet side, steam cooled tubing

Species	% by Weight
CO_2	0.042
Air	0.045
H_2O	0.23
CH_4	0.00017
C_5 + higher	0.013

Sample No. 5
Taken from bare tubing, Loop #2, gas outlet side, water cooled loop

Species	% by Weight
CO_2	1.80
C_2H_6	0.0013
C_3H_8	0.0023
Air	14.0 ??
CH_4	0.00014
H_2O	0.084
C_4	detected but could not quantify due to H_2O interference

Sample No. 6
Taken from water cooled loop, hard adherent layer

Species	% by Weight
CO_2	46.0*
C_2H_6	0.01
C_3H_8	0.02
CH_4	3.47×10^{-3}
C_4H_{10}	0.01
C_6+	>1.12
H_2O	53.18*

*(high CO_2 and H_2O values due to air contamination)

Table 7

Carbon Content of Soot Samples From LM-2500
NAVSECPHILA Soot Probe

Sample No.	% Carbon by Weight
1	57.0
2	60.0
3	55.0
4	57.0
5	64.0
6	58.0
(Analysis by combustion using LECO Carbon Determinator, Model 4000)	

The analyses are not particularly revealing other than indicating sulfur as a major constituent of the deposits. Iron, aluminum and silicon are also indicated, the latter two probably present as insulating material and airborne dust, respectively.

3.3 SELF-CLEANING INVESTIGATIONS

Up to this point, the discussion has centered on mechanisms of soot fouling and on the problem of trying to chracterize the soot via organic and inorganic chemical analysis. The following sections discuss the investigations covering the concept of self-cleaning whereby the water flow to the steam generator is turned off resulting in higher metal temperatures which in turn effect the removal of the soot deposits. Various rig investigations were carried out to study the phenomenon and the results are compared to STI's engine data and existing published results.

3.3.1 Furnace Rig

In order to examine the basic behavior of the self-cleaning mechanism at a controlled zero velocity and with pure atmospheres, a furnace rig was constructed which is shown in Figure 36. A soot-fouled specimen of finned tubing is sealed inside a gas-tight container which itself is mounted in a constant temperature furnace. A low volume of purge gas flows at close to zero velocity through the container and exhausts through a liquid nitrogen trap and filter.

Sample finned-tube sections that were obtained from engine test runs and from the combustor rig investigations were evaluated with identical self-cleaning

Table 8

Energy Dispersive X-Ray Analysis of Soot Samples From LM-2500 NAVSECPHILA Soot Probe

Sample No. 1*
Taken from bare tubing, Loop #2 gas outlet side, water cooled hard, crusty, deposit from tube surface

Element	% by Weight of Metals Detected: 1st Particle	2nd Particle
Sulfur	56.8	64.2
Si	24.8	19.3
Cr	6.4	--
Mn	6.1	--
Fe	5.9	7.7
Ca	--	8.8

Sample No. 2*
Taken from fins at 1.2 fins/cm (3 fins/inch), Loop #2, gas outlet side, water cooled

Element	% by Weight of Metals Detected: 1st Particle	2nd Particle
Sulfur	65.2	84.5
Si	11.2	10.0
Fe	9.5	5.5
Ni	14.1	--

Sample No. 3
Taken from fins at 1.2 fins/cm (3 fins/inch), Loop #1, gas inlet side, steam cooled

Element	% by Weight of Metals Detected: 1st Particle	2nd Particle	3rd Particle
Sulfur	34.8	42.3	25.0
Si	16.8	22.9	42.0
Ca	21.6	17.2	22.8
Fe	20.2	17.6	10.2
K	6.6	--	--

Sample No. 4
Taken from bare tubing, Loop #1, gas inlet side, steam cooled

Element	% by Weight of Metals Detected: 1st Particle	2nd Particle
Sulfur	71.9	58.3
Si	5.7	22.3
Ca	--	8.2
Cr	5.0	--
Fe	16.4	11.2
Ni	1.0	--

Sample No. 5
Taken from bare tubing, Loop #2, gas outlet side, water cooled

Element	% by Weight of Metals Detected: 1st Particle	2nd Particle
Sulfur	96.4	88.1
Si	2.0	5.5
Ca	--	2.4
Fe	1.6	4.0

*Analysis of this sample did not include background subtraction, i.e., subtraction of noise radiation. Therefore, reported analysis may deviate slightly from actual.

