TF41/Lamilloy® Accelerated Mission Test

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This paper describes the results of accelerated mission testing (AMT) of an Allison TF41 turbofan engine. The test was conducted to evaluate the durability characteristics of Lamilloy combustors. Lamilloy is an advanced quasitranspiration cooling material designed and fabricated by Detroit Diesel Allison (DDA). A 526-h AMT test was conducted with equal test time at DDA and Wright Patterson Air Force Base (WPAFB). This AMT generally accelerates engine distress at a rate which is estimated to simulate approximately 1000 h of service life on the Lamilloy liners. Pertinent background information on Lamilloy with regard to the TF41 combustion system, results of the DDA AMT test, details of the WPAFB AMT test, the final condition of the Lamilloy combustors, and conclusions are presented.

Introduction

OVER the past decade, increasing attention has been directed at combustor liner cooling. This attention reflects the emphasis on improving turbine engine component performance as well as the concern for durability and service life depreciation as operating temperatures are increased. Although cooling problems have traditionally focused on the high-pressure turbine, combustor liner cooling is now viewed as a technical problem of at least equal importance. If projected engine performance gains and hot section durability improvements are to be achieved, combustor cooling advancements must be addressed.

At modest burner outlet temperature (BOT) levels, experience has shown that liner cooling could be effectively achieved with film cooling from slots and louvers. In this configuration, relatively massive tangential slot flows provide adequate hot side cooling air film protection so that gas-to-wall heat flux levels can be reduced to manageable levels. This system has the inherent advantage of simplicity, and fabrication techniques are well in hand. However, the principal disadvantage of film cooling is that the heat sink potential of the cooling air (in terms of active wall cooling) is not effectively used. In addition, the cooling air represents a significant portion of the total air available to the combustor—often as much as from 50 to 60%. As burner outlet temperatures are progressively increased, cooling air requirements become increasingly intolerable.

Another factor of concern with pure film cooling is that the insulating film primarily affects the convective component of heat transfer, and has little effect on the radiative heat transfer from the highly luminous gas. This concern will become more significant with broadened specification alternative fuels usage, with their lower hydrogen and increased aromatic content. Effective control of the radiative heat transfer mechanism can be achieved only if the heat sink capability inherent in the coolant is more fully used in the active mode prior to injection as a film.

The motivation for reducing liner cooling flow is that achievable burner outlet temperature levels are severely constrained by cooling air usage, and that the tradeoff between cooling flow and dilution jet flow can significantly affect burner pattern factor. Consequently, attention must be focused on wall cooling schemes that minimize cooling air by maximizing effectiveness, thus allowing the designer greater latitude in airflow management.

Advances in metal-joining techniques over the past several years have led to the development of a multiple-laminate porous structure fabricated from diffusion-bonded, photo-etched metal sheets.[1-3] DDA has developed a porous cooling material, Lamilloy¶ (shown in Fig. 1), which provides design flexibility and heat transfer performance optimization in high-temperature combustor environments.

TF41 Lamilloy Combustor Development Background

A 1975 study of the TF41 engine hot section durability concluded that the nominal combustor exit maximum peak local temperature of 2780°F [pattern factor $(T_{max} - BOT/BOT - T_{in}) = 0.40$] contributed to premature turbine vane failure. Statistical projection of this temperature distribution indicated that maximum peak local temperatures of up to 3070°F could exist within the engine population. In order to fully assess the TF41 hot section, a group was formed which included personnel from the government and the engine manufacturers.

A combustion team was formed from this group with a goal to improve the combustor exit temperature pattern. A combustor "mod-exist" program was initiated whereby minor modifications to the existing combustion liners were to be developed to improve BOT profiles and thus reduce local peak temperatures. This was conducted under the TF41 Component Improvement Program (CIP) with the following program goals: maximum peak local temperature of 2600°F (pattern factor of 0.26 or less); radial profile peak ratio of 1.05 with the peak occurring between 65 and 75% turbine span; preservation of cold starting and altitude relight performance; and 1000 h of hot section time between overhauls.

