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Aero Propulsion Technical Memorandum 438

SMOKE EMISSION TESTS ON SERIES II AND SERIES III
ALLISON T56 TURBOPROP ENGINES

by
F.W. SKIDMORE

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**SMOKE EMISSION TESTS ON SERIES II AND SERIES III
ALLISON T56 TURBOPROP ENGINES**

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F.W. SKIDMORE

SUMMARY

This report presents the results of smoke emission tests on three Series II T56-A-7 and two Series III T56-A-15 Allison T56 Turboprop engines operating from idle to near full power. The results indicate a significant difference in the levels of emissions between the different engine series tested.



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CONTENTS

1.	INTRODUCTION	1
2.	THE ALLISON T56 TURBOPROP ENGINE	2
3.	METHODS OF MEASURING SMOKE EMISSIONS	5
4.	TESTS AT RICHMOND	8
5.	RESULTS	8
6.	DISCUSSION	13
6.1	Smoke Emission Tests	13
6.2	Fuel Analysis	13
7.	CONCLUSIONS	14
	ACKNOWLEDGEMENTS	15
	REFERENCES	16
	APPENDIX 1	17
	DISTRIBUTION	
	DOCUMENT CONTROL DATA	



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1. INTRODUCTION

The Aeronautical Research Laboratories (ARL) has been involved, since late 1984, in a program aimed at reducing smoke emissions from the General Motors Allison T56 Turboprop Engines. Smoke emission measurements have been reported (Skidmore, 1985) from the Allison T56-A-14 which powers the Orion P3C aircraft. This engine is very similar, from a combustion system point of view, to the Allison T56-A-15 that is used to power the Hercules C130H aircraft. However, the Allison T56-A-7 engine that is used in the Hercules C130E aircraft is significantly different in combustor design and subjectively appears to emit less smoke.

In order to quantify this perceived difference, measurements of smoke emissions were taken at the Richmond RAAF Base during September/October 1986 using two T56-A-15 engines and three T56-A-7 engines operating on a mobile engine test stand from low speed ground idle to near full power.

This memorandum presents the results of the trials at Richmond and discusses the differences in the two combustion systems that may be responsible for the variations in smoke emission characteristics.

2. THE ALLISON T56 TURBOPROP ENGINE

The Allison T56 turboprop engine has a 14 stage axial flow compressor with a pressure ratio of 9.5:1, six canannular type combustors and a 4 stage axial turbine. The engine is designed to operate at a constant speed of 13820 RPM and drive a propeller through a reduction gearbox. The RAAF operate 3 models of the Allison T56 engine details of which are listed in Table 1.

TABLE 1

ALLISON T56 ENGINES OPERATED BY THE RAAF

SERIES	ENGINE MODEL	AIRCRAFT
SERIES II	T56-A-7	C130E
SERIES III	T56-A-14	P3 ORION
SERIES III	T56-A-15	C130H

From a combustion system viewpoint the two Series III engines are identical, however, there are significant differences between the Series II and III engines, particularly in the airflow distribution through the combustors. A Series II combustor liner is shown in Figure 1a and a Series III combustor liner in Figure 1b.

(2)

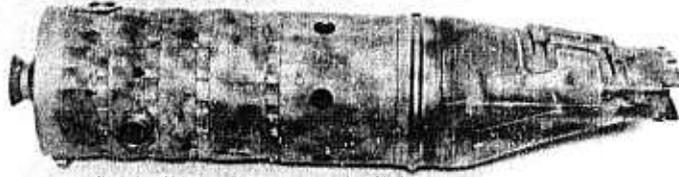


FIG. 1(a) ALLISON T56 SERIES II COMBUSTOR LINER

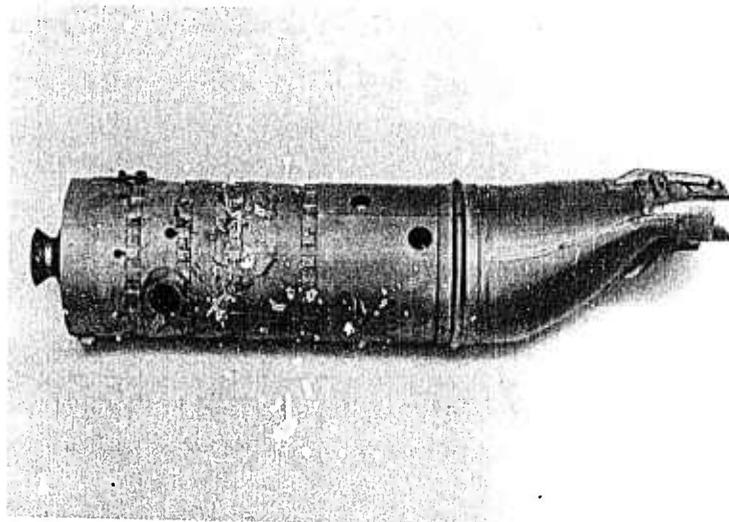


FIG. 1(b) ALLISON T56 SERIES III COMBUSTOR LINER

In an engine six of these liners are installed within an annular pressure casing and linked together with interconnector tubes. Two of the combustors, located at the top and bottom of the engine, have high energy igniters. As seen in Figure 1a and 1b there are several important differences in the design of the two liners; in particular the different distribution of air holes between the two liners and the variations in the outlet sections of the two liners that are necessary to accommodate different turbines.