Table 9

EDX* Analysis of Soot Deposits From Tubing in Centaur Generator Module (105.2 Hour Test - Diesel #2 Fuel)

Elements	% by Weight of Elements Detected					
	Sample #1 U-Tube	2 #6 Tube	3 #14 Tube	4 #32 Tube	5 #42 Tube	6 #2 Tube
Aluminum	10.0	5.2	8.0	5.3	--	3.1
Copper	--	1.5	2.2	1.4	--	--
Iron	6.6	10.7	4.8	30.1	95.9	16.6
Nickel	--	--	--	5.1	1.0	3.4
Silicon	8.9	8.0	8.4	9.9	--	4.0
Sulfur	74.5	74.5	76.6	48.2	3.1	72.9

*Energy Dispersive X-ray Analysis - useful for semi-quantitative analysis of elements of atomic number 13 and above.

Table 10

EDX* Analysis of Soot Deposits From Tubes Mounted in Centaur Generator Module Exhaust Duct (105.2 Hour Test - Diesel #2 Fuel)

Element	% by Weight of Elements Detected			
	Sample #1 Water Cooled Tube[1]	Sample #2 Ceramic Coated Tube[1]	Sample #3 Uncooled Tube	Sample #4 Uncooled Tube
Aluminum	5.3	2.9	1.3	4.1
Copper	2.2	1.9	--	--
Iron	--	--	5.1	1.4
Nickel	--	--	4.9	--
Phosphorus	--	--	2.7	--
Potassium	--	--	--	1.7
Vanadium	--	--	2.3	--
Silicon	5.9	3.8	--	3.5
Sulfur	86.6	91.4	83.7	87.7
Zinc	--	--	--	1.6

*Energy Dispersive X-Ray Analysis - useful for semi-quantative analysis of elements of atomic number 13 and above. Carbon = atomic number 6.
[1]Sample taken under N_2 atmosphere.

