

DTIC FILE COPY

(4)

ARL-PROP-R-182

AR-006-055



DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

AD-A227 750

Propulsion Report 182

THE REDUCTION OF SMOKE EMISSIONS

FROM ALLISON T56 ENGINES (U)

by

F.W. Skidmore
D.R. Hunt *
P.N. Doogood

*Royal Australian Air Force

DTIC
ELECTE
OCT 26 1990
S B D

Approved for public release.

(C) COMMONWEALTH OF AUSTRALIA 1990

MARCH 1990

This work is copyright. Apart from any fair dealing for the purpose of study, research, criticism or review, as permitted under the Copyright Act, no part may be reproduced by any process without written permission. Copyright is the responsibility of the Director Publishing and Marketing, AGPS. Inquiries should be directed to the Manager, AGPS Press, Australian Government Publishing Service, GPO Box 84, CANBERRA ACT 2601.

THE UNITED STATES NATIONAL
TECHNICAL INFORMATION SERVICE
IS AUTHORISED TO
REPRODUCE AND SELL THIS REPORT

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORY

Propulsion Report 182

THE REDUCTION OF SMOKE EMISSIONS FROM
ALLISON T56 ENGINES

by

F.W. Skidmore
D.R. Hunt *
P.N. Doogood

* Royal Australian Air Force

SUMMARY

Aeronautical Research Laboratory (ARL) has been working to reduce smoke emissions from the Allison T56 engines used in the Lockheed P-3C Orion aircraft operated by the Royal Australian Air Force (RAAF). The work consisted of a literature survey, design and manufacture of a water tunnel model, water tunnel testing of various modifications to improve the fluid dynamics of the combustion system, testing the modifications in a single liner combustion test rig, smoke emission comparative tests in ground run engine trials, performance tests in a calibrated test cell and flight trials of a modified engine. The modification that was developed in this program was found to significantly reduce smoke emissions and give substantial improvements in the specific fuel consumption of the engine. In addition, there were indications, in line with theoretical predictions, that the modification would extend the life of the hot end components of the engine.

This report describes the work up to August 1989 and outlines the final program on burner outlet surveys that will complete the program.



(C) COMMONWEALTH OF AUSTRALIA 1990

TABLE OF CONTENTS

1.	INTRODUCTION.....	1
2.	LITERATURE SURVEY	1
3.	THE ALLISON T56 TURBOPROP ENGINE.....	1
4.	INITIAL ENGINE TESTS.....	3
	4.1. Scope of Tests.....	3
	4.2. Results and Discussion.....	3
5.	WATER TUNNEL EXPERIMENTS	4
6.	COMBUSTION RIG TESTS	4
	6.1 Apparatus and Test Procedure.....	4
	6.2 Results and Discussion.....	5
7.	MODIFIED ENGINE GROUND TESTS	5
	7.1 Scope of Tests.....	5
	7.2 Open Test Stand Trials	6
	7.3 Results and Discussion - Open Test Stand	6
	7.4. Durability Tests.....	7
	7.5 Performance Tests	8
8.	FLIGHT TRIALS.....	8
	8.1 Scope of Flight Trials	8
	8.2 Results and Discussion.....	9
9.	FUTURE WORK.....	9
	9.1 Flight Trials.....	9
	9.2 Burner Outlet Temperature Surveys	10
10.	CONCLUSIONS.....	10
	ACKNOWLEDGEMENTS.....	11
	REFERENCES.....	12
	APPENDIX 1. Analysis of Fuel Samples.....	13
	FIGURES	
	DISTRIBUTION LIST	
	DOCUMENT CONTROL DATA	

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution	
Availability Codes	
Dist	Avail and/or Special
A-1	

1. INTRODUCTION

The Royal Australian Air Force (RAAF) uses the P-3C Orion aircraft in a multi-role capacity. One of these roles is in the surveillance and detection of submarines. In this role the smoke emissions from the Allison T56-A-14 engines can be clearly seen by submariners. The submarines, however, remain difficult to detect visually by the aircrew even in a calm sea.

As a result of this problem the Aeronautical Research Laboratory (ARL) was tasked by the RAAF to investigate methods of reducing the smoke emissions from the Allison T56 engines to an acceptable level. The work undertaken by ARL focussed on the combustion system and, in particular, the fluid dynamic aspects which are known to influence the formation of soot. The work program consisted of an initial literature survey, engine exhaust smoke measurements, water tunnel experiments, engine ground tests and, finally, flight trials. The final phase of the program will be a burner outlet temperature survey which has commenced but was not complete at the time of publication.

This work was carried out under Defence Science and Technology (DSTO) Tasks AIR 85/034 and AIR 89/086 and addresses part of the work required by Air Force Research Requirement AFRR 3/88 (1988).

2. LITERATURE SURVEY

An extensive literature survey was undertaken and revealed that the main factors influencing smoke emissions from gas turbine combustion systems include;

- ✱ the chemical composition of the fuel - in particular the aromatic content and the ratio of hydrogen to carbon,
- ✱ the physical design characteristics of the combustor, and
- ✱ fuel atomisation and mixing of fuel and air.

3. THE ALLISON T56 TURBOPROP ENGINE

The General Motors Detroit Diesel Allison T56 engine is a single spool gas turbine engine driving a propeller through a reduction gear box. This engine is installed in the Lockheed P-3C Orion and C-130 Hercules aircraft operated by the RAAF. The engine has a 14 stage axial flow compressor with a pressure ratio of 9.5 to 1 that delivers air to a can-annular combustion system. Following the combustors the gases pass through a 4 stage axial flow turbine.

The engine is designed to operate at a constant speed of 13,820 RPM which is controlled by using a variable pitch propeller. This implies that, at any given altitude and speed, airflow and pressure through the engine are constant. The combustion system has undergone only minor design changes since the engine was brought into service in the early 1960's. Figure 1 shows a diagrammatic layout of the system which consists of:

- inner and outer pressure casings that provide both the gas path connection between the compressor and turbine and the mechanical connection;
- six individual combustor liners that control the airflow distribution and airflow pattern required for stable combustion; and
- six dual orifice atomisers.

The RAAF operates three variants of the T56 engine as shown in Table 1.

TABLE 1.

T56 ENGINES OPERATED BY THE RAAF

ENGINE TYPE	SERIES	AIRCRAFT
T56-A-7B	II	Hercules C-130E
T56-A-15	III	Hercules C-130H
T56-A-14	III	Orion P-3C

All three versions emit visible smoke, but (subjectively) the Series III engine was considered to emit more smoke than the Series II engines. This contention was established as part of the present study. Souza and Daley (1978) showed that the Series II engines have an average SAE smoke number of 45 at maximum power, and Skidmore (1985), as part of the present study, measured the Series III, T56-A-14, engine exhaust smoke number as an average of 50.9 for the same power setting. Using the information contained in Champagne (1971) this can be shown to represent a 50% increase in the mass emissions of smoke particles at that power setting. Further analysis of the information contained in Souza and Daley (1978), Vaught et al. (1971) and Skidmore (1985) on the smoke emissions from the two series of engines shows that the Series II engine emits less smoke than the Series III over the entire power range.

The combustion systems of the two Series III engines are identical. However, there are certain differences between the Series II and Series III systems. Figure 2 shows a photograph of the two types of combustor liner. The larger outlet section of the Series III is necessary to accommodate a different turbine and there are variation in air hole geometry between the liners.

By using the work of Knight and Walters (1953) and Adkins and Gueroui (1986) in determining discharge coefficients of air holes and cooling corrugations in combustor liners, Skidmore (1986), as part of the present study, estimated the distribution of airflows for the two liners. These distributions are given in Figure 3. and show that the total primary zone airflow is estimated to have been increased from 14.3% to 15.3% of the total flow from the Series II to the Series III configuration. This involved an increase in the dome airflow from 5.4% to 8.1% and decrease in the airflow of the first primary zone holes from 6.4% to 3.4% of total airflow.

4. INITIAL ENGINE TESTS

4.1 Scope of Tests

Smoke emission tests were carried out at the RAAF Bases in Edinburgh, South Australia and Richmond, New South Wales on the three variants of T56 engine operated by the RAAF. Table 4.1. lists the types, series and serial numbers of the subject engines. All engines were tested for smoke emissions using the equipment and procedure described in the SAE's ARP 1179A (1980) over the full operating range from low speed ground idle to full power. Figure 4. shows an Allison T56-A-14 engine mounted on a mobile engine test stand at Edinburgh RAAF base during one of the smoke emission tests. Figure 5. shows the engine from the rear with the gas sampling probe in position.

TABLE 4.1

T56 ENGINES TESTED

ENGINE TYPE	SERIES	SERIAL NUMBER
T56-A-14	III	AE 110294
T56-A-14	III	AE 107029
T56-A-15	III	AE 108518
T56-A-15	III	AE110432
T56-A-15	III	AE106208
T56-A-7B	II	AE 105574
T56-A-7B	II	AE 106173
T56-A-7B	II	AE 105593

4.2 Results and Discussion

The results of these tests are fully presented in Skidmore (1985 and 1986). Summary data are presented in Figure 6 in terms of SAE Smoke Number against Engine Power. The results agree well with other published data on smoke emissions from Allison T56 engines (Souza and Daley, 1978 and Vaught et al, 1971). They confirm that the engines all emit smoke at a level which is both above the US EPA (1973) limit for smoke emissions for the T56 engine fitted to the C-130 Hercules aircraft (Matterson et al, 1980).

5. WATER TUNNEL EXPERIMENTS

A water tunnel model representing part of the T56 combustion system was designed and built at ARL and tested at the Swinburne Institute of Technology. The model, shown in Figure 7, was based on a carefully designed 60 degree sector of the annular pressure casing of the combustion system. The two plane radial sides and the curved walls representing the inner and outer casing segments were made from Perspex. The metal combustor liner was fitted with cutouts to permit Mylar windows to be inserted to allow the internal flow field to be observed when dye was injected at various stations along the model. The tests carried out with the model were conducted at Reynolds numbers that ensured that the large scale flow field of the engine was reproduced.

The flow field within the standard combustor was found to be deficient in several respects, and various modifications were developed to radically improve the turbulent mixing within the combustor. The development of the final modification was the result of an extensive series of tests in which a wide range of possibilities were considered.

6. COMBUSTION RIG TESTS

6.1. Apparatus and Test Procedure

The modifications that were developed in the water tunnel were tested in a combustion test rig at ARL for comparison with the performance of a standard combustion system.

A photograph of the rig is shown in Figure 8 and a cross sectional view appears in Figure 9. Like the water tunnel model, the rig was based on a single liner contained in a 60 degree sector of the Allison T56 combustion system. The sector, shown in Figure 10, had insulated radial side panels to reduce circumferential heat loss, and both the inner and outer pressure casings of the engine were reproduced in 0.5 mm stainless steel. There were two sectors available for the rig; the one, shown in Figure 10, accepted Series II combustor liners while the other accepted Series III liners. The sectors were used only to act as guides for airflow through the rig and the pressure was contained by a 300 mm mild steel casing. The inlet diffuser, shown in Figure 11, was an exact copy of the actual engine diffuser.

The validity of the combustion rig in representation of part of the full scale engine combustion system, could be assessed in two ways. These were in terms of gaseous and particulate emissions which were similar to published data, and in terms of the distribution of metal temperature on the surface of the combustor liner. Figure 12 shows the temperature distribution patterns revealed by thermal paint on the surface of a standard liner after operation in the rig together with the natural metal temperature discolourations on the same liner after operation in an engine. These patterns can be seen to be essentially the same, with even small features of the pattern accurately reproduced.

The rig could operate at pressures up to 1000 kPa (150 psi) and with inlet air temperatures up to 350°C (660°F).

The conditions chosen for these tests were:

- ✱ air mass flow - 2.15 kg/s (4.75 lb/s);
- ✱ rig inlet pressure - 760 kPa (110 psi); and
- ✱ rig inlet temperature - 300°C (570°F).

This corresponds to an operating condition for the T56 engine at a low level cruise in the P-3 Orion. While it was possible to have rig outlet (or turbine inlet temperatures) up to 1100°C, for this series of tests the outlet temperature was limited to 900°C, corresponding to a power setting just below the normal cruise setting for the engine.

Smoke emissions were determined using the same equipment used in the engine tests (see Section 4). Gaseous emissions were determined using the equipment and procedure described in the SAE's ARP 1256A (1980).