During the "mod-exist" program, improvements in temperature traverse were achieved with reworked liners. However, these improvements were made at the expense of

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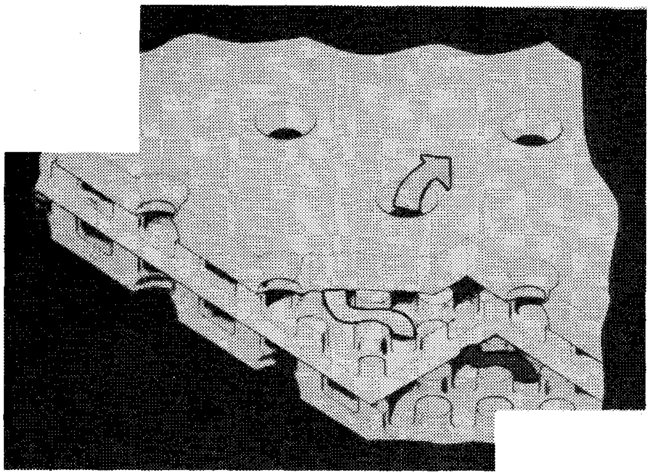

Fig. 1 Typical geometric arrangement of laminated porous wall structure.

liner durability. The constraints associated with the rework concept limited the ability to simultaneously achieve the performance and durability goals. Analysis indicated that temperature distribution improvements would require an increase in basic liner pressure drop. For the mod-exist concept, this could require altering nearly every opening in the liner. In 1977, it was concluded that a basic design change was needed to achieve the program goals. Recognizing the need for a more efficient wall cooling mechanism, design was initiated on a Lamilloy combustor.

The design parameters judged most important and most effective in achieving temperature traverse improvement are pressure drop and dilution zone airflow in concert with a uniform primary zone. These parameters can be adequately addressed with a redesigned combustion system incorporating Lamilloy cooling in the liner dome and barrel, and appropriate sizing of air entry holes.

Combustor design features established during this development included material selection, Lamilloy geometry, mechanical attachments, fabrication processes and liner air distribution to achieve the combustor performance and durability goals. The active cooling within the wall and the relatively large heat transfer rates into the Lamilloy structure induce thermal gradients which result in high stresses and potential thermal fatigue problems dependent upon configuration. Several iterations utilizing stress analysis techniques and cyclic bench test evaluations were carried out to establish the detailed Lamilloy geometry and base material for the TF41 combustor design. Liner mechanical design features (attachment points of supports, ferrules, crossover tubes, igniter ports, and air hole interruptions to the basic Lamilloy material) were investigated in component rig and engine tests. These features are generally dependent upon design requirements of specific combustor configurations and, although considerable progress was made in the TF41 program, further development is required to resolve all of the problems associated with these mechanical design features. Fabrication processes were satisfactorily resolved and limitations were identified in fabrication methods. Overall liner air distribution and pressure loss design was established to provide combustor performance complying with the program goals. Accelerated mission testing (AMT) was initiated as a final evaluation of the TF41 Lamilloy combustor. The operation and results of two 263-h AMT schedules are discussed below.

Combustion System Development

The TF41-A-1 engine shown in Fig. 2 is a mixed flow turbofan engine rated at 14,500 lb of thrust. It is a low bypass, high compression, twin spool, axial flow engine incorporating a fixed geometry inlet extension.

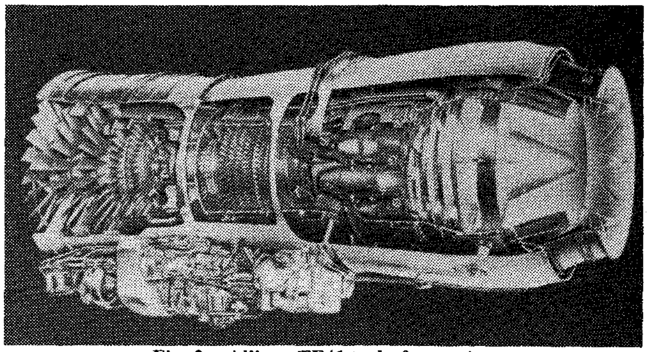

Fig. 2 Allison TF41 turbofan engine.