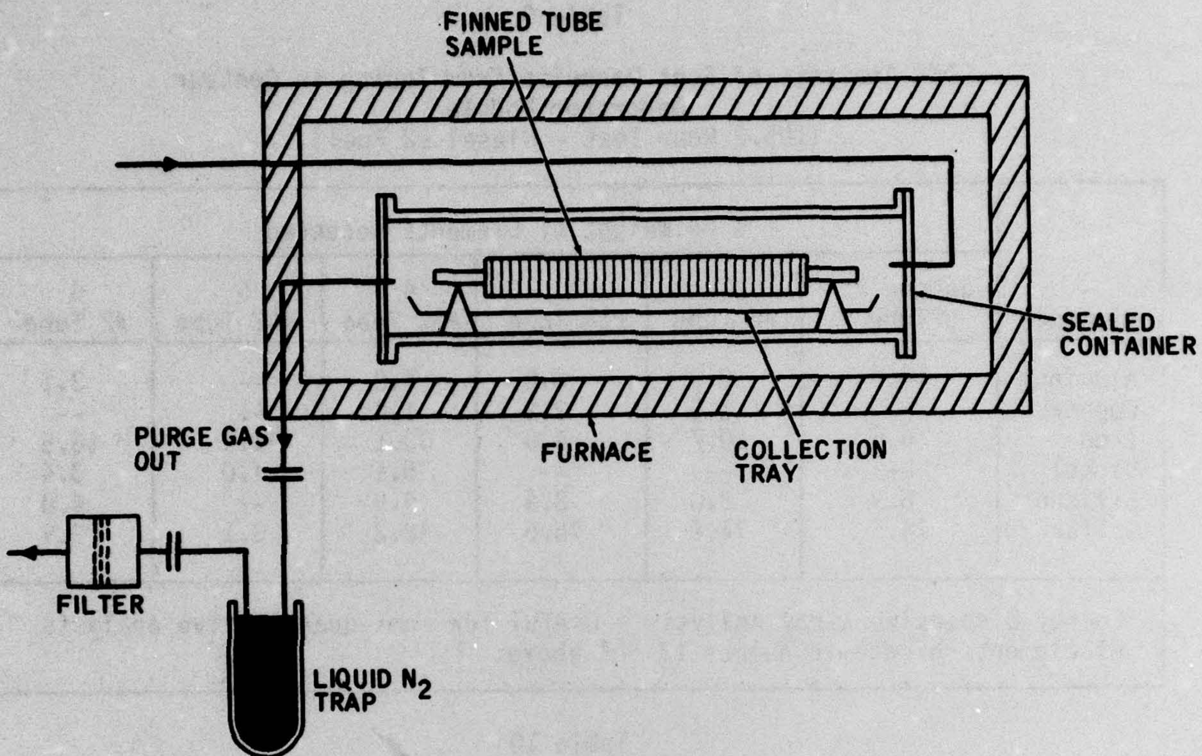

Figure 35. Schematic of Outgassing Furnace Rig

behavioral results. All of the samples evaluated were produced using #2 Diesel fuel.

Using a helium purge, no cleaning of deposits was observed with tube temperatures up to 756°K (900°F) and exposures of up six hours. The effects of further increases in time or temperature were not evaluated. With a hydrocarbon-free air purge no cleaning was observed at 672°K (750°F) for six hours but some cleaning was apparent at 686°K (775°F) after six and one-half hours, indicating a self-cleaning threshold temperature under these conditions of 672-686°K (750-775°F). At a temperature of 700°K (800°F) full cleaning was accomplished after six and one-half hours; when the temperature was raised to 747°K (885°F) full cleaning occurred in only one hour indicating the strong temperature dependency of the mechanism.

With identical time and temperature conditions, the presence of an inert atmosphere appears to negate the self-cleaning mechanism. This indicates that an oxidation reaction results in a decreased bonding between the soot particles and may be responsible for the shedding rather than the vaporization of an interface compound between the metal surfaces and the deposit.

This threshold self-cleaning temperature correlates closely with the results from a test of a waste heat recovery boiler designed for shipboard installation (Ref. 6).

The liquid nitrogen trap samples obtained during the various tests were analyzed using gas chromatography but no hydrocarbon compounds were detected in any of the samples.

When evaluating a heavily fouled sample, a rust-colored scale was observed adhering to the cleaned carbon steel fins and to the flakes in the catch tray underneath. A sample of the deposits and a small section of fin were subjected to Energy Dispersive X-Ray analysis and the results showed significant amounts of iron, sulfur, nickel and chromium present plus traces of phosphorus and silicon. The results suggest that the scale was the result of sulfuric acid attack on the carbon steel fins and may indicate that a heavy soot layer can absorb and hold any sulfuric acid condensate at the interface and thus intensify the corrosive effects.

A final observation from the furnace rig tests was that the Solaramic-coated tubes were cleaned to a greater degree than the untreated samples from the combustor rig. This result tends to indicate the importance of surface finish to the adhesion characteristics of the soot or possibly the presence of a catalytic reaction at the interface promoted by the coating.

3.3.2 Hot Air Rig

The self-cleaning phenomenon was also investigated using a hot air rig where a fouled tube sample is mounted horizontally across the outlet of an air supply pipe flowing non-vitiated, hydrocarbon free air at elevated temperatures. Fin tube and local gas temperatures were monitored and average velocity was calculated from the measured air mass flow rate and pipe size. The following observations were made using a fouled tube sample obtained from the combustion rig tests:

At flow velocities up to 18.3 m/sec (60 fps), no flaking away of deposits occurred below a fin temperature of 706°K (810°F). A gradual increase to a fin temperature of 739°K (870°F) and a velocity of 50.3 m/sec (165 ft/sec) over a period of 12 minutes had produced almost complete cleaning of the tube except for a portion of soot between the fins in the downstream wake of the tube. Very slow flaking of this area continued but the soot was rapidly removed when the velocity was further increased to 57.9 m/sec (190 ft/sec).