Figures 2a and 2b indicate the distribution of air entering into the Series II and III engine liners respectively. These flows were estimated from measured areas using the coefficients of discharge for combustion systems described in Knight and Walter (1953) and Adkins and Gueroui (1986).

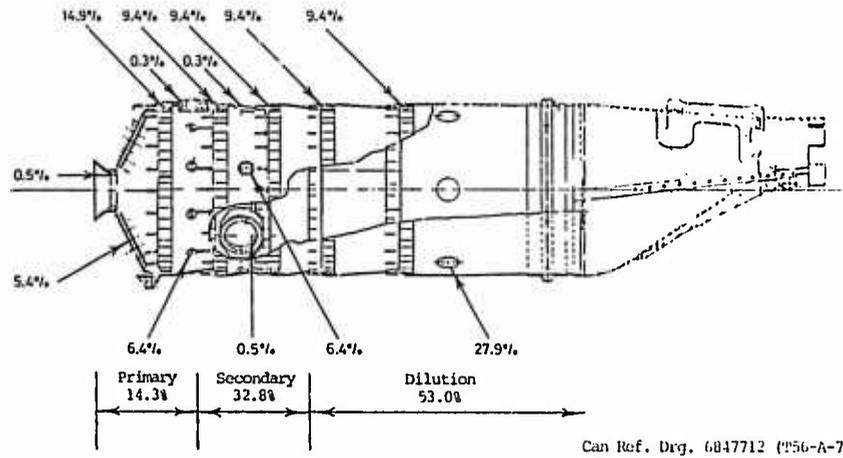


FIG. 2(a) AIRFLOW DISTRIBUTION OF T56 SERIES II COMBUSTOR LINER

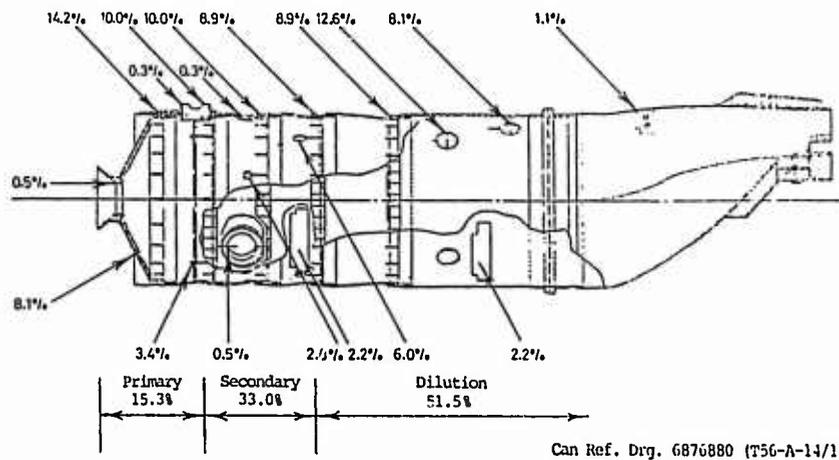


FIG. 2(b) AIRFLOW DISTRIBUTION OF T56 SERIES III COMBUSTOR LINER

(4)

Following usual practice in dividing the liner into the primary, secondary and dilution zones it was assumed that the primary zone included one third of the air that enters the first cooling corrugation around the dome plus half of the air that enters the first set of holes. The remaining part of these flows then forms part of the airflow for the secondary zone where combustion should be completed. Similarly the secondary zone includes half of the air entering the holes in the third segment of the liner and one third of the air entering the third cooling corrugation with the remaining part of these flows becoming dilution air. Similar methods were used by Allison (1985) to assign and divide airflows into different zones in a similar liner.

Fuel is injected into the dome of the liner via a duplex or twin orifice type atomiser shown in Figure 3.