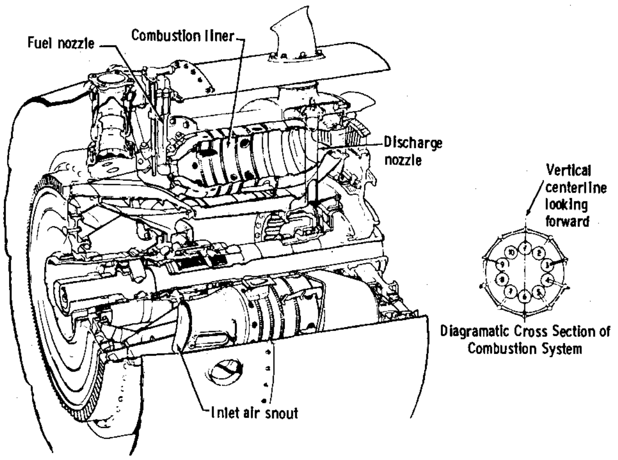

Fig. 3 TF41 combustion system.

The combustion system shown in Fig. 3 is a compact cannular design incorporating ten combustion liners in an air chamber formed between the outer combustor case and the turbine cooling air heat shield. The standard combustion liner is a welded assembly of formed sheet metal and machined forging details. Liner wall cooling is accomplished by film cooling air through five wiggle-strip corrugations which connect the conical wall sections comprising the liner body. The discharge nozzle walls are cooled by three rows of baffled cooling holes. Primary holes are chuted to improve mixing and flow distribution. A backstop and splitters are fitted to the dilution zone holes to insure consistent, uniform airflow into the liner.

Pattern factor improvements require a modification in the airflow proportioning among primary combustion, dilution mixing, and liner wall cooling. Engine temperature rise requirements establish the combustion reaction (primary) zone airflow quantity. Liner wall cooling flow quantities are established by the cooling scheme heat transfer effectiveness and the liner wall material selection. After these needs are satisfied, the remainder of the airflow is used for dilution. Temperature traverse control is highly dependent upon dilution zone mixing, primarily controlled by the available dilution airflow quantity and combustor pressure drop.

Since primary combustion airflow requirements are fixed by the chemistry of combustion, the only air that can be traded for additional dilution is cooling air. If combustor durability is to be maintained with reduced wall cooling airflow, then cooling effectiveness must be increased.

Transpiration cooling material has been developed which is approximately double the cooling effectiveness of the current film cooling in the TF41 combustor. Local cooling air addition required by the mechanical design must be carefully conceived, as it detracts from the potential total cooling air reduction afforded by the Lamilloy material. The cooling air saved can then be used to provide an increase in dilution zone airflow, thus permitting improved temperature traverse control.

The Lamilloy combustor and the standard combustor, shown in Figs. 4 and 5, have the same airflow in the primary combustion zone. The Lamilloy liner dome shape and fuel nozzle design are also unchanged from the standard. The primary zone liner geometry, aerodynamics, fuel distribution, and ignition system were unchanged in the design to preserve altitude and cold starting characteristics.

AMT Program

The objective of the AMT program was to evaluate the durability of the Lamilloy combustors in the TF41 engine. In addition to the AMT schedule, pre- and post-AMT testing was conducted to determine burner outlet temperature distribution and exhaust smoke density.

TF41 AMT testing is divided into three basic cycles: flight, start, and ground. These cycles were derived from joint Navy, Air Force, and DDA programs and are designed to simulate, on an accelerated basis, the operational field use of the engine. These mission profiles are defined in terms of time/speed relationships. To determine these simulation profiles the Navy Inflight Engine Conditioning Monitoring System Program provided records of engine history during actual flight. Specially instrumented engines flown at Edwards Air Force Base provided typical ranges of engine parameters during flight. Also, engine data recorded during flights of the Engine/Airframe Structural Integrity Program were assessed. Pilot interviews were utilized in determining types of missions flown, including effects of flight position (i.e., wingman, lead, etc.) and pilot experience on engine use. Typical mission profiles were then defined from these data. In order to accelerate or compress the cycles, nondamaging portions such as cruise power were removed.