At high velocities, in the 52-70 m/sec (170-230 ft/sec) range, some cleaning effects were seen at fin temperatures as low as 646°K (720°F) indicating that the effective self-cleaning threshold temperature may be a function of velocity.

Fouled tube samples obtained from the exhaust of the Centaur boiler module were also evaluated on the hot air rig. The soot on the uncooled samples was loosely bonded and blew off as the tubes were inserted into the rig. The soot on the sample that had been water cooled did not blow off, however, and as the metal temperature increased to the local gas temperature 727°K (850°F) blue smoke/vapor was seen to be emitted from the sample over a period of approximately one minute. This was followed by a cleaning process that resulted in the tube being approximately 90 percent cleaned after a period of 60 minutes.

3.3.3 Combustor Rig

In order to observe the self-cleaning threshold temperature on the combustor rig, one of the instrumented top row tubes was isolated from the water cooling circuits and equipped with air cooling. These tubes were observed when the rig was operating and the tube temperature varied by modulating the cooling air flow.

Starting with a maximum fin tip temperature of about 533°K (500°F) the air cooling flow was slowly reduced until initial flaking of soot from the hottest fins (outlet end) of the tube was noticed at a fin tip temperature of 806°K (990°F). The air cooling was then increased again until the fin temperature was reduced to 767°K (920F). A further increase in fin temperature resulted in no signs of cleaning until a temperature of 822°K (1020°F) was reached at which point fin and tube cleaning was observed; a previous pause at the 806°K (990°F) fin temperature had not produced any noticeable cleaning.

After five minutes at 822-833°K (1020-1040°F) fin temperature, the air cooling was gradually increased to a maximum fin temperature of 781°K (945°F) when further deposits could be observed building on the fin tips.

Additional tests on the combustor rig indicated that the cleaning threshold temperature was unaffected by the soot loading of the combustor operating point.

After the initial tests, when flaking of the deposits was the mode of self-cleaning, further testing brought to light another mechanism; that of oxidation or burning away of the deposits. This phenomenon was first observed during a simulated dry operation cleaning cycle which began with an unplanned wet start. Fin tip temperatures were increased to 700-755°K (800-900°F) by decreasing cooling air flow to a minimum. With no flaking off occurring, the cooling air was then completely shut off and metal temperatures rapidly rose to about 866°K (1100°F). Almost simultaneously the deposits started to oxidize as evidenced by glowing soot. Cooling air was then reintroduced to the tube. This action resulted in some flaking of deposits and more intense combustion of the soot. The unit was shut down for an inspection which revealed that all of the deposits had been removed from the top air-cooled row of tubing via the oxidation mechanism.

In two successive combustor rig tests with the 4 x 5 tube matrix steam generator model, this same mechanism was observed to be the only mode of self-cleaning. At no time was flaking of deposits observed. These latter two tests used gasoline as the fuel during the dry operation cleaning so as to reduce hydrocarbons in the combustor exhaust. The soot deposits, however, were formed on the tubes using No. 2 Diesel fuel. During one test the tubing was in a staggered configuration while the other utilized the in-line configuration. In each case, however, the oxidation was observed to begin at a fin temperature of 561°K (550°F). This continued as the cooling air to the top row of tubes was reduced and fin temperatures increased to 811°K (1000°F). The oxidation was sporadic and over a period of 1-1/4 hours would effect an overall cleaning of the tubes. The oxidation generally took the form of locally glowing soot deposits, however, on occasions, light blue local flames were also observed.

3.3.4 Combined Cycle Steam Generator

As mentioned previously, the Centaur Engine-Combined Cycle steam generator was run for 105.2 hours in order to build up sufficient soot deposits on the tubing for a subsequent dry operation cleaning evaluation.