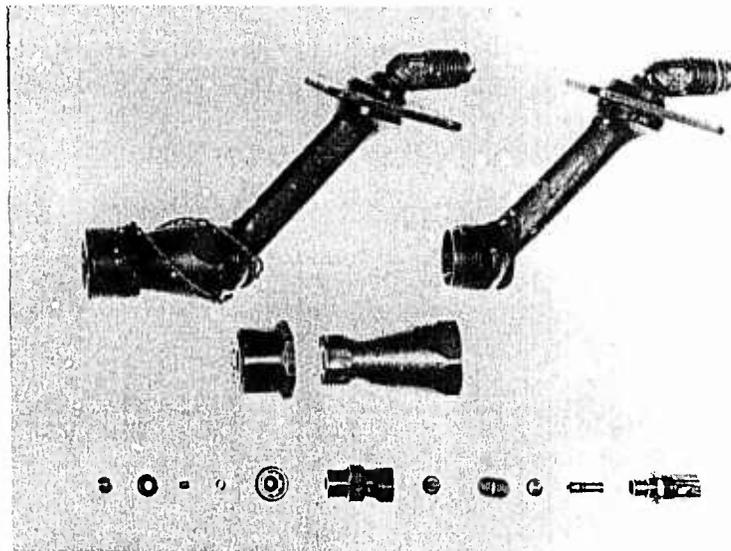


FIG. 3 ALLISON T56 ATOMISER-ASSEMBLED AND UNASSEMBLED

The secondary stage of the atomiser has a pressure operated variable orifice in the fuel passage to enable fuel to be shut off and also to provide an approximate linearity in flow versus pressure characteristic. A typical flow calibration curve is shown in Figure 4.

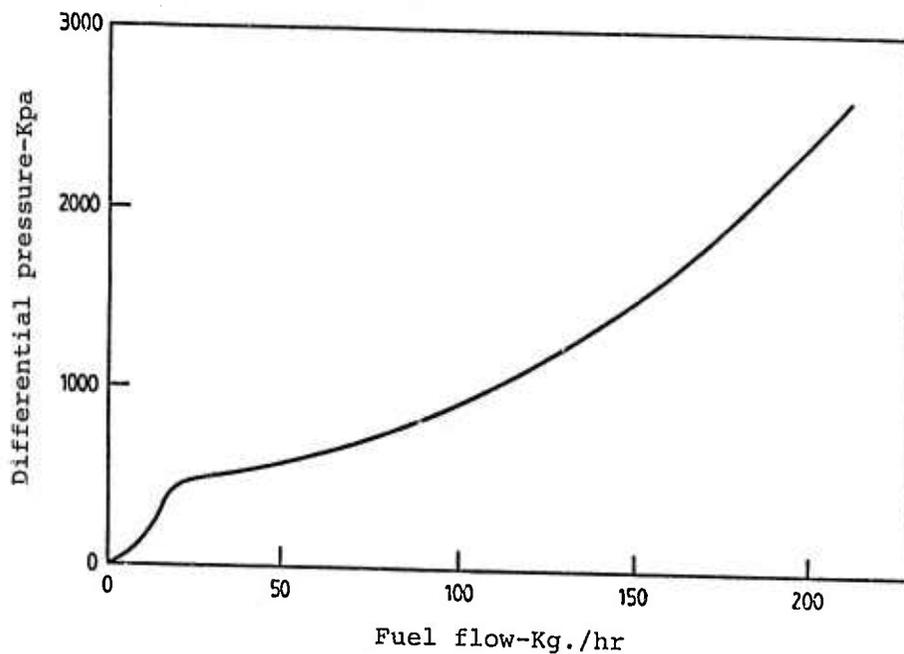
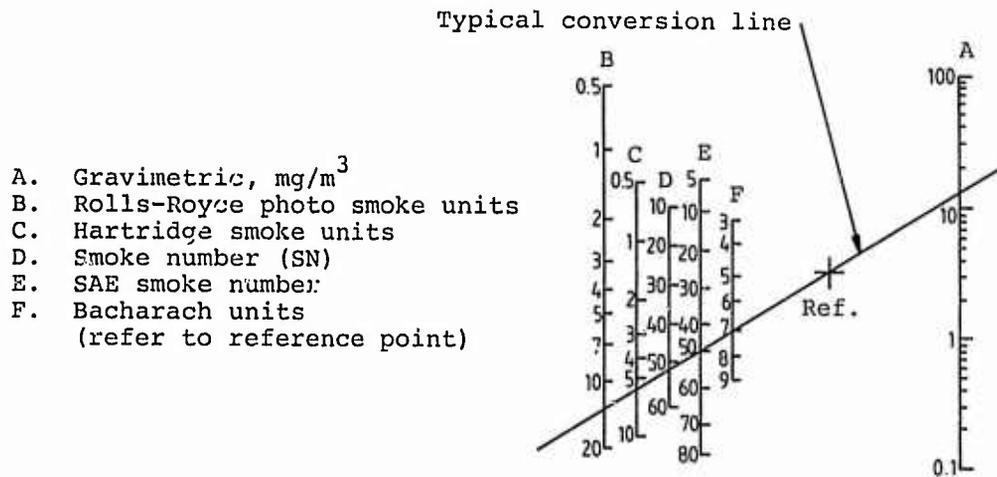


FIG. 4 ALLISON T56 ATOMISER FLOW CHARACTERISTIC

3. METHODS OF MEASURING SMOKE EMISSIONS

There are numerous methods for measuring smoke emissions from aircraft engines. The majority of these rely on an accurately known volume of exhaust gas being drawn through a filter paper. The resultant stain on the paper is then analysed to give a measurement of smoke emissions. Odgers (1982) gives a summary of the more commonly used methods and Figure 5 (taken from Odgers) shows the approximate relationship between the various scales used.