To obtain the proper mix of mission profiles, an AMT block is defined. One block consists of 20 flight cycles, 4 start cycles, and 1 ground test cycle. Fifteen blocks are required for one AMT test.

Figure 6 depicts the flight cycle. A 43-min 29-s cycle represents the typical flight mission for an air-to-ground attack profile. For trending of engine deterioration, data are obtained after 5 min on the 6-min flat near the end of the cycle. In order to simulate Navy aircraft carrier deck takeoff conditions, "double datum" (an electronic control engine thrust augmentation technique) is used during the first accel to intermediate power.

Figure 7 illustrates the start cycle, which lasts 10 min 30 s. This cycle represents engine flight line maintenance.

Figure 8 illustrates the ground test cycle, which lasts 2 h 6 min 15 s, representing trim pad and test cell operation.

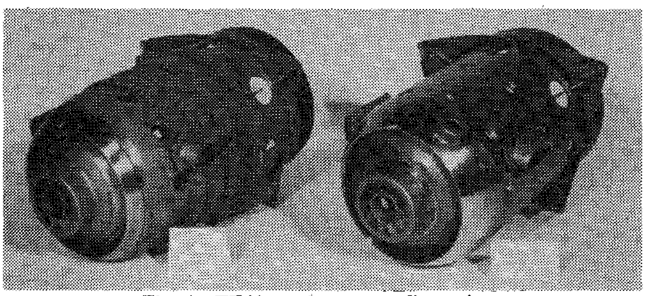

Fig. 4 TF41 combustor configurations.

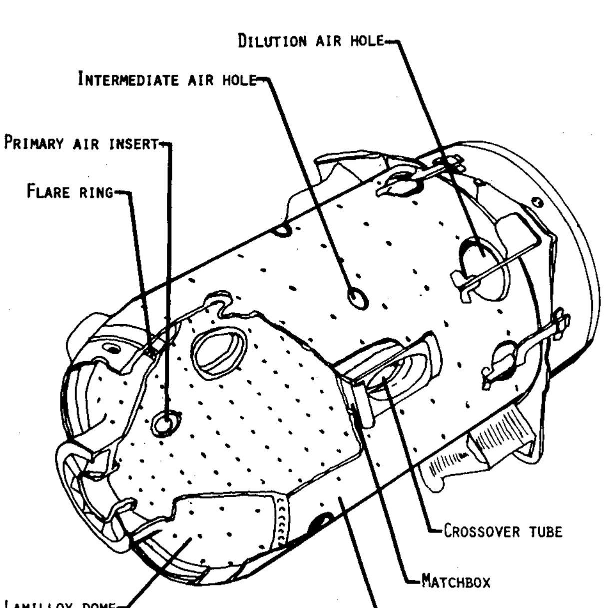

Fig. 5 TF41 Lamilloy combustor.

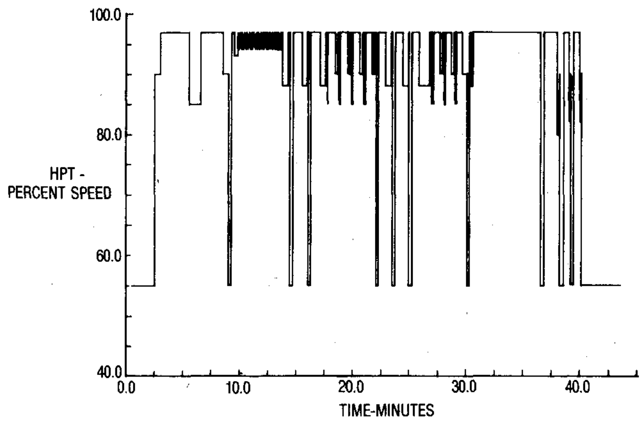

Fig. 6 TF41 flight cycle.