6.2 Results and Discussion

The effectiveness of a modification was assessed in terms of SAE Smoke Number, gravimetric carbon emissions (smoke), emissions of unburnt hydrocarbons, carbon monoxide and oxides of nitrogen. The modification developed in the water tunnel work was tested and subsequently modified in minor ways to achieve the final modification. The results for the final modification developed at ARL are shown plotted against turbine inlet temperature in Figures 13 to 17. Figure 14 was obtained by converting the SAE Smoke Number to emissions of carbon using the information contained in Champagne (1971).

These results, with the exception of oxides of nitrogen, all show a reduction in emissions. (The levels of unburnt hydrocarbons at higher turbine inlet temperatures were very low for both the standard and modified liners and probably reflect the background levels of hydrocarbons or oil in the inlet air to the rig rather than an effect due to the modification). The slight increase in oxides of nitrogen indicate a higher flame temperature or an increase in residence time in the combustor which is consistent with more stable and efficient combustion in the modified combustor. All of the results show that combustion in the modified combustor liner had been improved. In particular smoke emissions had been reduced significantly, and the overall results pointed to an increase in combustion efficiency.

7. MODIFIED ENGINE GROUND TESTS

7.1 Scope of Tests

The performance of the modified combustion system was compared with the performance of a standard system in a series of ground run engine trials addressing three aspects.

These were:

- exhaust smoke emissions (measured on an open test stand);
- engine performance and specific fuel consumption (measured in a calibrated test cell); and
- durability of the combustor liner, nozzle guide vanes and turbine blades.

7.2 Open Test Stand Trials

The open test stand trials were conducted on an Allison T56-A-14 engine (S/N AE 110298) at the RAAF Base in Edinburgh, South Australia. The engine was initially tested in standard form for smoke emissions over the entire power range from low speed ground idle (start position) to maximum power, to establish a valid base-line measurement. This test involved about four hours of engine running. The engine was then dismantled and modified to incorporate the ARL low smoke combustor liners that contained the final geometry established in the ARL laboratory rig tests. Care was then taken to ensure that the engine was rebuilt with all components in exactly the same position; **i.e. the only difference was the ARL low smoke modification to the combustor liners.** The engine was then retested at the same conditions that were used previously in testing the standard engine. A fuel sample was collected at the conclusion of each trial and analysed by the Australian Department of Defence, Materials Testing Laboratory in New South Wales for physical and chemical characteristics (including hydrogen and aromatic contents). These analyses are reproduced in Appendix 1. At the conclusion of the smoke reduction trials a durability test commenced.

7.3 Results and Discussion - Open Test Stand

The results of the smoke emission tests from the ground run engine for both the standard and modified engine builds are shown in Figure 18 in terms of SAE Smoke Number versus engine power and in Figure 19 for mass emissions of carbon (smoke) versus engine power. Figure 20 shows the percentage reduction in mass emissions of carbon attributable to the combustor modification together with corresponding data from the combustion rig.

These results show that smoke emissions were reduced by a substantial margin over the entire operating range of the engine. The percentage reduction is also in close agreement with the reduction observed in the laboratory rig tests (Figure 20).

The results of the fuel analysis (Appendix 1) show that the difference in both aromatic and hydrogen content is very small and would have had a negligible effect on smoke emission differences.

The level of smoke emissions from the modified engine approaches the visibility threshold level for a C-130 Hercules aircraft, see Matterson et al (1980). No information regarding the visibility threshold level could be found for the P-3 Orion aircraft. However, a comparison of the two engine installations suggests that the P-3 would be more likely to generate discrete visible smoke trails than would the C-130 aircraft.

The smell of unburnt fuel is usually noticeable in the exhaust of standard T56 engines, particularly at low power settings. During the ground trials there was no smell * of unburnt fuel in the exhaust of the modified engine at any power setting. This was consistent with the rig results for unburnt hydrocarbon emissions.

Another positive aspect which was noticed during ground running was that the modified engine was easier to start and emitted no smoke during the starting cycle. Peak start-up temperatures were also lower.

7.4 Durability Test

The same modified engine was subjected to an extended run designed to test the durability of the modified liners and to ensure that the modification did not reduce the life of the nozzle guide vanes or turbine blades. The test consisted of running the engine for 10 minutes at ground idle (start position) followed immediately by 10 minutes at maximum continuous power (1010°C turbine inlet temperature). Both increases and decreases in power were carried out as rapidly as possible. This cycle was repeated for approximately 12 hours per day until 150 hours of engine running time had been accumulated. This testing program was considered to be the equivalent of at least 1000 hours of normal flight operation by the RAAF. During the run, regular boroscope examinations were undertaken of the liners, nozzle guide vanes and first stage turbine blades. Subsequently the engine was dismantled and inspected by experienced RAAF Engine Fitters. Inspection revealed that there was no sign of any distress or any other problem in hot end components. In fact the hot end components appeared to be in significantly better condition than those of a standard engine; this was particularly so for the liners. The modified liners after the 150 hour endurance test were completely free from any cracks or any other sign of distress, whereas the (new) standard liners that had been run for only about four hours all contained cracks in the area near the exhaust. It was most noticeable that the modified combustor liners were virtually free from carbon build-up and this contrasted with the standard liners which were coated in carbon. Figure 21 shows comparative boroscope photographs of the area around the dome of the liner for both a standard and modified liner.

It is anticipated that the significant reduction in carbon generation will increase the life of turbine blades and nozzle guide vanes. This is based on evidence that the protective coatings on these components are eroded by carbon particles which decreases the life of the coatings, and thus the life of the blade. Current testing will, in time, provide data on this aspect of the modification.

*

The smell of unburnt hydrocarbons can be an operational problem for the C-130 when taxiing for extended periods with troops on board, with the rear ramp deployed for ventilation.

7.5 Performance Tests

The modified engine was installed in the calibrated T56 test cell at QANTAS in Sydney, and subjected to a series of performance measurements. The engine was then returned to standard configuration and retested for performance. Subsequently another T56-A-14 and a T56-A-15 engine were tested with modified liners in the calibrated test cell to expand the data base on engine performance with the modified liners.

The results in terms of the percentage improvement in corrected specific fuel consumption versus turbine inlet temperature are presented in Figure 22 for the three modified engines. Figure 23 provides the same information but as an average of the results for the three engines. The results demonstrate that, for the engines tested, specific fuel consumption was reduced by approximately 1% at the normal cruise condition for the engine.

These results will be confirmed by testing further modified engines.

8. FLIGHT TRIALS

8.1 Scope of Flight Tests

At the conclusion of the calibrated test cell runs, the first engine (S/N AE 110298) was again rebuilt to the low smoke configuration and fitted to number 3 position on the RAAF's P-3C Orion aircraft, A9-661. Engine performance and behaviour were monitored in flight using standard aircraft instrumentation that had been calibrated. A video camera mounted behind the co-pilot was used to record the engine instrumentation parameters. A second hand-held video camera was also used on some tests to record instrument and general flight information. The flight trials were conducted under RAAF Special Technical Instruction TI 1045 (1989) during June 1989.

The trials were conducted in two phases. The first phase was based on the standard flight test following an engine change as required by the P-3C Flight Manual (RAAF, 1983) and included safety checks of the relight capabilities of the engine. The second phase was designed to test the modified engine throughout the flight envelope of the P-3C aircraft to ensure that relight or flameout characteristics of the engine were not compromised.

A chase aircraft was used to record, photographically, variations in smoke emissions from the engines in flight. Photographic and video recordings were also taken from the ground during take-offs and landings and also during a series of fly-overs.

The program for the second series of tests was:

- a. Tests to identify any changes in the relight characteristics of the modified engine.
This was achieved by flying the aircraft at an indicated airspeed of 170 Kts and shutting down an unmodified engine for 30 minutes to allow the engine to be cold soaked. The engine was then restarted and the following recorded: (1) time to start, (2) maximum peak turbine inlet temperature reached during start up, and (3) the time for the temperature to stabilise following ignition. This procedure was then repeated with the modified engine. The test was conducted at altitudes of 30,000, 20,000, 10,000 and 500 feet.

- b. A test requiring the aircraft to be flown at maximum speed at altitudes of 30,000, 20,000, 10,000 and 500 feet and reducing power on engines number 2 and 3 (standard and modified) as rapidly as possible to check for possible lean extinction.
- c. Tests including aircraft stalls, negative and positive accelerations, full reverse power operation, and general rough handling.
- d. A ground test requiring the aircraft to pass through the aircraft washing facility ("bird bath") with all engines operating.

8.2 Results and Discussion

Observations from the ground and from the chase aircraft confirmed a significant smoke reduction. Photographic recordings (Figure 24) show a very faint smoke emission from the modified engine but this is minimal compared with the large trails that can be seen from the three standard engines. The poor definition in the photograph is due to the heavy rain that persisted throughout the tests.

These tests showed that:

- a. for all tests the modified engine performed within the allowable limits in the flight manual specifications and;
- b. the modified engine showed no tendency to flame out during extreme in-flight manoeuvres and operation in the aircraft washing facility.

At the conclusion of the flight tests the RAAF accepted the modified engine for normal squadron operation without restrictions or further testing apart from routine maintenance. At the time of writing this report the engine had completed 250 hours on-wing. Boroscope examination showed that carbon build-up within the combustor was still very light compared to standard systems.

9. FUTURE WORK

9.1 Flight Trials

The current aim is to have a RAAF P-3C Orion fitted with four modified engines within the next 12 months. Trials with additional engines will proceed as engines become available for overhaul. The next modified engine flight trials are scheduled to commence in October 1989 when a P-3C will be fitted with two modified engines. These trials will be similar to the single engine trials. The modification will also be tested for performance on a Series II, (T56-A-7B) engine before the end of 1989. Complete fleet conversion will occur over a period of several years as engines become available following normal scheduled overhaul.

9.2 Burner Outlet Temperature Surveys

There are quantitative data indicating that the ARL modification has improved the temperature distribution at the burner outlet and decreased the metal temperature of the liner. Additional tests to gather further data to support this conclusion have commenced. The test program comprises:

- a. A series of tests to determine the combustor outlet temperature pattern factor for both a standard and modified combustor in the ARL test rig. This will be carried out using a thermocouple rake that will traverse the outlet of the combustor in small increments at various operating conditions allowing 300 individual temperature data points. The conditions will include take-off, maximum continuous power and normal cruise.
- b. Liner surface temperature surveys using attached thermocouples and temperature sensitive paints for both the standard and modified liners, to determine changes in metal temperature caused by the liner modification,
- c. A series of tests to accurately determine the relight and flame-out characteristics for both the standard and modified liner, and,
- d. A series of trials to determine burner outlet temperature profiles on a ground run engine with both standard and modified liners.

10 CONCLUSIONS

It has been demonstrated that the ARL developed low smoke modification for the Allison T56 Series III engine reduces smoke emissions from the engine by 80% at low altitude cruise power settings and about 70% at high power settings. The modification at the same time reduces the specific fuel consumption by about 1% at the cruise condition. Flight and endurance trials have not revealed any impairment of behaviour or durability of the modified engine; on the contrary, the modification appears to have increased the durability of the hot end components. The present evidence for this is the absence of liner cracking and a marked reduction in carbon build-up. On-wing durability testing now in progress will provide further data on this conclusion. The engine is easier to start, has lower peak start up temperatures and emits no smoke during start up. The engine is also less smelly due to the reduction of unburnt hydrocarbon emissions. There has been no penalty to be traded for these benefits.

The modified engine has now been released for service on the RAAF's P-3C Orion aircraft A9-661 without any restrictions or further testing and, at the time of publication, the aircraft was operating in normal squadron service. During 250 hours of normal squadron operation, boroscope examination has revealed no cracking and only a very light build-up of carbon confined to small areas, unlike the standard combustor which tends to have large areas covered in carbon with some areas of heavy carbon build-up.

ACKNOWLEDGEMENTS

The work described in this report relied on the cooperation and expertise of the staff of many organisations. In particular the following are thanked by the authors:

Dr. W.H. Schofield, Chief, Flight Mechanics and Propulsion Division, ARL for advice, encouragement and enthusiasm throughout the entire program.

Mr. J.L. Kepert, Structures Division, ARL, for his assistance in gaining access to T56 combustion system components.