Taken from Odgers (1982)

FIG. 5 CHART FOR CONVERSION OF GRAVIMETRIC EXHAUST SMOKE TO VARIOUS INSTRUMENT READINGS

ARL has adopted a smoke meter based on the method described in the SAE ARP 1179A. This technique requires, for each engine power setting, several different volumes of exhaust gas to be drawn through a known area of Watman No. 4 filter paper. By comparing the reflectance of the resultant stained filter paper with that of clean filter paper a smoke number (SN) is calculated using

$$SN = 100 (1 - R_s/R_w) \quad (1)$$

where R_s = Reflectance of the smoke stain

R_w = Reflectance of the clean filter paper.

(7)

The actual smoke number for the particular power setting is then determined by interpolating to the point where the mass of exhaust gas being drawn through the filter paper is equivalent to 16.2 kg/m^2 .

Figure 6 shows schematically the ARL smoke measuring equipment.

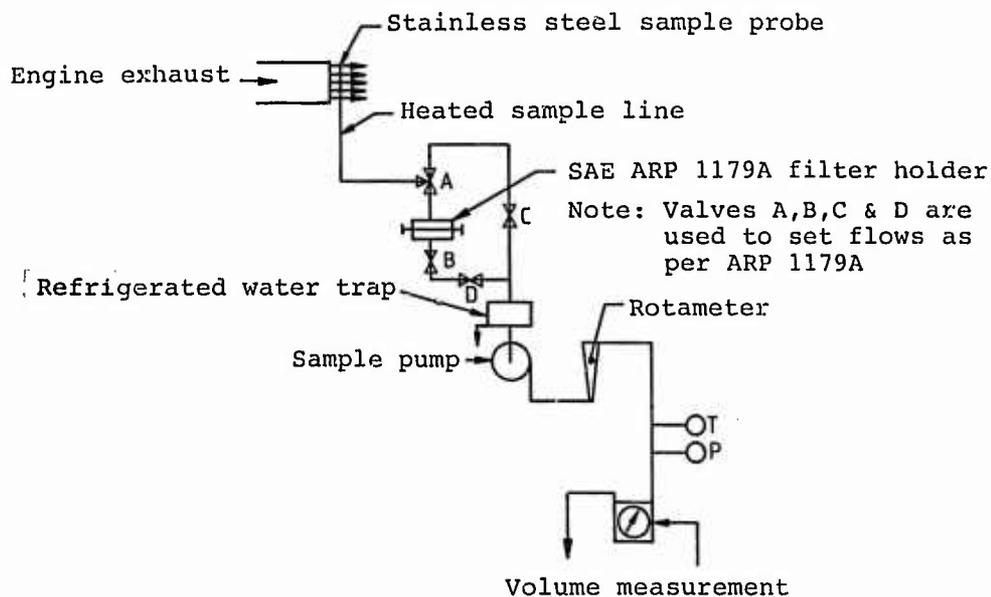


FIG. 6 SCHEMATIC LAYOUT OF THE ARL EXHAUST GAS SMOKE SAMPLING SYSTEM

Campbell et al (1980) gives an overview of the operation and problems associated with a system based on ARP 1179A. Experience at ARL has confirmed one major criticism of condensed water effecting the filter paper. This was largely overcome by ensuring that the stainless steel lines and filter holder were maintained at a temperature of 70°C . The addition of a refrigerated water trap after the filter paper holder and before the sample pump was found essential to ensure condensation in the pump, rotameter and volume meter did not cause equipment malfunction.

The inclusion of the refrigerated water trap causes a small but calculable error in the volume of exhaust gas drawn through the filter paper due to the removal of water vapour. This error is variable with a maximum near 4%

and is dependent on the temperature and pressure of the air entering the combustion system and the fuel/air ratio.

4. TESTS AT RICHMOND

Smoke emission tests were carried out on three T56-A-7 engines from the Hercules C130E aircraft and two T56-A-15 engines from the Hercules C130H aircraft. Table 2 shows the engines used, serial numbers and hours since overhaul.

TABLE 2
T56 ENGINES TESTED AT RICHMOND

ENGINE TYPE	SERIAL NUMBER	HOURS SINCE OVERHAUL
T56-A-7	105593	857
T56-A-7	106173	1621
T56-A-7	105574	1657
T56-A-15	106208	3134
T56-A-15	110432	239

The T56-A-7 engines were mounted on a mobile engine test stand and operated at low speed ground idle, ground idle, 700°C, 800°C, 900°C and 977°C turbine inlet temperatures. For the T56-A-15 engines the same conditions were tested up to 900°C with a maximum turbine inlet temperature of 1000°C as well. For one of the T56-A-15 engines an extra sample point was taken at 1000°C with the engine air bleed valve fully open. At each condition the engine was allowed to stabilize before smoke emission tests were undertaken using the procedure described in Section 3.

Figure 7 shows a general view of a T56-A-15 engine mounted on the mobile engine test stand and Figure 8 shows the sample probe in position across the exhaust nozzle.