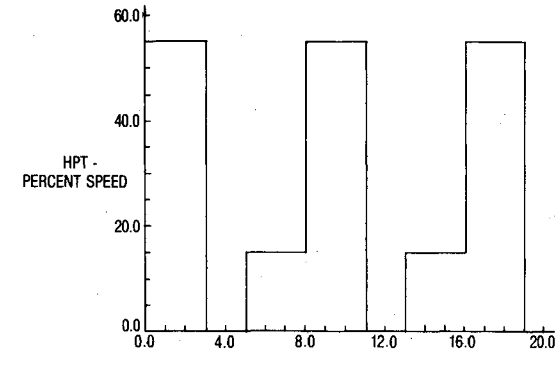

Fig. 7 TF41 start cycle.

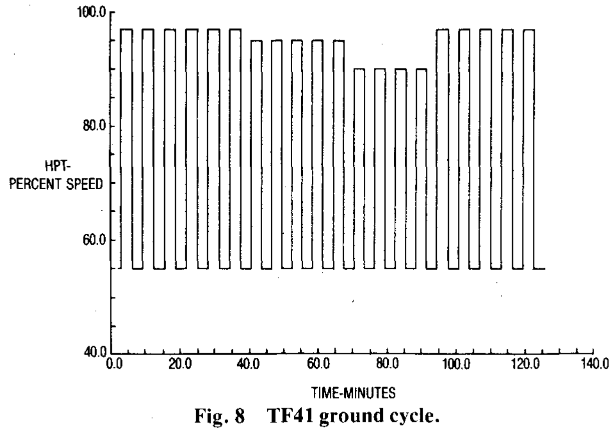

Fig. 8 TF41 ground cycle.

In order to achieve the 263-h AMT goal, five extra flight cycles are added to the 15 blocks of AMT cycles. By including the higher power and transient cycles of typical flight operations in A-7 aircraft, and minimizing running time at the least severe operating conditions, a time severity ratio of 1.9:1 is achieved. Experience with turbine vane durability has shown this ratio to be a reasonable factor for evaluating vane durability in AMT schedules. Other engine components do not necessarily follow this time ratio for durability comparisons. Combustion liner comparisons are not known because the current liner service life limit has not been encountered. However, it is thought that liners should respond similarly to turbine vanes.

AMT I

The first engine AMT was conducted at DDA in a test cell capable of producing heated engine inlet temperatures within a tolerance of ±10°F for all engine power settings. Turbine exhaust temperature, compressor speed, and mass flow limiting functions were set to allow the engine to operate at the proper environmental severity conditions during intermediate power conditions. Figure 9 shows the engine inlet and turbine inlet temperature distributions for the flight cycles completed.

All 15 AMT blocks plus five extra flight cycles were concluded in December 1979. This totaled 263 h of AMT plus an extra 49 h of engine run time for engine checkout, trim, performance calibration, BOT survey and smoke testing.

The general conclusion of AMT I was that the Lamilloy combustors had successfully demonstrated their durability. The Lamilloy structure revealed no buckling, cracking, or oxidation. Minor damage was observed on non-Lamilloy parts of the can. Cracking of air entry hole inserts and welds were observed at various cooling hole stations (primary, intermediate, and dilution). The observed cracks are attributed to temperature gradients due to end-wall heat transfer effects along with complex three-dimensional flow effects in the near-hole region. Some of the combustors exhibited varying degrees of damage at the flare ring. This damage ranged from buckling and cracking to loss of flare ring pieces. Flare ring distress was caused a local over-temperature condition. However, these problems were not considered to be a factor in demonstrating the durability of the Lamilloy combustor.

Erosion of the inner crossover tube attachment area, as seen in Fig. 10, was also observed. A "matchbox" is used to collect cooling air for the crossover tube attachment welds. The matchbox is welded to the barrel using a solid plate base. This solid base covers the transpiration cooling holes at this location, lending itself to heat errosion. It should be noted that this particular region is the only Lamilloy area indicating heat erosion distress.