Staff of the Combustion Group (now Aerothermodynamics and Combustion Group) ARL, and in particular Mr. G.F. Pearce and Mr. N.J. Repacholi for assistance and guidance during rig tests and Mr. G.L. Collins and Mr. L. Dubay for the test rig construction.

Mr. N. Root, ARL for the design of the water tunnel and, in particular, the novel idea of using a combustor liner with Mylar windows as the basis for the tunnel.

Mr. P. O'Connor, ARL for developing the technique to modify the combustor liners without dismantling the sheet metal.

492SQN, and in particular FLGOFF M. Graham, FLTSGT R. Willett and staff, at the RAAF base Edinburgh for cooperation and assistance during engine tests.

36SQN at Richmond RAAF Base for cooperation during engine tests.

Dr. J. Perry and staff for advice and cooperation at Swinburne Institute of Technology during the water tunnel tests,

Staff of the AIRENG2 Office at Support Command for advice and cooperation throughout the program.

Mr. D. Parslow, ARL and SGT. C. Buley, RAAF, for assistance and expertise during the modified engine trials.

The crew of P-3C A9-661 under WGCDR Jim Brown for expertise during flight trials.

Mr John King, Powerplant Engineer at Qantas Jet Base, Sydney for organisation of engine tests at the base and Mr Ron Bennett for the professional manner in which they were conducted.

REFERENCES

- Adkins, R.C. and Gueroui, D. 1986: 'An Improved Method for Accurate Prediction of Mass Flows Through Combustor Liner Holes'. J. of Eng. For Gas Turbines and Power. Vol. 108, 491-497.
- Champagne, D.L. 1971: 'Standard Measurement of Aircraft Gas Turbine Engine Smoke'. ASME Paper 71-GT-88.
- Environment Protection Agency. 1973: 'Control of Air Pollution From Aircraft Engines'. US Federal Register, Vol. 30, No. 136, Pt. 2, 13088-19103.
- Knight, H.A. and Walker, R.B. 1953: 'The Component Pressure Losses in Combustion Chambers.' NGTE. R. 143..
- Matterson, L.A. et al. 1980: 'Photographic Smoke Analysis of the T56 Engine.' Air Force Eng. Service Centre. ESL-TR-81-05.
- Royal Australian Air Force. 1989: Special Technical Instruction STI Orion 269, and AIR2/4080/ET56/44-2/3 (55) of 25 May 1989.
- Royal Australian Air Force. 1989: Technical Instruction 1045.
- Royal Australian air Force. 1983: P-3C Flight Manual, P-3C Orion. Defence Instruction (Air Force), AAP 7215.004-1.
- Skidmore, F.W. 1985: 'The Problem of Smoke in Allison T56-A-14 Engines.' ARL Aero-Prop-TM-425.
- Skidmore, F.W. 1986: 'Smoke Emission Tests on Series II and Series III Allison T56 Turboprop Engines.' ARL Aero-Prop-TM-438.
- Society of Automotive Engineers. 1980: 'Procedure for Continuous Sampling of Gaseous Emissions from Aircraft Gas Turbines.' ARP 1256A.
- Society of Automotive Engineers. 1980: 'Aircraft Engine Exhaust Smoke Measurement.' ARP 1179A.
- Souza, A.F. and Daley, P.S. 1978: 'U.S. Air Force Engine Emissions. Vol. 2. Individual Test Reports.' Scott Environmental Tech. Inc. 1492-50-0877.
- Vaught, J.M. et al. 1971: 'Final Technical Report. Collection and Assessment of Hydrocarbon Emission Data. Turbo Prop Engines (T56). Detroit Diesel Allison. EDR 7200.

APPENDIX 1
ANALYSIS OF FUEL SAMPLES

MATERIALS TESTING LABORATORIES - NSW

EXAMINATION OF AVIATION FUEL

RESULTS OF EXAMINATION:

Schedule A to:
Laboratory Report 89/201
Samples Nos. 89/545 to 552
File FL/REP/DEF

TEST	METHOD (IP/ASTM)	SPECIFICATION	RESULTS			
			S89/545	S89/546	S89/547	S89/548
Appearance	Visual	Clear, bright and free from sediment, suspended matter and undissolved water.	Trace of sediment present. (1.0)-1.25	Conforms (0.75)-1.0	Trace of sediment present. (0.75)-1.0	Trace of sediment present. (0.75)-1.0
Colour (Lovibond)	178/-	4 Maximum				
Distillation	123/D86					
Initial Boiling Point	OC	Report	150.0	146.5	149.0	148.5
20% Vol Recovered at	OC	200 Maximum	170.5	170.0	173.0	172.0
50% Vol Recovered at	OC	Report	187.5	187.0	190.0	188.5
90% Vol Recovered at	OC	Report	221.0	222.5	225.0	223.0
Final Boiling Point	OC	300 Maximum	259.0	250.5	253.5	250.5
Residue	% vol	1.5 Maximum	1.5	1.5	1.5	1.0
Loss	% vol	1.5 Maximum	1.5	1.0	1.0	1.0
Density at 15 OC	kg/L	0.775 to 0.830	0.7894	0.7912	0.7909	0.7906
Flash Point (Abel)	OC	38 Minimum	43.5	42.5	41.5	41.0
Copper Corrosion (Bomb, 2h at 100OC)	170/-					
Classification	154/D130					
mg/100 mL						
Existent Gum	131/D381	1 Maximum	1a	1a	1a	1a
Water Reaction	289/D1094	7 Maximum	8	1	5	<1
Interface Rating						
Separation Rating						
Aromatics						
% vol	156/D1319	1b Maximum	1b	1b	1b	1b
% vol	156/D1319	2 Maximum	2	2	2	2
Hydrogen Content		22 Maximum	15.0	16.8	16.1	15.7
% mass	338/D3701	5 Maximum	1.3	0.8	1.2	1.2
Smoke Point	mm	To be reported	14.09	14.06	14.04	14.04
Aniline Point	OC	20 Minimum	27	27	26	26
Gravity, OAPI	160/D1298	To be reported	61.70	60.70	61.10	61.40
Aniline Gravity, Product	2 & 57	To be reported	47.7	47.3	47.3	47.4
	D611 & 1298	4 800 Minimum	6.824	6.682	6.716	6.755

The latest edition of the test methods was used unless otherwise stated.

SAMPLE S89/545 WAS USED ON THE STANDARD ENGINE
SAMPLE S89/546 WAS USED ON THE MODIFIED ENGINE

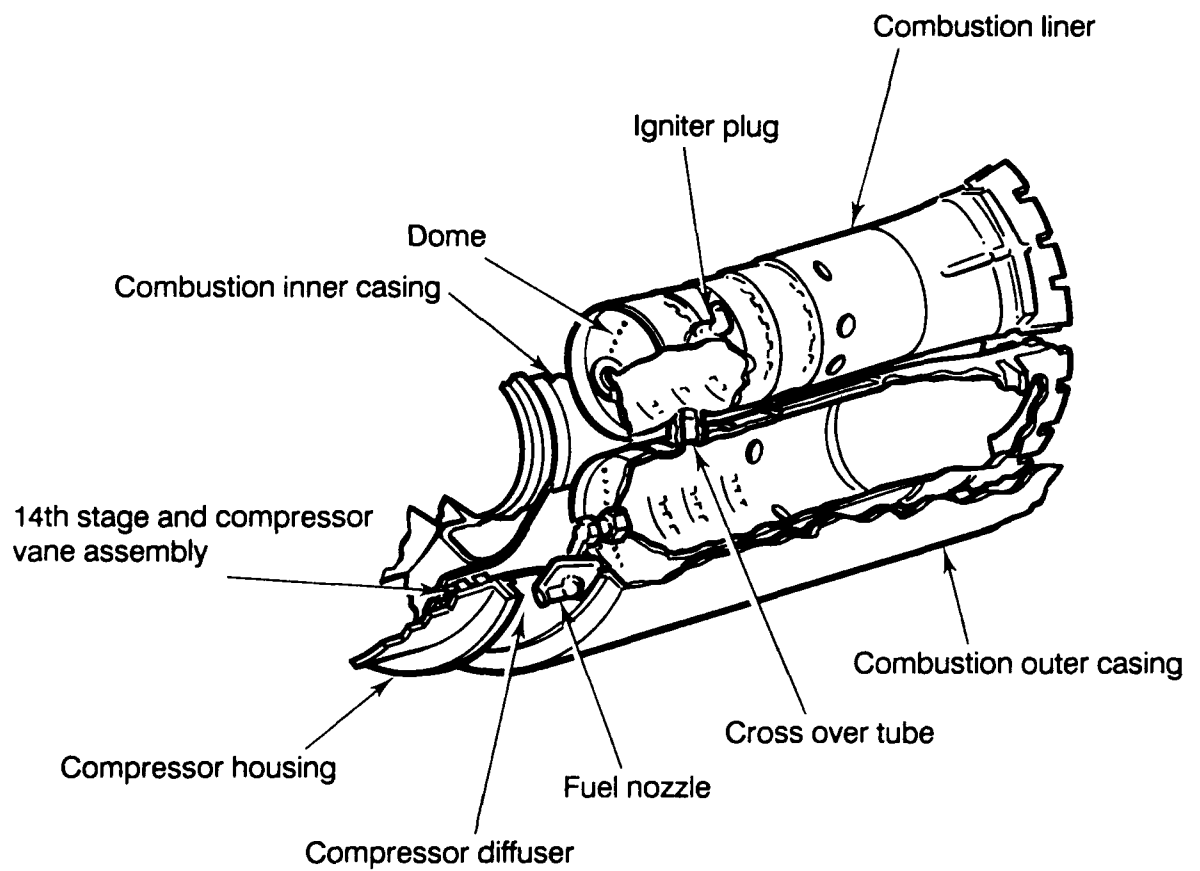
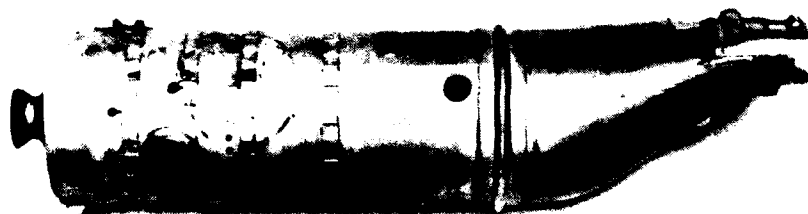