Fuel samples were taken from the mobile fuel tank for later analysis to determine physical and chemical properties, including aromatic content, of the fuel used during the tests.

5. RESULTS

The results of smoke emission tests are plotted in Figure 9. Also plotted on this figure are the results of smoke emission tests on a T56-A-15 engine by Vaught et al (1971) and the results of smoke emission tests on two T56-A-14 engines by Skidmore (1985). A reference line for detection of visible plumes (Stockham and Betz (1980)) is also presented in Figure 9 for

(9)

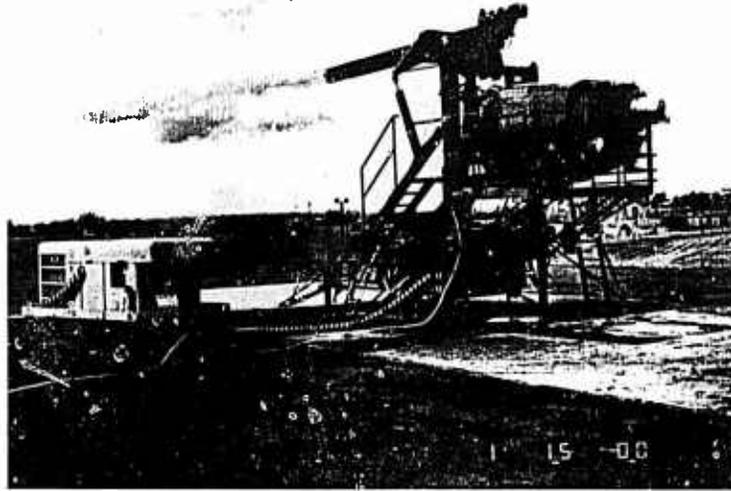


FIG. 7 T56-A-15 ENGINE OPERATING ON THE MOBILE ENGINE TEST STAND

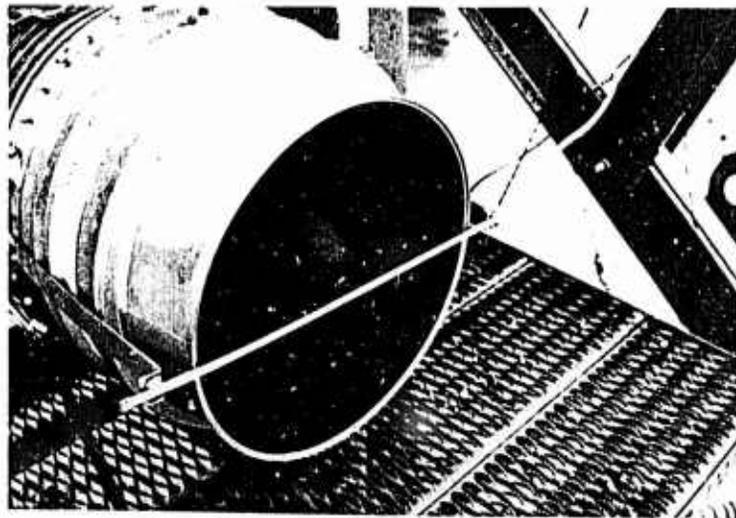
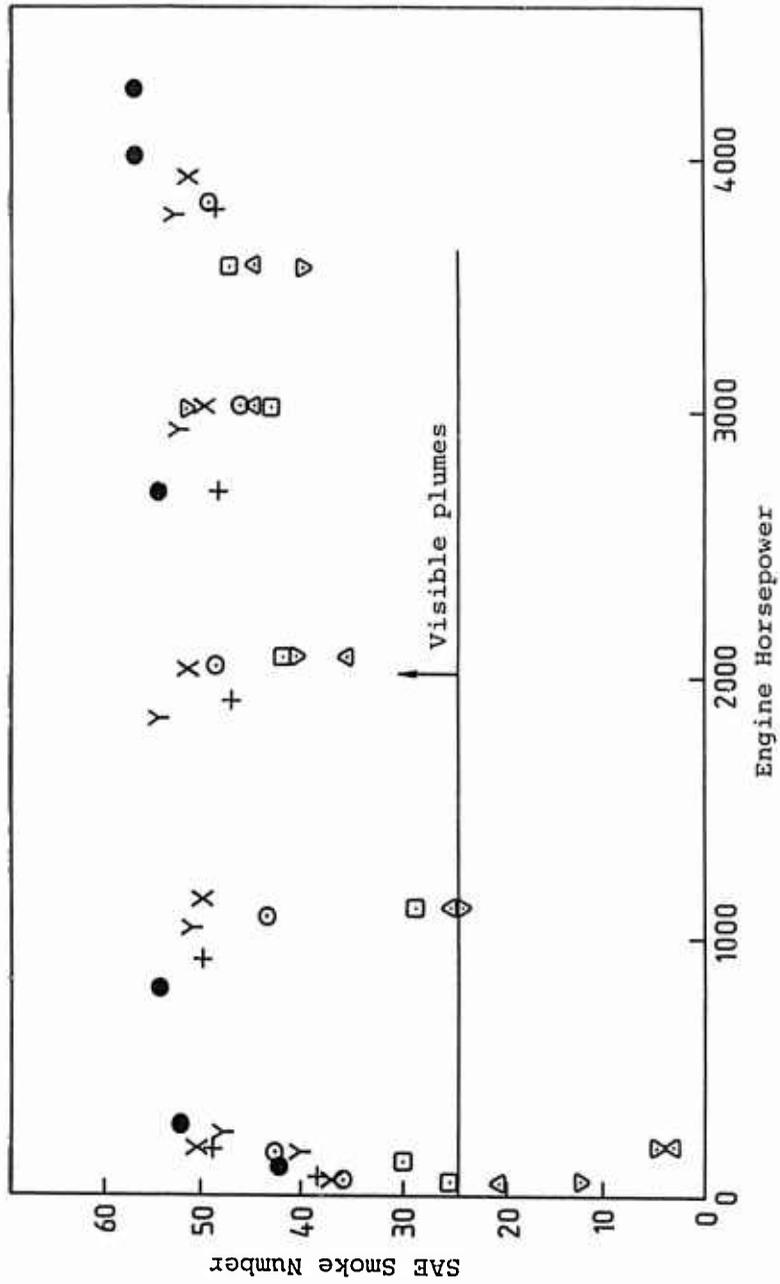