The Lamilloy cans completed the test with very encouraging results. Low cycle fatigue (LCF) problems in the basic Lamilloy material did not appear.

The post-AMT burner outlet temperature profile survey shown in Fig. 11 indicated essentially no change in pattern factor distribution. This AMT survey was conducted using a clean set of fuel nozzles, eliminating any possible contribution of fuel injector coking to pattern factor deterioration. This allowed a closer examination of any dome, flare, and liner deterioration affecting pattern factor. The post-AMT BOT survey substantiated the lack of temperature traverse deterioration.

Pre- and post-AMT smoke test results are shown in Fig. 12. The change in the smoke index during the AMT could be attributed to the deterioration observed in the liner flare ring which controls local film cooling between the liner dome and barrel in the primary combustion zone. Although a change is evident, the absolute maximum results observed still fall below the visibility limit.

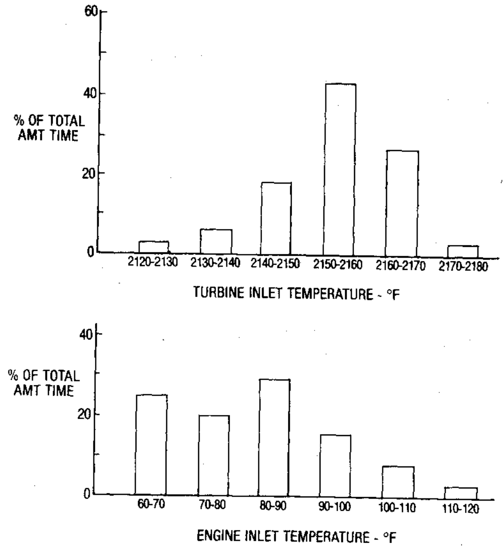

Fig. 9 AMT I time/temperature summary.

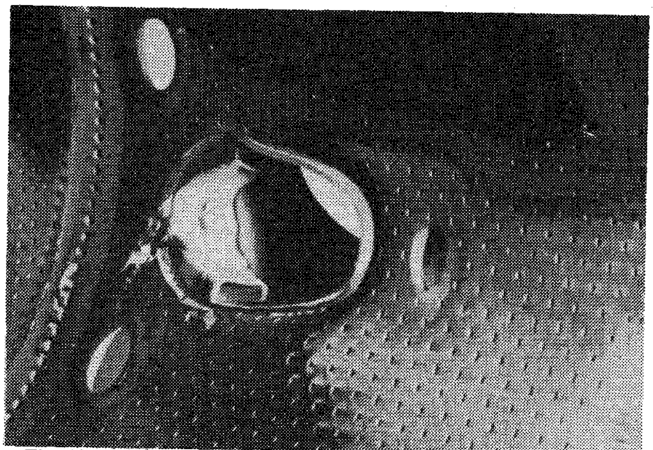
Fig. 10 TF41 Lamilloy combustor crossover tube (internal view).

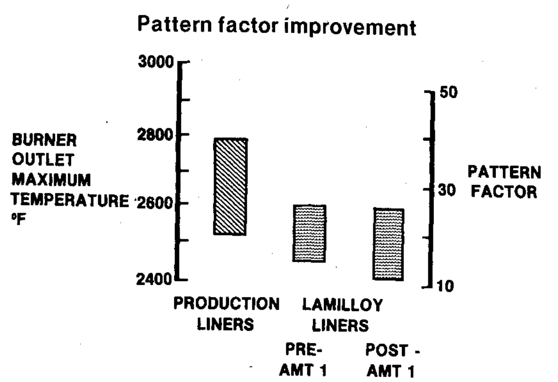

Fig. 11 Burner outlet temperature survey results.

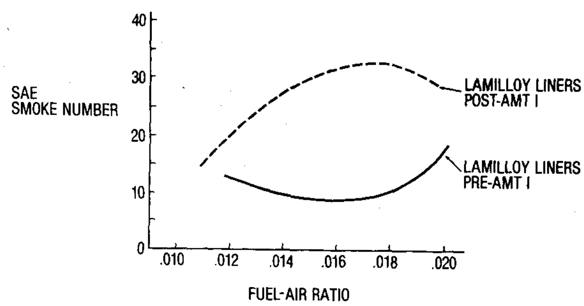

Fig. 12 Smoke emissions test summary.