FIG. 1 ALLISON T56 COMBUSTION CHAMBER DETAILS

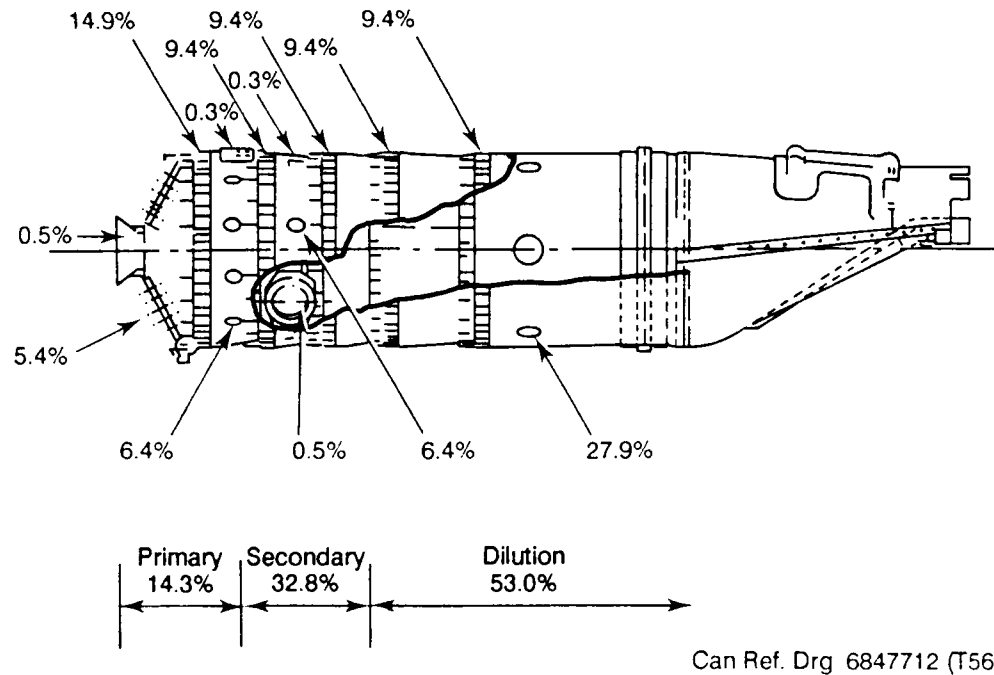


ALLISON T56 SERIES II COMBUSTOR LINER

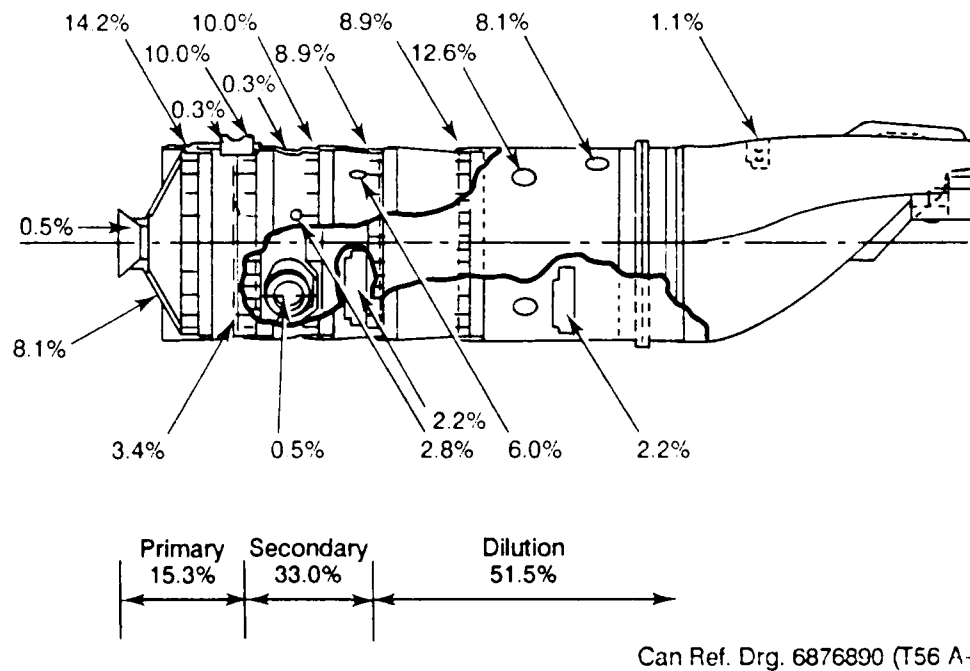


ALLISON T56 SERIES III COMBUSTOR LINER

FIG. 2 ALLISON T56 COMBUSTOR LINERS



AIRFLOW DISTRIBUTION OF T56 SERIES II COMBUSTION LINER



AIRFLOW DISTRIBUTION OF T56 SERIES III COMBUSTOR LINER

FIG. 3 AIRFLOW DISTRIBUTION OF ALLISON COMBUSTOR LINERS

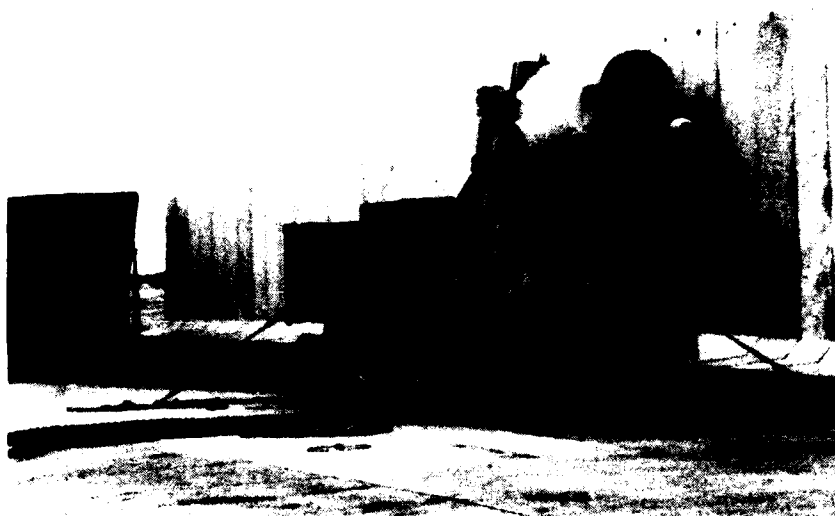


FIG. 4 T56-A-14 ENGINE MOUNTED ON A MOBILE ENGINE TEST STAND

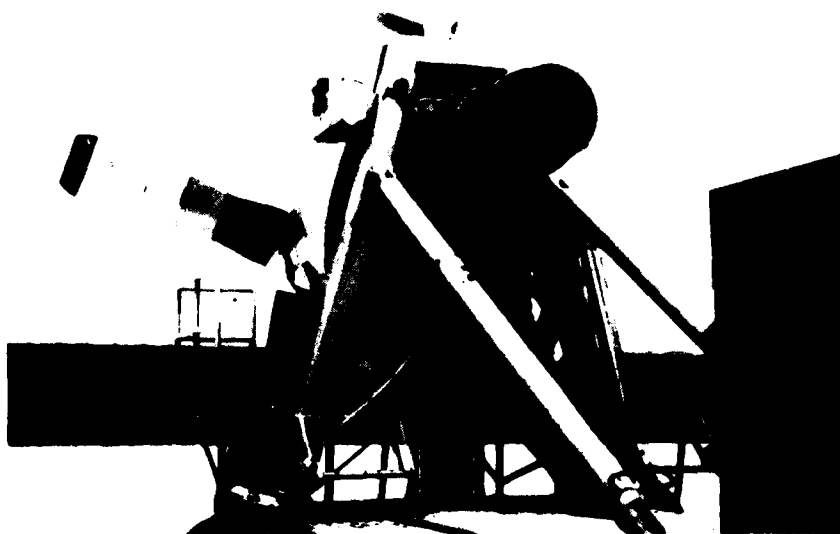


