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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 110

Technical Evaluation Report on the 49th (B) Propulsion and Energetics Panel Specialists' Meeting on Power Plant Reliability

by

G.P.Sallee

NORTH ATLANTIC TREATY ORGANIZATION

AGARD-AR-110

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.110

TECHNICAL EVALUATION REPORT

on the 49th (B)

PROPULSION AND ENERGETICS PANEL SPECIALISTS' MEETING

on

POWER PLANT RELIABILITY

by

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Pratt & Whitney
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The Proceedings of the Propulsion and Energetics Panel 49th (B) Specialists' Meeting, which was held at The Hague, Netherlands, on 31 March and 1 April 1977, are published as AGARD Conference Proceedings CP 215.

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- Exchanging of scientific and technical information;
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

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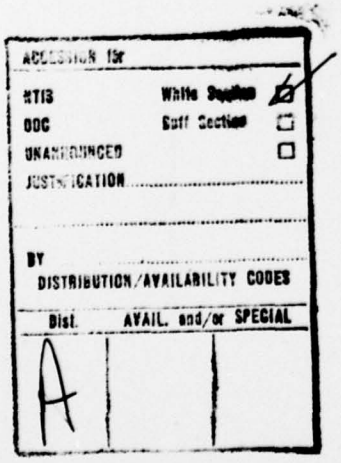

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NOTE D'EVALUATION TECHNIQUE

par

J.C.Ripoll

FAITS SAILLANTS

Les exposés et discussions ont fait ressortir que:

- la fiabilité des propulseurs aéronautiques n'a pas encore atteint un niveau satisfaisant pour l'ensemble des utilisateurs.
- les moteurs les plus récents ne sont pas les moins affectés par cette insuffisance.
- le mode effectif d'utilisation des moteurs, spécialement militaires, est mal connu et souvent plus pénalisant que prévu pour la durée de vie.
- toutefois, des différences notables de fiabilité apparente existent entre divers utilisateurs.
- le coût réel de la maintenance est très élevé et mal connu.
- des utilisateurs civils préfèrent une meilleure fiabilité à des performances excessivement brillantes.
- la poursuite d'essais de vieillissement de groupes de moteurs se généralise dans le développement des programmes.
- des analyses telle que celle menée par le Groupe No. 08 du Panel sur la "Détérioration en Service" conduisent à dégager des tendances générales.

Cependant il faut noter que, au cours de cette réunion, le problème de la fiabilité de l'ensemble propulsif et en particulier des accessoires et équipements n'a pas été abordé.

RECOMMANDATIONS

A partir des constatations faîtes au cours de la réunion, il est indiqué de recommander les actions suivantes auprès des Gouvernements et des autorités de conduite des programmes.

- améliorer la connaissance des cycles d'emploi réels, en particulier par l'enregistrement généralisé des paramètres de vol dans le cadre de la surveillance continue. . .
- développer l'information sur les cas et les causes de pannes, de défaillances, de ruptures, au profit de l'ensemble des utilisateurs et surtout des bureaux de conception.
- évaluer avec plus de réalisme le coût de la maintenance et du manque de fiabilité, de façon à choisir de meilleurs compromis avec la recherche des performances.
- utilsier systématiquement les essais de vieillissement accéléré en simulant bien l'ensemble des charges internes et externes appliquées aux moteurs en Service.
- employer largement les procédés de surveillance continue de l'état des moteurs.
- soutenir des études spécifiques de l'établissement des clauses techniques et règlements en vue d'assurer que l'ensemble des caractéristiques exigées des moteurs, constitue un compromis raisonnable.

En ce qui concerne les activités du Panel on peut recommander de s'intéresser également à tous les éléments du système en dehors du moteur proprement dit: engrenages, hélices, pompes, régulateurs, etc. . .

CONCLUSION

L'utilité des réunions organisées par les Panels AGARD, a été confirmée. La présence nombreuse de spécialistes, qui ont pu très librement échanger leurs expériences et leurs idées a été bénéfique. Il convient de noter que les préoccupations nationales ou commerciales, même si elles n'ont pas été totalement absentes, n'ont pas entravé les échanges; c'est ce qui distingue les réunions patronnées par AGARD.

L'approfondissement ou un prolongement des travaux du Groupe No.08 sur la *Détérioration en Service*, à la lumière des travaux de la réunion de Spécialistes sur la *Fiabilité des moteurs*, paraît présenter un intérêt certain.