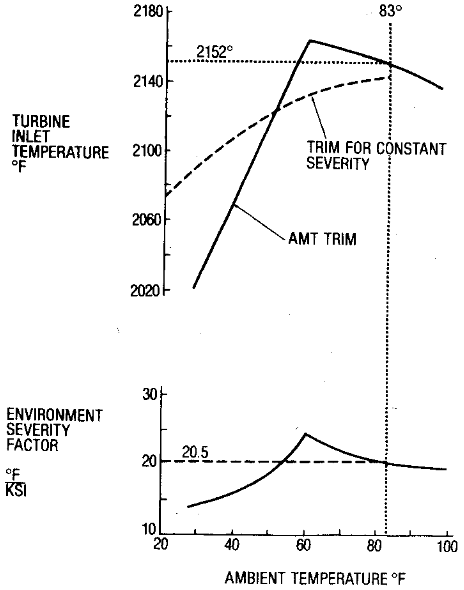

Fig. 13 AMT II engine trim.

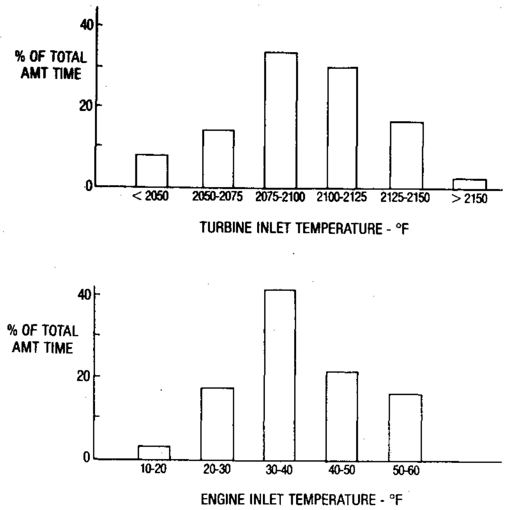

Fig. 14 AMT II time/temperature summary.

AMT II

Prior to AMT II, modifications were made to the flare rings in the Lamilloy liners, and some primary hole inserts which showed severe distress in AMT I were replaced. There was, however, no repair or replacement of any Lamilloy material.

An overhauled service TF41 engine was observed from the Air Force Logistics Command and the Lamilloy liners were installed by DDA. After appropriate checkout runs, the second AMT commenced in November 1980 at WPAFB in the Aero Propulsion Laboratory's Sea Level Engine Test Facility.

Since this facility does not have heated air capability, a correlating test procedure had to be derived so that Lamilloy durability assessment continuity could be maintained.

Lamilloy experience indicates that thermal gradients normal to the structure produce the most severe stress environment. A study of typical AMT tests at DDA showed that the average engine inlet temperature (T_I) run is 83°F. Turbine inlet temperature (TIT) histograms show that this correlates to an average TIT of 2152°F. A thermal gradient environment severity factor was defined as the ΔT across the structure divided by the ultimate tensile strength of the Lamilloy material at the hot side metal temperature. A plot, as shown in Fig. 13, is drawn for any inlet temperature with a nominal AMT trim. The average of the severity curve is given as 20.5 °F/ksi and if recomputed back to a ΔT for any T_I, a TIT trim curve for constant severity is defined as shown. The WPAFB endurance test was trimmed to a ± 5°F error band of the TIT constant severity curve. In order to achieve this trim, various amounts of high pressure (HP) compressor bleeds were used in conjunction with engine limiter trims.