FIG. 5 SMOKE SAMPLING PROBE MOUNTED ON T56-A-14 EXHAUST NOZZLE

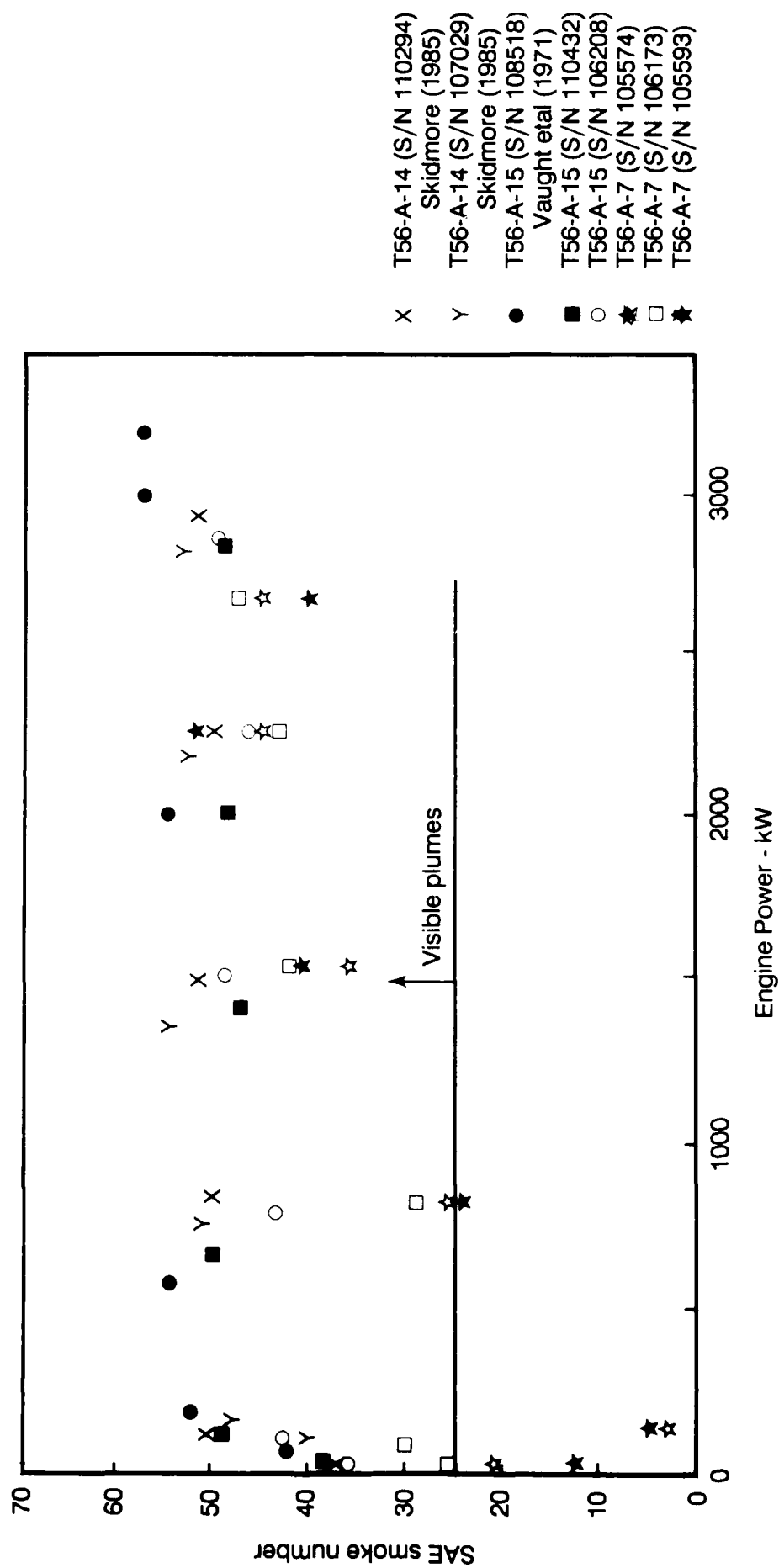


FIG. 6 SMOKE NUMBER VERSUS POWER - T56 ENGINES

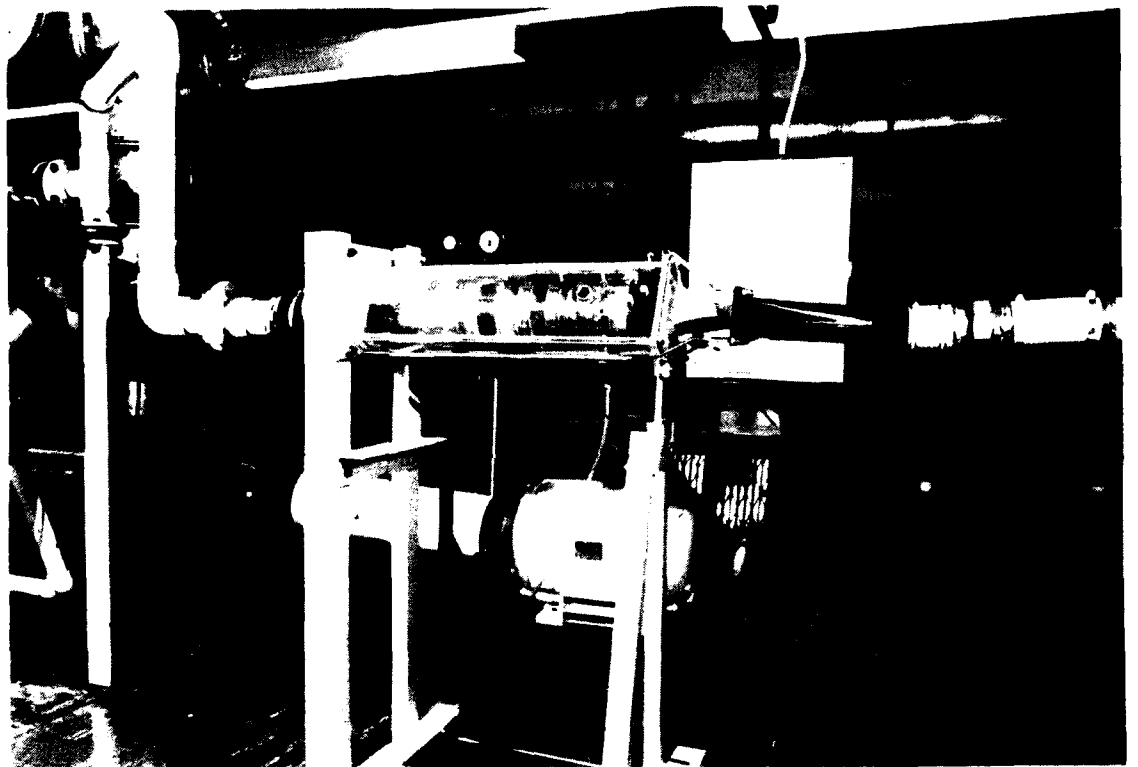


FIG. 7 T56 WATER TUNNEL

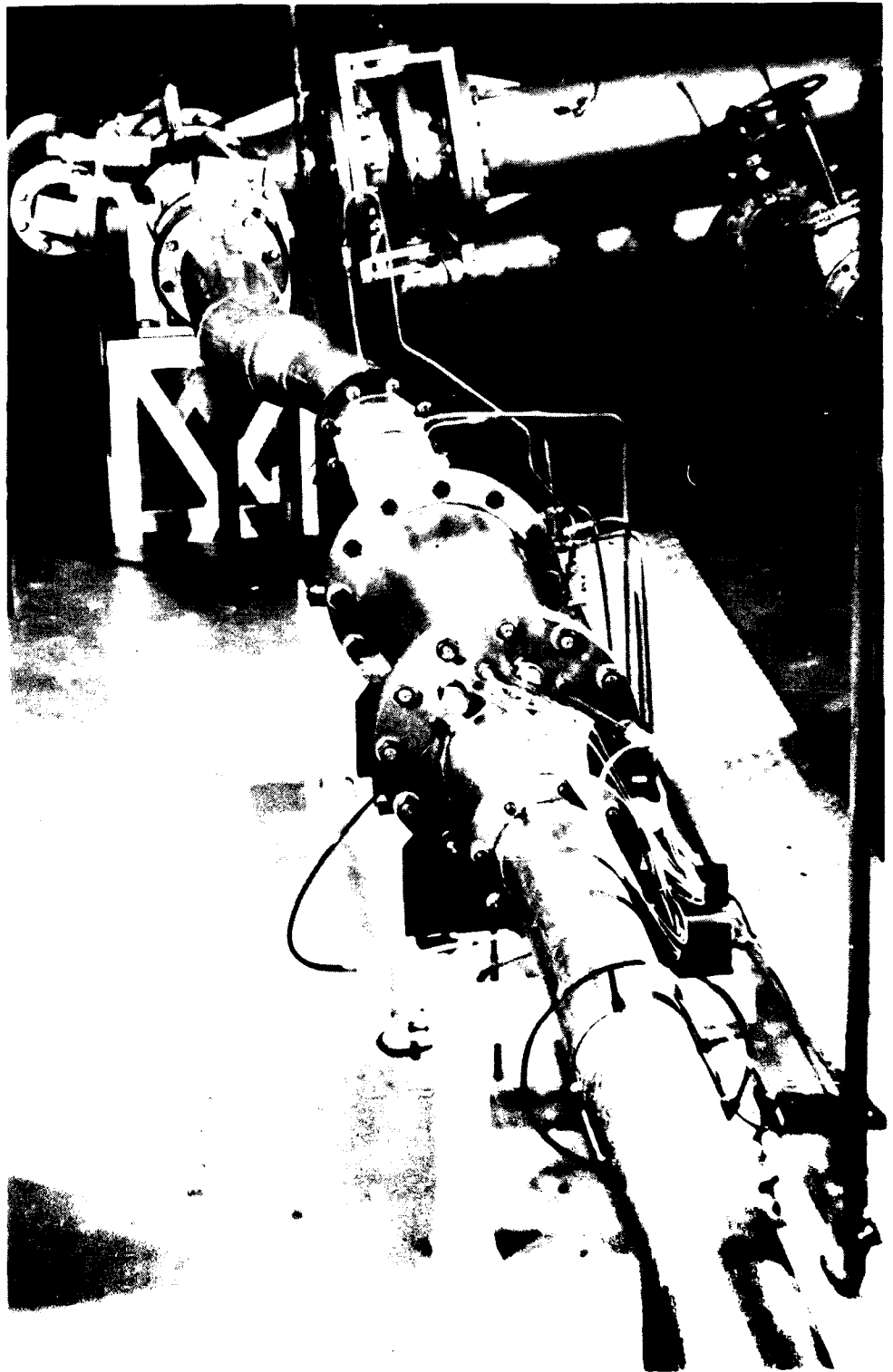


FIG. 8 T56 COMBUSTION TEST RIG

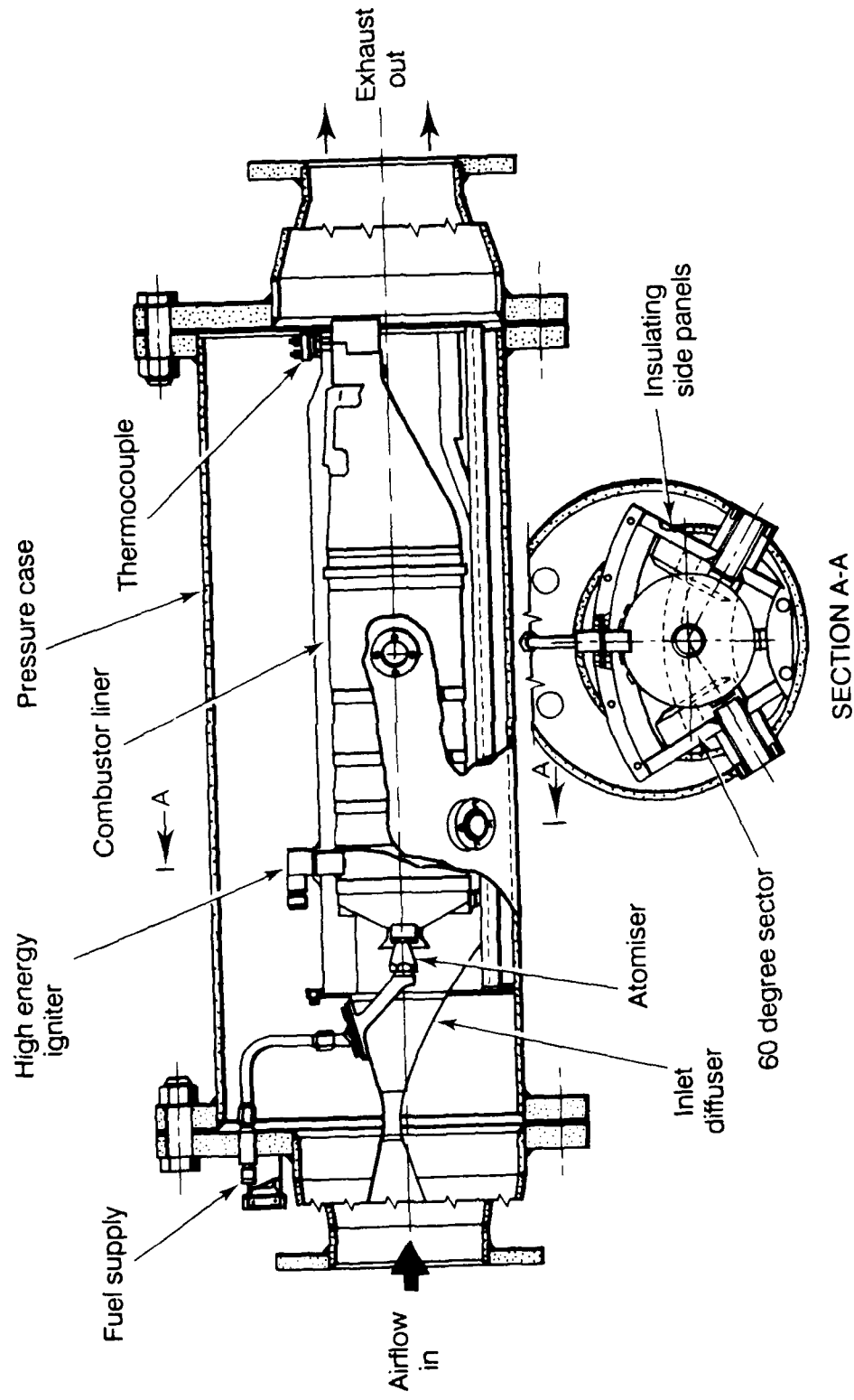


FIG. 9 SCHEMATIC OF T56 COMBUSTION TEST RIG

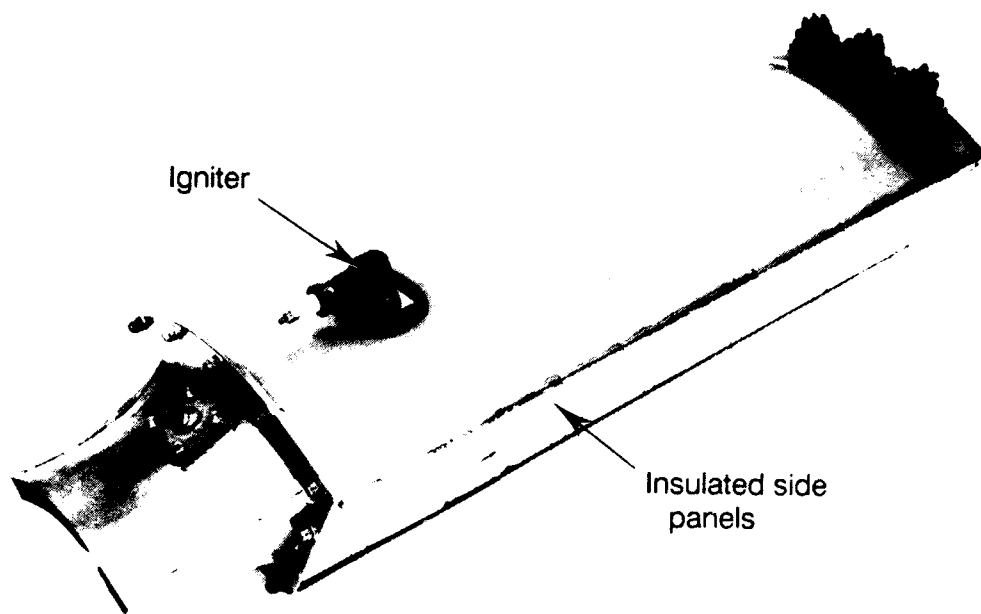


FIG. 10 T56 60 DEGREE SECTOR

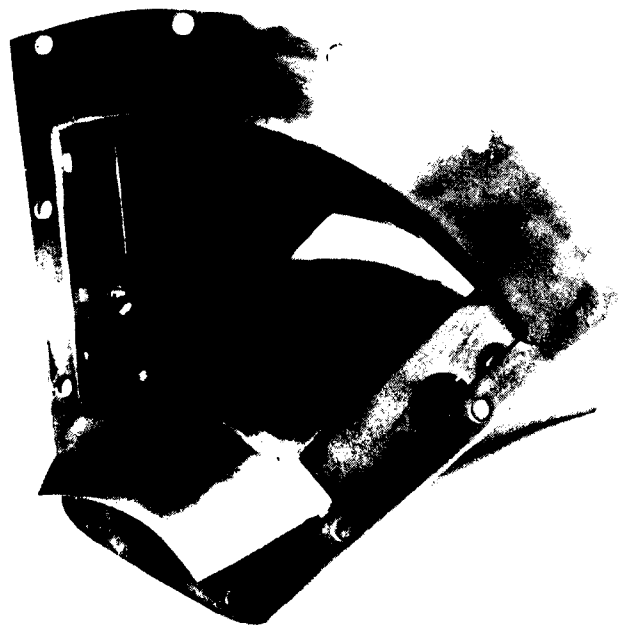
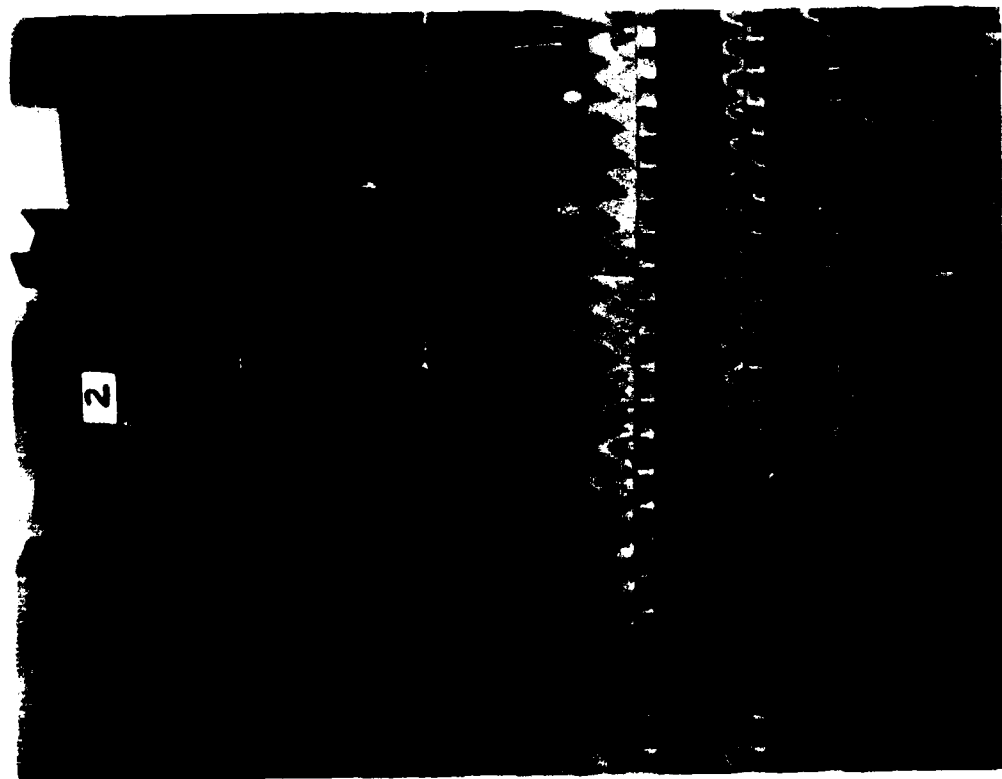
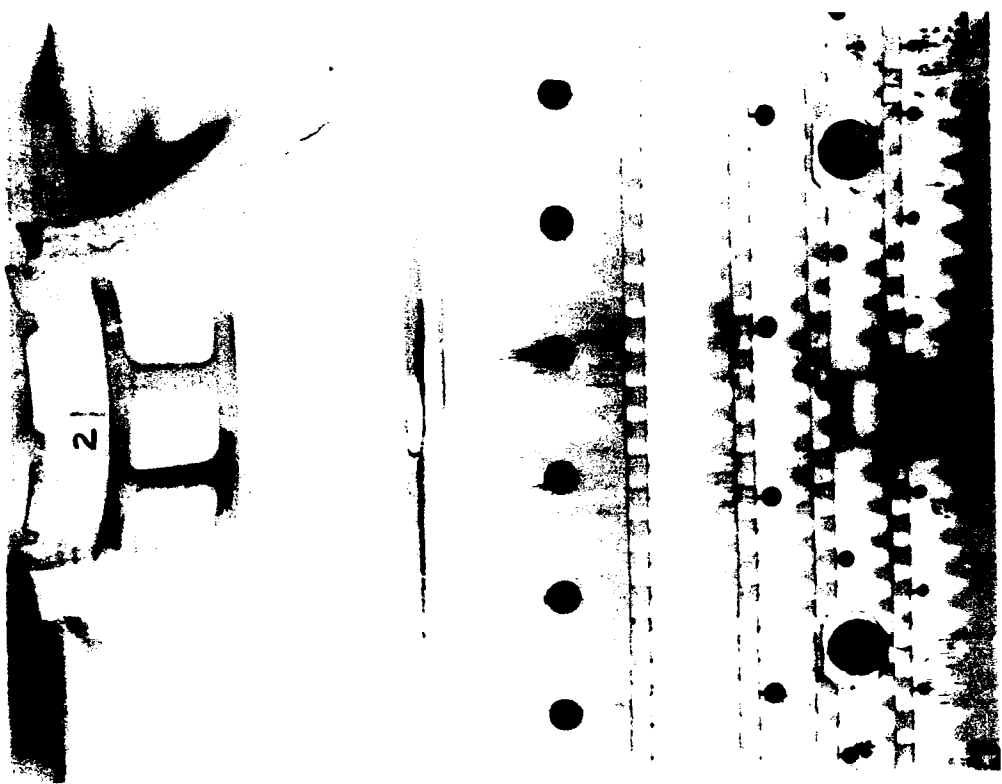