The total time between the completion of the fouling test and the next engine start was 255 hours. A pre-dryout calibration showed that the boiler performance had recovered from the eight percent deterioration at the completion of the fouling test to a three percent deterioration level. This calibration point was followed by 1.5 hours of dry boiler operation at the full load engine conditions. After an overnight cool-down period the boiler was recalibrated and the results showed that dry running had reduced the total deterioration to 1.5 percent below a clean, new unit, or only 0.5 percent below the level at the beginning of the fouling test. A summary of the dry cleaning experience is shown in Figure 36.

3.3.5 LM-2500 Soot Fouling Probe

Only a single self-cleaning test was conducted on the probe after the combustor rig running (see Section 3.1.2) has produced a thin soot deposit approximately 0.50-0.75 mm (2-3 mils) in thickness. With a reduction of cooling flows the metal temperatures were raised to 711°K (820°F) and maintained at this level for 40 minutes. Although no flaking off or oxidation of the deposits were observed during the test, a subsequent inspection showed that complete cleaning had occurred.

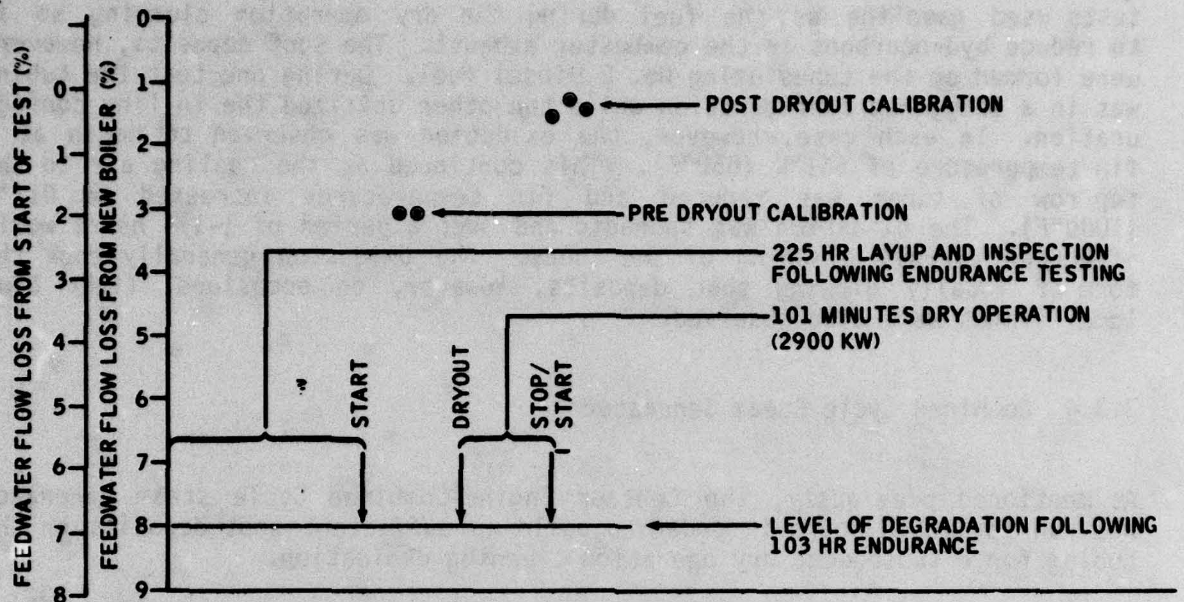

Figure 36. Summary of Centaur Steam Generator Dry Operation Cleaning

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CONCLUSIONS

- Soot fouling rates and the type of soot encountered in a combined cycle gas turbine steam generator can be well simulated by a combustion rig using a geometrically identical heat exchanger matrix if duplication of the controlling parameters is achieved. For soot fouling the dominant controlling parameters appear to be soot loading in the exhaust, fuel type and metal temperature.