TECHNICAL EVALUATION MEMORANDUM

by

J.C.Ripoll

REMARKABLE FACTS

The papers which were presented and the discussions thereafter showed that:

- the reliability of the aero engines has not yet reached a level which is satisfying to the community of the users.
- the most recent engines are not those least affected by this insufficiency.
- the real mode of using the engines, particularly those in miliatary services, is poorly known and is, thus, penalizing the engine life time more than anticipated.
- there are notable differences in the apparent reliability between various users.
- the real maintenance cost is not well known and seems to be very high.
- some civil users prefer a better reliability to excessively high performance.
- accelerated mission testing is more and more introduced in development programmes.
- analyses such as those undertaken by the PEP Working Group 08 on 'Aero Engine Deterioration' give insight to general trends.

It should be noted that during this meeting the problem of the reliability of the complete propulsion system and, in particular, that of accessories and equipment, has not been considered.

RECOMMENDATIONS

According to the statements made at the meeting, the following actions should be recommended to Governments and authorities in conducting their programmes:

- enhance the knowledge of really employed cycles, in particular by general recording of flight parameters with continuous surveillance systems.
- accumulate information on engine shut-downs, failures and fractures, and their reasons, for the benefit of the users and, foremost, of the designers.
- evaluate, more realistically, the cost of maintenance and the lack of reliability in order to better select compromises in the choice of performance level.
- use systematically the accelerated mission tests to simulate the realistic combination of internal and external loads as being exerted to engines in service.
- employ continuous surveillance procedures regarding the condition of the engines.
- spend specific effort to establish technical specifications and rules in order to ensure that the sum of the characteristics which are to be met by the engines give a reasonable compromise.

As regards the Panel activities, it is recommended that the interest should be devoted to all components besides the engine, that is to say: gears, propellers, pumps, controls, etc.

CONCLUSION

The usefulness of the meetings organized by AGARD Panels was again confirmed. The attendance by many specialists being able to exchange their experience and their ideas quite freely, has been beneficial. It should be noted that national or commercial preoccupations although not being absolutely absent did not hinder the exchange, this being a distinct feature of meetings sponsored by AGARD.

In the light of the results of this Specialists' Meeting on *Power Plant Reliability*, it seems that it is worthwhile to continue further and in more depth the work of Working Group 08 on *Aero Engine Deterioration in Air Force Service.*

TECHNICAL EVALUATION REPORT

by

G.P.Sallee

1. INTRODUCTION

The 49th meeting of the Propulsion and Energetics Panel on Power Plant Reliability was held at the Koninklijk Instituut Van Ingenieurs, The Hague, Netherlands on 31 March and 1 April 1977. The meeting was organized to review and discuss engine reliability from four aspects:

- the reliability of current civil and military engines as experienced by the users,
- civil and military authorities' plans to promote improved reliability in future engines,
- what manufacturers are doing to improve reliability through design and testing programs,
- the role that engine health monitoring and diagnostics is taking in minimizing the impact of engine unreliability for both civil and military users.

The meeting was divided into four sessions with a total of 18 papers. The presentations were well received and the meeting was beneficial in establishing a basis for future discussions.

2. SUMMARY

The following observations reflect the tone of the meeting and the major results.

- Engine reliability is not satisfactory in either commercial or military services. In particular the newer commercial engines are not living up to operators expections.
- It seems that civil and military authorities are considering the promulgation of more stringent requirements and standards concerning the development, certification/qualification and acquisition of future engines with respect to the reliability requirements that must be met.
- Manufacturers are designing for improved maintainability and employing improved testing techniques to expose problems early. Further progress is possible, but is contingent on the availability of engineering data on actual engine usage in military service. In addition detailed part failure data is needed to determine the causes for part failure with respect to usage and the relationships that exist between the various modes of failure.
- The economic impact of military engine unreliability has not been discussed. The cost consequences of premature engine removals, aborts, part failures, etc., are needed to establish the role of engine reliability in engine life cycle cost.
- The growth of engine health monitoring in the commercial airlines and the increased experimentation of such approaches in the military are indicative of the serious consequences of poor engine reliability. The future growth/potential for such techniques is impressive.

3. RECOMMENDATIONS

Engine reliability will continue to increase in importance in the light of current economic pressures. The following recommendations are believed by the writer to be worthy of consideration as items for further research.

- The reliability history of todays engines beginning with their initial entry into service needs to be examined such that trends and major causes of unreliability are visible to both designers and users. Comparison of available data between users suggests that major differences exist in causes for engine removals on identical airframe/engine combinations. Concurrent with examining historical reliability data is the need to quantify the cost of engine maintenance. The availability of such data would permit proper assessment of the trade-offs between performance improvements and reliability improvements for future designs.
- Continued documentation on the manner in which engines are actually used in service is needed. The data currently available from recent testing show that actual thermal cycles during flight are more numerous and different than contemplated by design specifications or qualification test programs.
- Broader adaptation and experimentation in engine health monitoring techniques is recommended for the military services. Preliminary estimates on military engine maintenance cost indicate that they are four to ten times higher than levels previously reported. When fully documented the cost of maintenance will undoubtably support strong action for cost reductions, and health monitoring has the potential for providing the cost savings from controlling unnecessary maintenance actions and reducing the costs of failures.