FIG. 11 T56 RIG INLET DIFFUSER



T56 FLAME TUBE
natural heat discolouration



SAME FLAME TUBE
with temperature indicating paint

FIG. 12 PERIPHERAL CAMERA RESULTS

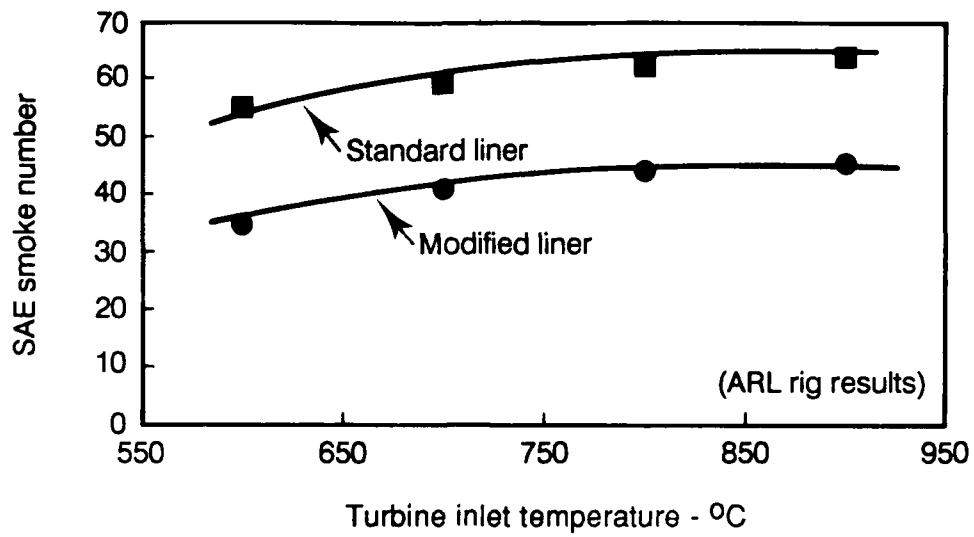


FIG. 13 SAE SMOKE NUMBER VS TURBINE INLET TEMPERATURE

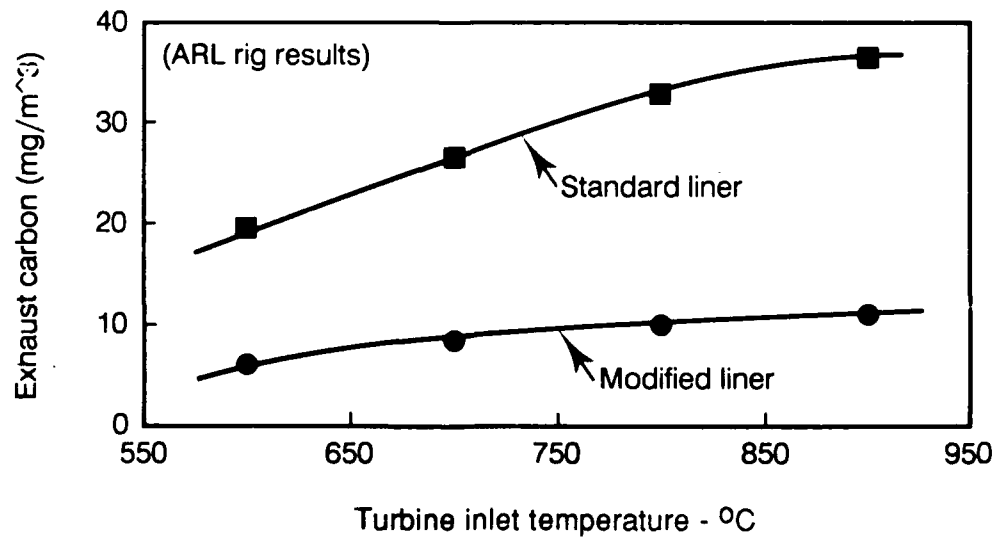


FIG. 14 EXHAUST CARBON VS TURBINE INLET TEMPERATURE

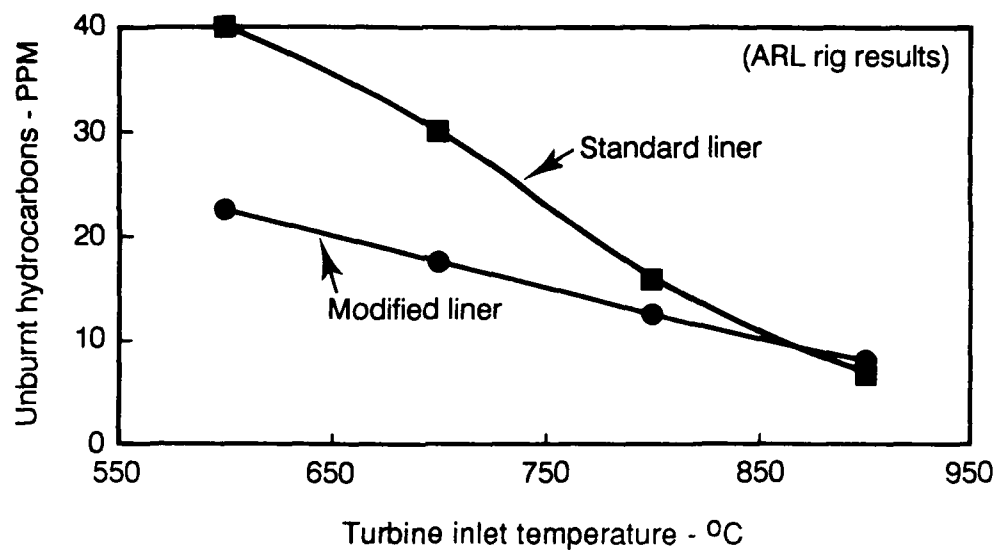


FIG. 15 UNBURNT HYDROCARBONS VS TURBINE INLET TEMPERATURE

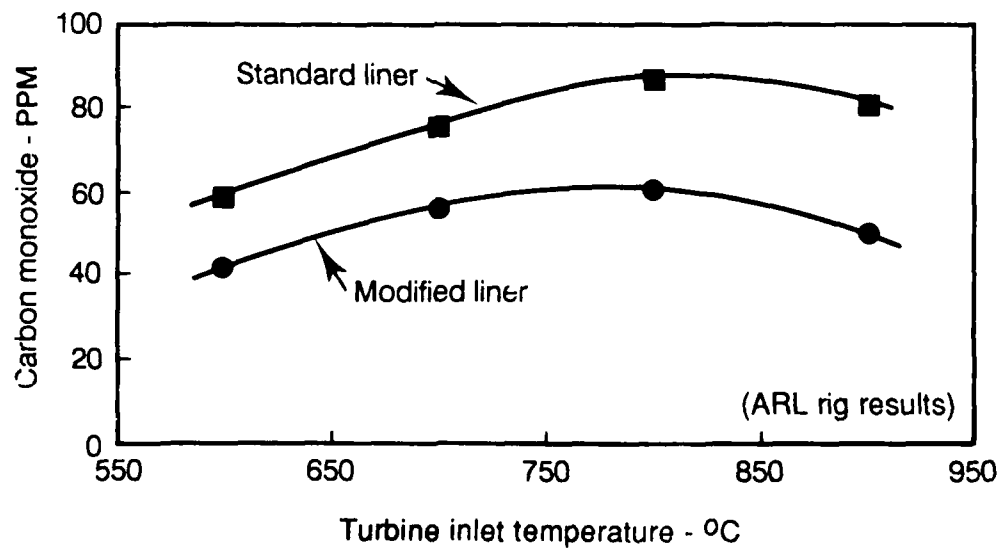


FIG. 16 CARBON MONOXIDE VS TURBINE INLET TEMPERATURE