FIG. 8 VIEW OF EXHAUST NOZZLE OF A T56 WITH SAMPLE PROBE IN POSITION



(10)

- X T56-A-14 (S/N 110294)
 - Y T56-A-14 (S/N 107029)
 - T56-A-15 (S/N 108518)
 - + T56-A-15 (S/N 106208)
 - T56-A-7 (S/N 105574)
 - △ T56-A-7 (S/N 106173)
 - T56-A-7 (S/N 105593)
 - ▽ T56-A-7 (S/N 105593)
- Skidmore (1985)
 Skidmore (1985)
 Vaught et al (1971)

FIG. 9 SN VS HP-T 56 ENGINES

comparison. Table 3 presents actual smoke numbers for the T56-A-15 engines tested over the operating range of 1000 to 4000 HP (700°C - 1000°C turbine inlet temperatures) together with the results of the tests from T56-A-14 engines taken from Skidmore (1985). This table also shows the averages for the two engine types and differences at each nominal condition.

TABLE 3
T56 SERIES III SMOKE NUMBERS

ENGINE SERIAL NO	TURBINE INLET TEMPERATURE			
	700°C	800°C	900°C	1000°C
110294 (T56-A-14)	50.5	53.7	51.5	51.6
107029 (T56-A-14)	50.4	49.4	48.3	50.1
110432 (T56-A-15)	50.9	46.6	47.8	46.5
104208 (T56-A-15)	42.0	47.8	44.1	47.2
T56-A-14 (AVERAGE)	50.5	51.6	49.9	50.9
T56-A-15 (AVERAGE)	46.5	47.2	46.0	46.9
DIFFERENCE	4.0	4.4	3.9	4.0

The complete analysis of the fuel by Materials Testing Laboratories for compliance with DEF(AUST)5208 is presented in Appendix I. The aromatic content of the fuel was 16.1% with a hydrogen content of 13.56%. The aromatic content is plotted onto a graph (Figure 10) showing the history of aromatic content for JET A, the equivalent of AVTUR, and limited data