- Self-cleaning by dry boiler operation is a viable alternative to air or steam blowing of the steam generator surfaces. Combustor rig experience suggests that engine self-cleaning threshold temperatures and cleaning rates can be simulated if the level of unburned hydrocarbons in the exhaust is duplicated. Further work is required in this area to see if the self-cleaning threshold temperature can be depressed or the rate of cleaning increased by surface finish or other effects.

- Although the ultimate solution to the problem of steam generator fouling is the zero soot-producing combustion system, it will be many years before these advanced systems are incorporated in gas turbines and the problem of cleaning soot deposits will exist for a considerable period. The results of the combustor rig tests indicate that a more conservative approach to fin density, although increasing steam generator size for a given effectiveness, can serve to extend the time between cleaning cycles and avoid the problems of fin bridging.

- A number of soot samples indicated the presence of organic compounds, particularly those of C_5 and higher molecular weights. The results from both the engine and combustor rig tests tend to confirm the important role of exhaust stream trace hydrocarbons with respect both to fouling and cleaning characteristics.

- Further study is needed in the area of the interaction between soot deposits and the gas side corrosion products that can occur when local gas temperatures are below the sulfuric acid dewpoint temperature. It is possible that the main impact of soot fouling will be not be in the area of performance degradation but in the role that soot deposits may play in catalyzing sulfuric acid condensation and magnifying corrosion effects.

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SUMMARY

Liquid-fueled gas turbines can produce serious steam generator fouling in combined cycle applications and other waste heat recovery systems. Compact matrix designs, compatible with gas turbine packaging, may not be compatible with standard "soot blowing" practices. Therefore, a test program was conducted with the objective of evaluating the effects on gas side soot fouling rates of various operational parameters such as soot loading, metal temperatures, and velocity. Particular attention was given to the effectiveness of the self-cleaning concept where elevated steam generator metal temperatures obtained by dry running are utilized to remove soot deposits.

The majority of the experimental data were obtained from two test rigs: a small combustor fitted with a steam generator model consisting of finned tubing arranged five tubes wide by four tubes deep, and a one-sixth slice of a full scale Solar finned tube steam generator mounted in the exhaust of a Solar Centaur gas turbine. In addition a small soot fouling probe consisting of two circuits of finned tubing was used to obtain data from a General Electric LM-2500 gas turbine at the U.S. Naval Ship Engineering Center, Philadelphia.

The analysis of a number of soot samples indicate that trace amounts of hydrocarbons in the exhaust stream play an important role with respect to both fouling and cleaning characteristics. Visual inspections of soot fouled surfaces lend support to the two-stage mechanism of soot buildup where trace quantities of heavy hydrocarbons in the gas turbine exhaust are thought to condense on the heat transfer surface resulting in a thin, possibly monomolecular, coating of an adhesive nature. Particulate matter then becomes attached or entrapped by the coating.

The dominant parameters controlling soot fouling rates appear to be the soot loading in the exhaust, the fuel type, and metal temperatures. Surface coatings such as Solaramic S5-8A, a low temperature vitreous coating, showed no apparent advantage in reducing soot build-up, nor did fin spacing or tube configuration (staggered versus in-line). In terms of fouling factors, a measure of the performance loss due to soot build-up, the Solar steam generator module in the exhaust of a Solar Centaur engine experienced a fouling factor of 0.93 after 105.2 hours of continuous operation. This was the point of greatest performance degradation, it appears from the data that longer run times could produce lower fouling factors.

The self-cleaning approach by dry operation was shown to be a viable alternative to air or steam blowing of the finned tube steam generator surfaces.

The time required for self-cleaning and the final effect was found to depend primarily on the exhaust gas temperature and to a lesser extent on the gas velocity. Indications are that the threshold temperature for self-cleaning lies between 627-691°K (670-785°F). In the case of the Centaur steam generator, self-cleaning reduced the performance loss from seven percent to only 0.5 percent. Further work is required in this area to determine if the self-cleaning threshold temperature can be depressed or the rate of cleaning increased by surface or other effects.

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