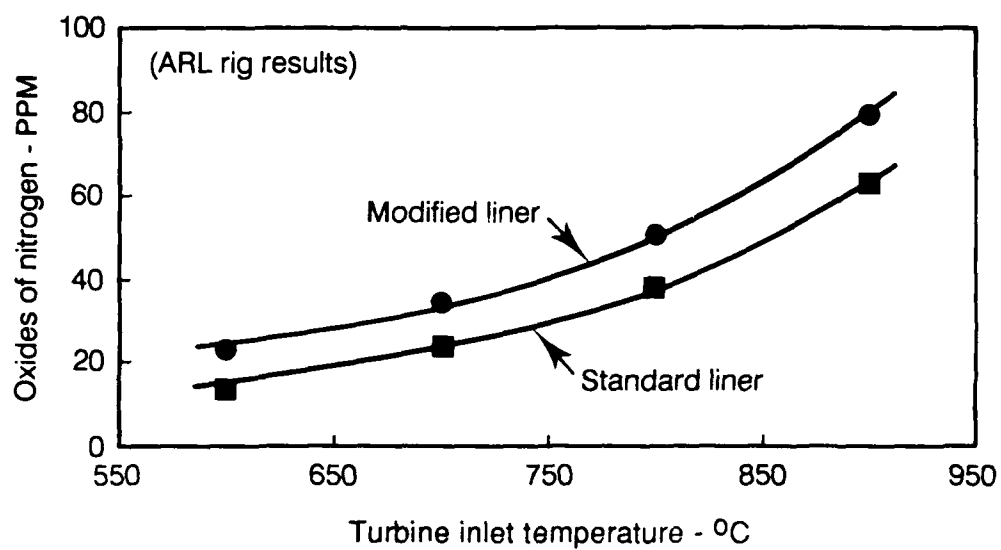


FIG. 17 OXIDES OF NITROGEN VS TURBINE INLET TEMPERATURE

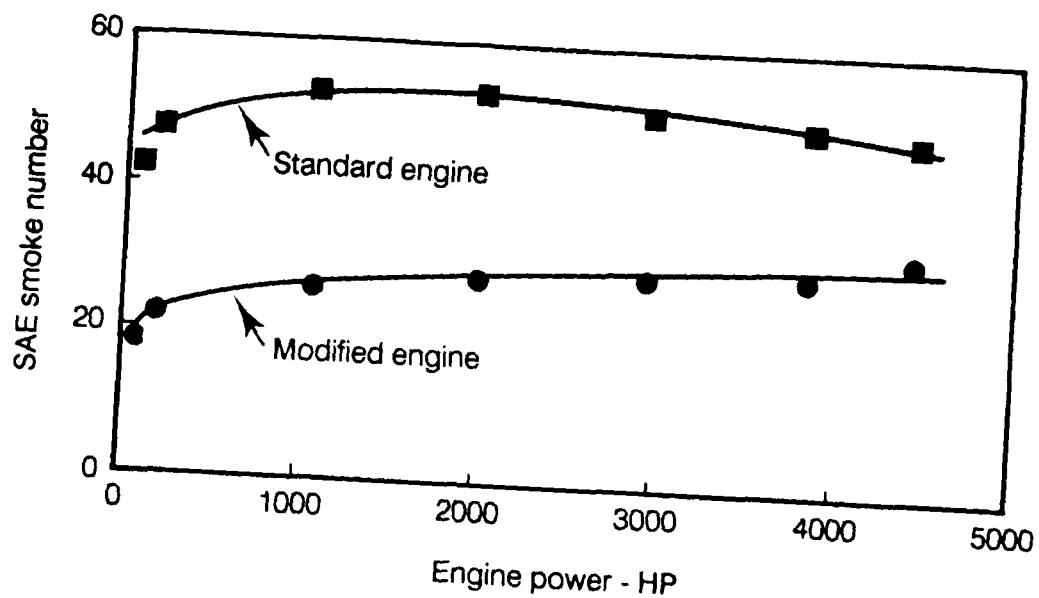


FIG. 18 SAE SMOKE NUMBER VS ENGINE POWER

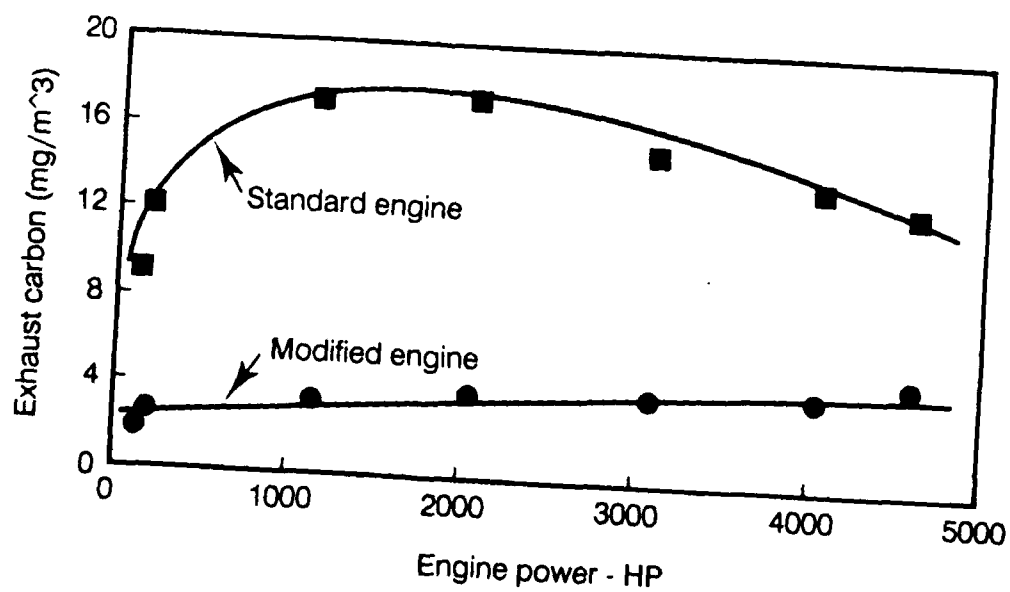


FIG. 19 EXHAUST CARBON VS ENGINE POWER

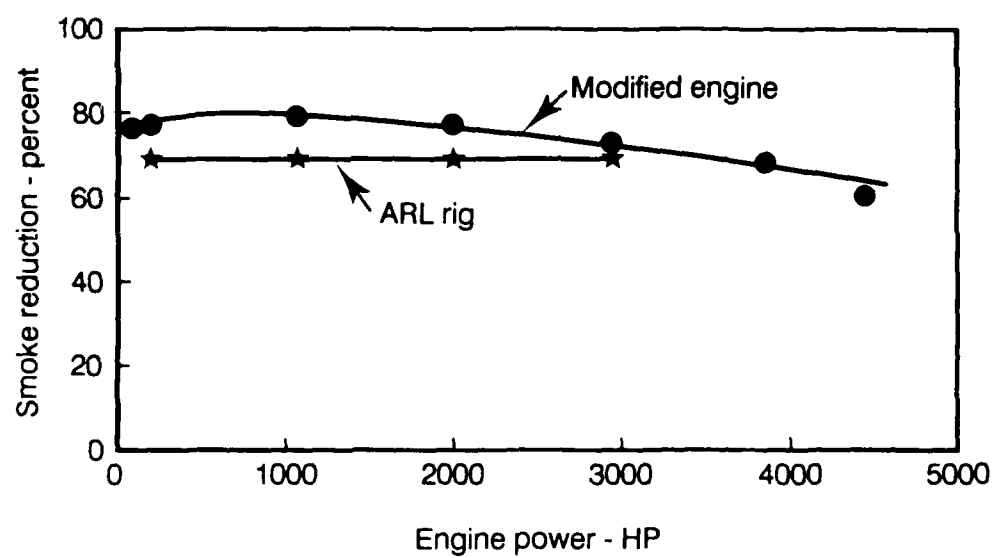


FIG. 20 SMOKE REDUCTION VS ENGINE POWER(ENGINE AND ARL RIG)

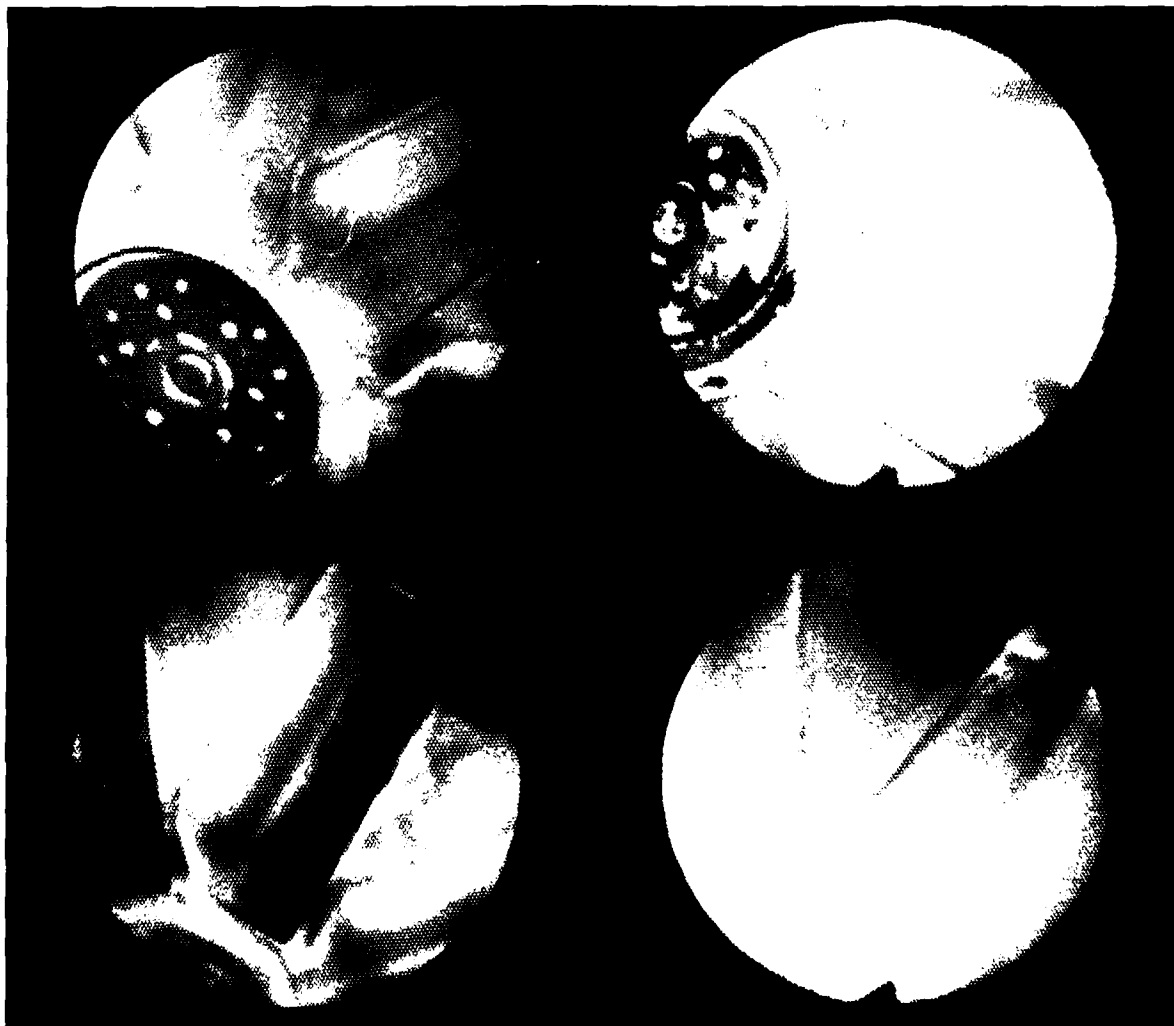


FIG. 21 BOROSCOPE PHOTOGRAPHS OF CARBON BUILD UP IN
STANDARD (LEFT) AND MODIFIED LINER (RIGHT)