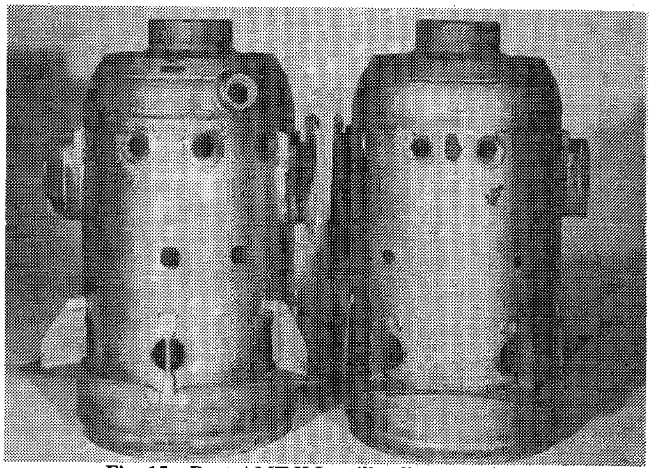
Fig. 15 Post-AMT II Lamilloy liner condition.

Midway through the second AMT testing, engine borescoping was conducted. Four cans were inspected in detail. The inspection revealed that only minor distress to non-Lamilloy areas in two cans had occurred, with no apparent damage to the others. Upon completion of the borescope inspection, the engine was cleared for the remainder of AMT schedule. Testing terminated 30 h short of the test goal of 263 h owing to a mechanical failure not attributed to the Lamilloy combustion liners. All ground test cycles, 57 of 60 start cycles, and 266 of 305 flight cycles were completed. Owing to power calibration procedures and various troubleshooting procedures conducted during the course of the test, the number of extra starts, full throttle cycles, and time at intermediate power compensated fully for deficient AMT time.

In adhering to the trim curve during the AMT testing, Fig. 14 illustrates the T_I and TIT test summary statistics. This temperature breakdown equates to an average error of -0.23% from the TIT trim curve.

Figure 15 illustrates the condition of two typical Lamilloy combustors after AMT II testing. Some thermal stress cracking in the air hole inserts along with erosion at crossover tube attachments was observed. However, no combustors showed any stress or fatigue in the weld areas of the Lamilloy dome or barrel.

Two major test results were observed for all liners:

1) The general condition of the basic Lamilloy material was excellent. There was no thermal fatigue cracking or material oxidation. The durability of the Lamilloy liner material is considered to be successfully demonstrated for at least 1000 h of TF41 field service.

2) The condition of the inner weld areas of the dome and barrel was excellent. No major cracking or erosion was observed, demonstrating the success of welding and manufacturing techniques developed for Lamilloy.

Conclusions

The cyclic durability of the basic Lamilloy material was successfully demonstrated in a full-scale engine AMT simulating approximately 1000 h of flight service.

Improved combustor outlet temperature distribution was achieved in the TF41 engine through the application of Lamilloy material. The reduction of cooling air and the lack of mod-exist constraints permitted the application of increased pressure drop and dilution air quantity design principles to combustor outlet temperature distribution improvement.

The reduction of liner cooling to minimum levels demands careful attention to the design of mechanical attachments, section joints and combustion air entry ports. Owing to these features, the cooling air reduction potential of the basic Lamilloy material was not fully exploited in the TF41 combustor design. Further development is required to achieve fully satisfactory durability of these features.

Lamilloy material has also proven to be an effective cooling technology in DDA advanced high temperature combustion systems. The successful demonstration of the cyclic durability capability of Lamilloy material in the high-pressure ratio TF41 engine provides further confidence that it is a viable combustor cooling material for high performance turbine engines.

Acknowledgments

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References

[1] Nealy, D.A. and Reider, S.B., "Evaluation of Laminated Porous Wall Materials for Combustion Liner Cooling," *Engineering for Power*, Vol. 102, No. 2, April 1980.

[2] Nealy, D.A., "Combustor Cooling—Old Problems and New Approaches," in *Gas Turbine Combustor Design Problems*, Hemisphere Publishing Corporation, 1980, pp. 151-185.

[3] Wear, J.D., Trout, A.M., and Smith, J.M., "Performance of Semi-Transpiration Cooled Liner in High-Temperature-Rise Combustor," NASA TP 1806, March 1981.