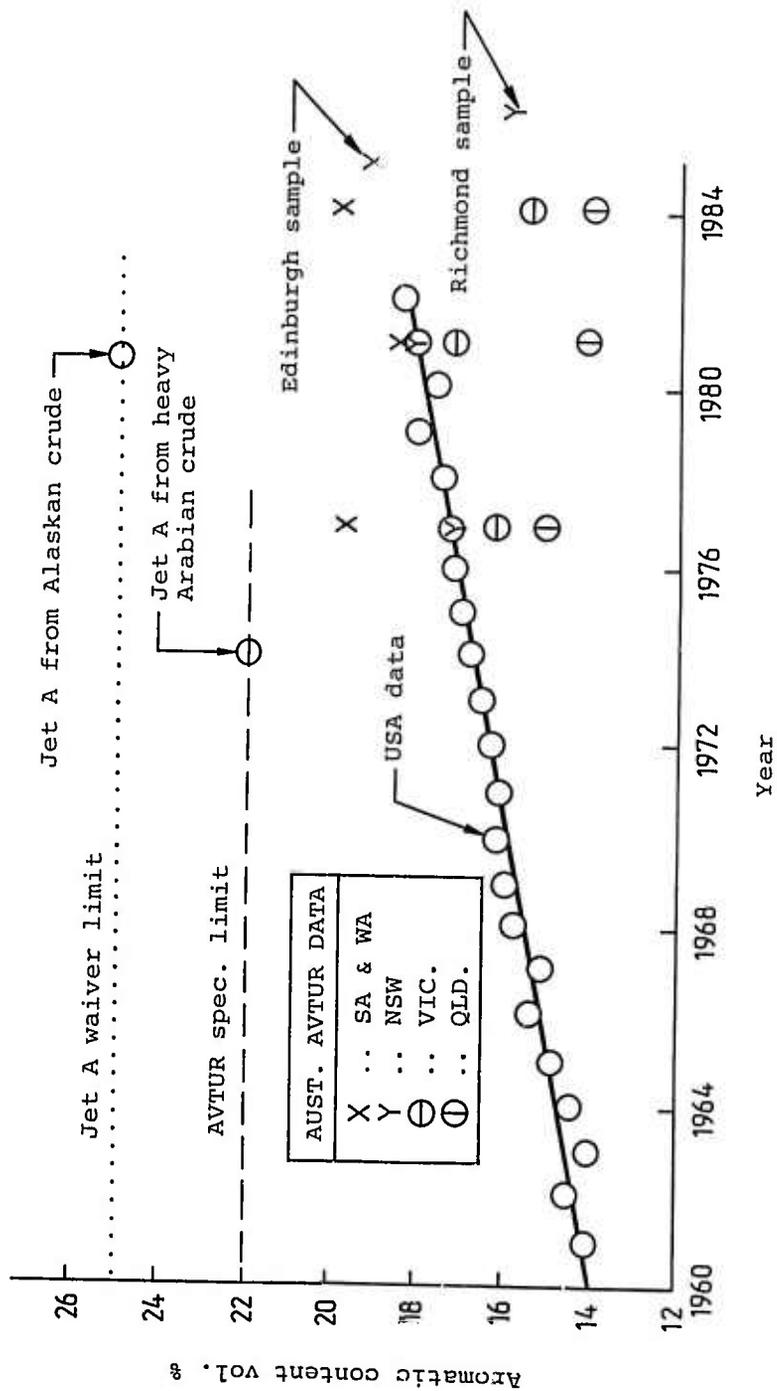


FIG. 10 TREND IN AROMATIC CONTENT OF JET A AND AVTUR

available to ARL of aromatic content of AVTUR from Australian sources. The US data was obtained from information contained in Sheldon (1981) and Sheldon and Dickson (1983).

6. DISCUSSION

6.1 Smoke Emission Tests

The smoke emission tests carried out at Richmond confirm the results of Vaught et al (1971) and Skidmore (1985) that the Series III T56 engines (T56-A-14 and T56-A-15) have an average smoke number of approximately 50 over the engine operating range of 1000 to 4000 horsepower (ie in the range of 700°C to 1000°C turbine inlet temperature). It is also apparent from Figure 9 and Table 3 that over the same range there is a variation of approximately 4 in smoke numbers between the T56-A-15 and the T56-A-14 engines tested by Skidmore (1985) at Edinburgh. The work of Blazowski (1975) Rudley and Grobman (1978) and Odgers and Kretschmer (1983) show that smoke emissions increase as hydrogen content of the fuel decreases. The hydrogen content of the fuel used at Richmond is known to be 13.56% (Appendix 1), unfortunately the fuel used at Edinburgh was not analysed for hydrogen content. However, using the work of Rudley and Grobman (1978) it is possible to estimate an increase of 0.15% in hydrogen content for the Edinburgh fuel sample above the Richmond fuel sample from the different levels of aromatics.

Blazowski (1975) used a T56 combustion system as the basis for a test rig to investigate the effects of fuel hydrogen content on the systems performance including smoke emissions. His results show that a decrease in hydrogen content of 0.15% will lead to an increase in smoke number of approximately 3 over a wide range of hydrogen contents and operating conditions.

Figure 9 also shows that the Series II T56-A-7 engines emit less smoke than the Series III engines. The smoke emissions of the T56-A-7 engine rise from a smoke number of approximately 27 at 1000 HP to a smoke number of approximately 42 at 3500 horsepower. At 3500 horsepower the Series III engines have a smoke number of approximately 50. This difference in levels of emission is not linear and by reference to the conversion chart, Figure 5, shows that the difference gravimetrically is from 8 mg/in³ to 12 mg/in³ of exhaust which is a 50% increase from Series II to Series III.

The reason for this difference is most likely to be the design of the primary zone of the combustor system and in particular the amount of air that is allowed into the liner through the first set of circumferential holes. Figures 2a and 2b shows this difference to be a decrease from 6.4% to 3.4% of the total airflow. The effect of modifying this hole size on smoke emission is the subject of a separate study being undertaken at ARL and preliminary results are expected by early 1987.

Subjective visual observation during the tests on both the Series II and Series III engines at Richmond showed that the smoke emissions were not continuous although intermittency was most noticeable in the T56-A-7. The

smoke appeared to be emitted from the engine in relatively short bursts of dense smoke interspersed by periods of relatively clean exhaust. The frequency of these bursts was 2-3 hertz.