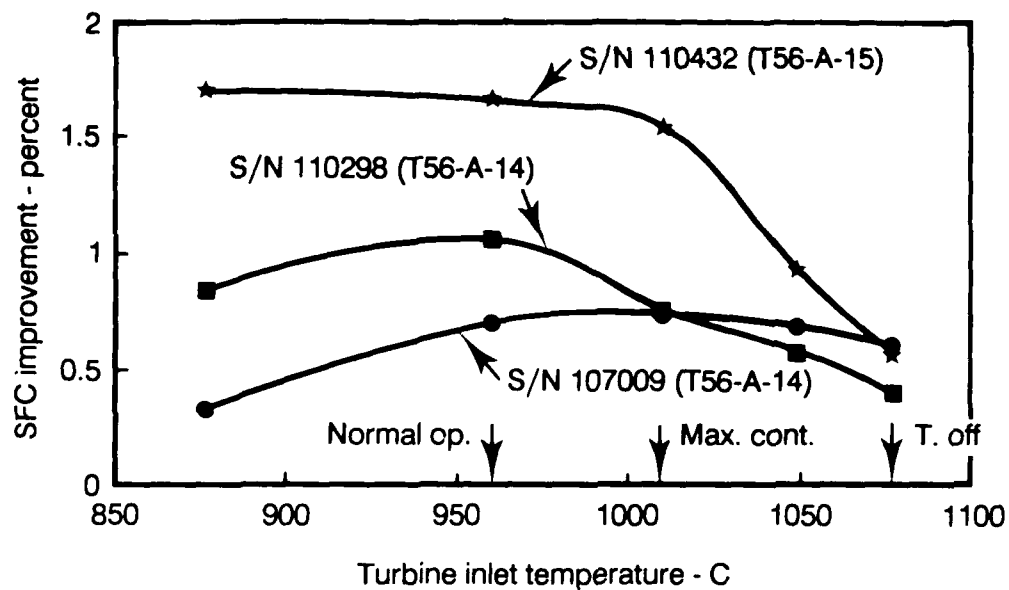


FIG. 22 SPECIFIC FUEL CONSUMPTION IMPROVEMENT

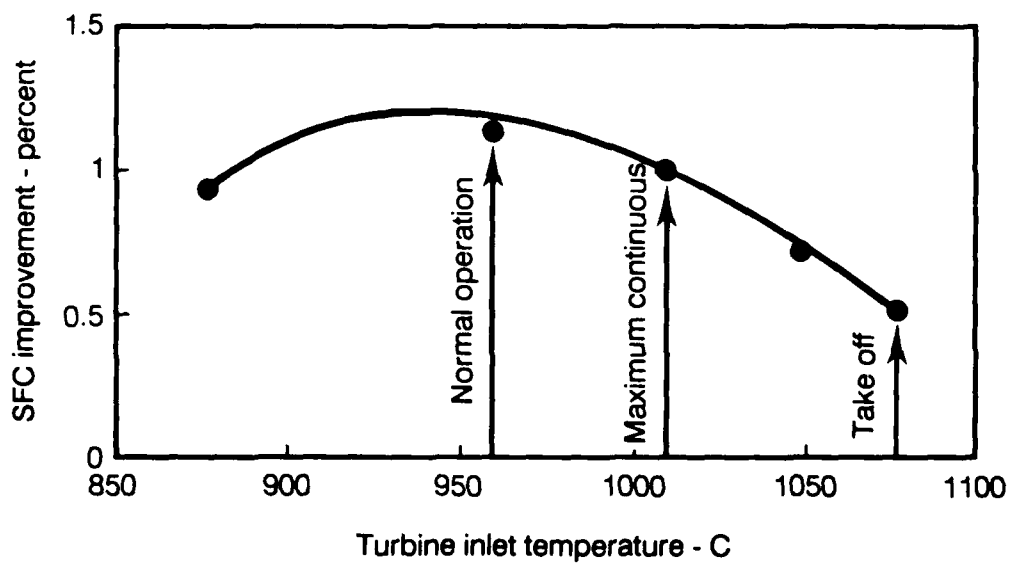


FIG. 23 SPECIFIC FUEL CONSUMPTION IMPROVEMENT (AVERAGE OF THREE ENGINES)



FIG. 24 P-3C ORION AIRCRAFT A9-661 WITH MODIFIED ENGINE FITTED TO
NUMBER 3 POSITION

DISTRIBUTION

AUSTRALIA

Department of Defence

Defence Central

Chief Defence Scientist
AS, Science Corporate Management (shared copy)
FAS, Science Policy (shared copy)
Director, Departmental Publications
Counsellor, Defence Science, London (Doc Data Sheet Only)
Counsellor, Defence Science, Washington (Doc Data Sheet Only)
SA to the Thailand Military R and D Centre (Doc Data Sheet Only)
OIC TRS, Defence Central Library
Document Exchange Centre, DISB (18 copies)
Librarian H Block, Victoria Barracks, Melbourne
Director General - Army Development (NSO) (4 copies)
Defence Industry and Materiel Policy, FAS

Aeronautical Research Laboratory

Director
Library
Chief Flight Mechanics and Propulsion Division
Head Propulsion Branch
Branch File Propulsion
Authors:
 F.W. Skidmore
 P.N. Doogood
 D.R. Hunt (RAAF)
D.E. Glenny
L.W. Hillen
S.M. Henbest
G.F. Pearce
J.L. Fowler
N.J. Repacholi
D.R. Parslow
P.A. O'Connor

Materials Research Laboratory

Director/Library

Defence Science & Technology Organisation - Salisbury

Library

ERL

Electronic Warfare Division
 J. Gardner
 S.S. Ti
 R. Oermann

WSRL

Maritime Systems Division (Sydney)

Navy Office

Navy Scientific Adviser (3 copies Doc Data sheet)
Aircraft Maintenance and Flight Trials Unit
RAN Tactical School, Library
Director Naval Engineering Requirements - Aviations Systems
Director Aircraft Systems Engineering - Navy
Director of Naval Air Warfare

Army Office

Scientific Adviser - Army (Doc Data sheet only)
Engineering Development Establishment Library

Air Force Office

Air Force Scientific Adviser
Aircraft Research and Development Unit
Scientific Flight Group
Library
Engineering Branch Library
Director General Engineering - Air Force
Director General Air Warfare Plans & Policy
AHQ (SMAINTSO)
HQ Logistics Command
SLENGO
AIRENG 2
RAAF BASE EDINBURGH
Officer Commanding
CO 492 Squadron
CO 292 Squadron
RAAF BASE RICHMOND
Officer Commanding
CO 486 Squadron

Statutory and State Authorities and Industry

Aero-Space Technologies Australia, Manager/Librarian (2 copies)
Ansett Airlines of Australia, Library
Australian Airlines, Library
Qantas Airways Limited
Library
Senior Power Plant Engineer
J. King
C. Pemberton
R. Bennett
Civil Aviation Authority
SEC of Vic., Herman Research Laboratory, Library

Universities and Colleges

Swinburne
Library
Dr J.H. Perry

CANADA

International Civil Aviation Organization, Library
National Defence Headquarters
Capt R. La Grandeur
NRC
Aeronautical & Mechanical Engineering Library (2 copies)
Division of Mechanical Engineering Library (2 copies)
Gas Dynamics Laboratory (2 copies)

Universities and Colleges

Quebec
Laval University
Professor D. Kretchner
Professor J. Odgers

FRANCE

ONERA Library

INDIA

Defence Ministry, Aero Development Establishment Library
Gas Turbine Research Establishment, Director
Hindustan Aeronautics Ltd, Library
National Aeronautical Laboratory, Information Centre

ISRAEL

Technion-Israel Institute of Technology
Professor J. Singer
Israel Airforce HQ
Z. Moshe
B. Schatz

JAPAN

National Aerospace Laboratory
Institute of Space and Astronautical Science, Library

NETHERLANDS

RNLN
Lt H. Vanderkloster
Lt R. Dorsman
National Aerospace Laboratory (NLR), Library

NEW ZEALAND

Defence Scientific Establishment, Library
RNZAF
Sqndr P. Guy
WO O. Cuncliff
Transport Ministry, Airworthiness Branch, Library

Universities

Canterbury
Library

SINGAPORE

Director, Defence Materials Organisation

SWEDEN

Aeronautical Research Institute, Library
Swedish National Defense Research Institute (FOA)

SWITZERLAND

F + W (Swiss Federal Aircraft Factory)

UNITED KINGDOM

Ministry of Defence, Research, Materials and Collaboration
Mr D. Burgham

RAF

Sqnldr. H. Villingray
CAARC, Secretary

Royal Aircraft Establishment
Bedford, Library

Pyestock, Director
Commonwealth Air Transport Council Secretariat

National Industrial Fuel Efficiency Service, Chief Engineer
National Physical Laboratory, Library
National Engineering Laboratory, Library
British Library, Document Supply Centre
Aircraft Research Association, Library
Ruston Gas Turbines Ltd, Technical Director

UNITED STATES OF AMERICA

NASA Scientific and Technical Information Facility

USN

Commander Patrol Wing Pacific Fleet (RADM J.J.Hernandez)
COMNAVAIRPAC Code 722 (CDR M. Graves)
COMNAVAIRLANT
Science Adviser (S. Boyd)

Naval Air Systems Command

S. Bazaro
D. Peckham
Eng Class Desk

USAF

Pentagon
A. Olsen LEY
Col P. Thompson LEYY
Action Officer LEYYC

Kelly AFB
A. Elsasser MMPCRE
D. Owen MMPI

Lockheed-California Company

Lockheed Aeronautical Systems Company

Allison Gas Turbine Division
J. Leach
L. Banks
D. Schroft
J. Dillard

Naval Air Test Centre
R.M. Chubb

Naval Air Propulsion Centre
H Chun

Naval Aviation Depot
A. Rivera
F. Ho
A. Follett

SPARES (100 COPIES)

TOTAL (249 COPIES)

DOCUMENT CONTROL DATA

PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

1a. AR NUMBER AR-006-055	1b. ESTABLISHMENT NUMBER ARL-PROP-R-182	2. DOCUMENT DATE MARCH 1990	3. TASK NUMBER AIR88/056
4. TITLE THE REDUCTION OF SMOKE EMISSIONS FROM ALLISON T56 ENGINES		5. SECURITY CLASSIFICATION (PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF. (C) RESTRICTED (R), UNCLASSIFIED (U)). U U U DOCUMENT TITLE ABSTRACT	6. NO. PAGES 34 7. NO. REFS. 14
8. AUTHOR(S) F.W. Skidmore D.R. Hunt (RAAF) P.N. Doogood		9. DOWNGRADING/DELIMITING INSTRUCTIONS Not applicable	
10. CORPORATE AUTHOR AND ADDRESS AERONAUTICAL RESEARCH LABORATORY P.O. BOX 4331, MELBOURNE VIC 3001		11. OFFICE/POSITION RESPONSIBLE FOR: RAAF SPONSOR _____ SECURITY _____ DOWNGRADING _____ APPROVAL _____ DART	
12. SECONDARY DISTRIBUTION (OF THIS DOCUMENT) APPROVED FOR PUBLIC RELEASE OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH ASIDS, DEFENCE INFORMATION SERVICES BRANCH, DEPARTMENT OF DEFENCE, CAMPBELL PARK, ACT 2601			
13a. THIS DOCUMENT MAY BE ANNOUNCED IN CATALOGUES AND AWARENESS SERVICES AVAILABLE TO NO LIMITATIONS			
13b. CITATION FOR OTHER PURPOSES (IF CASUAL ANNOUNCEMENT) MAY BE: X UNRESTRICTED OR AS FOR 13a			
14. DESCRIPTORS Smoke abatement P-3C aircraft Combustion products Exhaust emissions. Allison engines			15. DRDA SUBJECT CATEGORIES 0081D
16. ABSTRACT Aeronautical Research Laboratory (ARL) has been working to reduce smoke emissions from the Allison T56 engines used in the Lockheed P-3C Orion aircraft operated by the Royal Australian Air Force (RAAF). The work consisted of a literature survey, design and manufacture of a water tunnel model, water tunnel testing of various modifications to improve the fluid dynamics of the combustion system, testing the modifications in a single liner combustion test rig, smoke emission comparative tests in ground run engine trials, performance tests in a calibrated test cell and flight trials of a modified engine. The modification that was developed in this program was found to significantly reduce smoke emissions and give substantial improvements in the specific fuel consumption of the engine. In addition, there were indications, in line with theoretical predictions, that the modification would extend the life of the hot end components of the engine.			

PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

THIS PAGE IS TO BE USED TO RECORD INFORMATION WHICH IS REQUIRED BY THE ESTABLISHMENT FOR ITS OWN USE BUT WHICH WILL NOT BE ADDED TO THE DISTIS DATA UNLESS SPECIFICALLY REQUESTED.

16. ABSTRACT (CONT).

This report describes the work up to August 1989 and outlines the final program on burner outlet surveys that will complete the program.

17. IMPRINT

AERONAUTICAL RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER

Flight Mechanics and
Propulsion Report 182

19. COST CODE

424030

20. TYPE OR REPORT AND PERIOD COVERED

21. COMPUTER PROGRAMS USED

22. ESTABLISHMENT FILE REF(S)

23. ADDITIONAL INFORMATION (AS REQUIRED)