6.2 Fuel Analysis

Materials Testing Laboratories noted in the covering letter to Appendix 1 that the fuel sample conformed to the requirements of DEF(AUST) 5208 where tested, except for appearance.

The aromatic content of the fuel used at Richmond was 16.1% with a hydrogen content of 13.56%. The fuel used in the Edinburgh tests (Skidmore, 1985) had an aromatic content of 18.4% and an estimated hydrogen content (see Section 6.1) of 13.41%. A difference in hydrogen content of this magnitude (ie about 0.15%) is estimated to cause a change in smoke number of about 3. This correlates well with the measured difference of 4 smoke number units between the Edinburgh and Richmond tests on the Series III engines. However, both fuels were well under the DEF(AUST)5208 limit of 22% for aromatic content. Use of AVTUR fuel having an aromatic content of 22% is likely to result in the smoke number increasing by an estimated 9 units over the Richmond results for T56 Series III engines.

7. CONCLUSIONS

The tests at Richmond confirm that there is a significant variation in smoke emissions between Series II and Series III T56 engines. Both engine types do emit visible smoke at normal operating power levels although the Series III procedures approximately 50% more than the Series II.

The tests also confirm that smoke emissions are exacerbated by increasing the aromaticity of fuel.

ACKNOWLEDGEMENTS

The work carried out in this publication relied heavily on the cooperation and expertise of many Department of Defence personnel. In particular:

- . AFSA office staff for support and liaison in setting up the trial.
- . 486 Squadron at Richmond whose cooperation allowed 5 engines to be tested in one week.
- . Offices of MTL for fuel analysis.
- . Mr N. Repacholi for his expertise and work in assembling and operating the smoke measuring equipment used at Richmond.

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APPENDIX 1

EXAMINATION OF AVIATION FUEL

Schedule A to:
 Laboratory Report 86/983
 Sample No. S86/4512
 File No. FL/REP/F7

MATERIALS TESTING LABORATORIES - NSW

EXAMINATION OF RAAF METS FUEL

RESULTS OF EXAMINATION:

TEST	SPECIFICATION	RESULTS
<u>Appearance</u>	Visually clear and bright and visually free from sediment, suspended matter and undissolved water at temperature of delivery.	Trace of sediment present
<u>Freezing Point</u> °C	-47 Maximum	-50.5
<u>Distillation</u>		
Initial Boiling Point °C	To be reported	148.0
20% Vol recovered at °C	200 Maximum	170.0
50% Vol Recovered at °C	To be reported	190.0
90% Vol Recovered at °C	To be reported	228.5
Final Boiling Point °C	300 Maximum	247.5
Residue % Vol	1.5 Maximum	1.5
Loss % Vol	1.5 Maximum	0.5
<u>Density at 15°C</u> kg/Litre	0.775 to 0.830	0.7936
<u>Flash Point (Abel)</u> °C	38 Minimum	40.5
<u>Copper Corrosion (Bomb, 2h at 100°C)</u> Classification	1 Maximum	1a
<u>Silver Corrosion (4 h at 50°C)</u> Classification	1 Maximum	0
<u>Existent Gum</u> mg/100 mL	7 Maximum	<1
<u>Water Reaction</u>		
Interface Rating	1b Maximum	1b
Separation Rating	2 Maximum	2
<u>Aniline Point</u> °C	-	59.3
<u>Colour (Lovibond)</u>	4 Maximum	0.25-(0.5)
<u>Copper Content*</u> µg/Kg	150 Maximum	10.6

Schedule A to:
Laboratory Report 86/983
Sample No. S86/4512
File No. FL/REP/F7

MATERIALS TESTING LABORATORIES - NSW

EXAMINATION OF RAAF METS FUEL

RESULTS OF EXAMINATION:

TEST		SPECIFICATION	RESULTS
<u>Aromatics Content</u>	% vol	22 Maximum	16.1
<u>Olefins Content</u>	% vol	5 Maximum	1.2
<u>Sulphur, total</u>	% mass	0.30 Maximum	<0.005
<u>Doctor Test</u>		Negative	Conforms
<u>Viscosity at -20°C</u>	mm ² /s	8.0 Maximum	3.423
<u>Gravity °API</u>		-	46.71
<u>Aniline Gravity Product</u>		4800 Maximum	6479
<u>Smoke point</u>	mm	20 Minimum	24
<u>Hydrogen Content*</u>	% mass	To be reported	13.56

The test methods used were those required by the specification.
*Method used not covered by NATA registration.

M. Perdrisat
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Fuels and Lubricants Section

H.S. Milham
(H.S. MILHAM)
For Director

20 Nov '86



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16. Abstract This report presents the results of smoke emission tests on three Series II T56-A-7 and two Series III T56-A-15 Allison T56 Turboprop engines operating from idle to near full power. The results indicate a significant difference in the levels of emissions between the different engine series tested. Keywords: Turboprop engines; Jet engine exhaust emissions; T-56 engines; C-130 aircraft. (Australia)			

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