- Continued development and application of accelerated engine testing techniques and lead-the-fleet engine concepts are recommended. In addition there is a need to more closely simulate the installed engine environment. Externally applied aerodynamic, gravitational and gyroscopic loads can cause ovalization of cases and local seal rubouts. The resulting losses in performance are important to the life of critical hot section parts.
- Examination of the role of subsystem reliability in overall propulsion system reliability is needed. The cost consequences of flight delays, cancellations or mission aborts to both military and commercial engine users need to be defined and exposed to the technical community.
- The military services, like the commercial airlines, must insure that the consequences of missing reliability goals are similiar to those for missing performance guarantees. In order for this to occur more definitive research will be needed to support the establishment of reasonable requirements in keeping with the overall demands placed on future engines.
- Regarding engine health monitoring the military use of commercial airline procedures should be initiated slowly in an evolutionary rather than revolutionary fashion. The airlines have more engineering personnel per installed engine than the military services which permits them to monitor trends on an individual engine basis and take corrective action quickly. The availability of trained personnel is critical in the successful application of such techniques.

4. DISCUSSION

In preparing this evaluation report, the papers presented were regrouped to provide a more harmonious presentation on each of the four aspects of engine reliability. The first aspect to be reviewed was a status report on civil and military engine reliability and concerns related thereto. In listening and reviewing these papers and the discussions that followed the impact of poor reliability on safety and life cycle costs were stressed.

Session I

Paper No. 6 by J.A.Aguer discusses problems being experienced in todays high bypass ratio commercial engines and the origin of major structural and fire hazards. Foreign object damage, titanium fires, coking of fuel nozzle passages, bearing sump fires and bearing failures are typical of such problems. Maintenance can not correct such deficiencies and improvement in design standards to avoid such problems must be sought,

Historically, engine weight is increased in early service through modifications to improve reliability and durability and at significant cost to the users. More emphasis is needed on structural integrity and durability in engine development programs and less on weight reduction.

Paper No.5 by S.K.W.J.Demarteau continues this discussion and provides an understanding of the cost consequences of poor engine reliability to commercial airlines. As an example, an engine removal at an airport close to the main maintenance base is 1/10 the cost of a removal at a distant airport overseas. Early detection of failures is also essential to control the high cost of secondary damage. Low time failures and removals of recently repaired high bypass engines are a major concern today and are slowing progress toward attainment of desired reliability goals. The only way to achieve a justified cost/reliability level is to look for cost effectiveness in modifications, maintenance and monitoring practices.

Paper No. 2 by Gen. L.Giorgeri and Col. G.Facca discusses the broad aspects of reliability and related cost in Military Air Forces. Engines have a tendency to lose performance with the passage of time in service and this loss is not fully recovered during maintenance. Many of the causes for engine removals are common for all nations; however, many unique items exist in each nation for the same engine and aircraft combination. The cost of engine maintenance in the military services is much higher than previously believed. These factors lead to concern about future engines of increased complexity. Additional detailed studies are needed to understand the overall reliability picture of today's engines.

These papers summarized the status of current engine reliability. The reliability of high bypass ratio engines entering commercial service are still less than what is needed. These new engines, even after five to seven years and millions of hours of service, are still poorer than their predecessors. The military experience, while not alarming, is less than satisfactory. A study of airline experience with their newer high performance engines brings serious concern about the initial reliability of future military engines. Consideration of changing military design objectives and contract incentives to favor improved reliability even at the expense of some performance losses may be needed to ensure adequate readiness and reasonable life-cycle-costs.

Session II

Civil and military authorities appear to be reacting to this perceived state of affairs. Mr. J.Slatford presents some of his thoughts concerning future civil engine reliability requirements in Paper No. 4 and the form that such requirements might take. The changes in engine development and procurement program policies being contemplated by the

United States Air Force are discussed in Paper No. 1. The revised program policies stress more steps in the process going from original concept to actual full scale production, and increased emphasis on demonstration testing for structural integrity and reliability. More decision points and reviews would be undertaken prior to full production release. The paper by R.Holl (No. 7) discusses the evaluation of general engine specifications and type test requirements. He points out that little effort was made until recently to obtain meaningful data of how engines were actually used in military service. Problems with engine reliability and establishment of appropriate engine part life standards led to development of equipment to gather data on how engines were operated in service. The results of these efforts show actual usage to be far more severe than estimated and signal that a rather severe change is needed in engine design, development testing, maintenance and reliability criteria. Further work in correlating parts life consumption based on actual speed and temperature excursions and their variation with flight type is planned and will be beneficial in establishing improved part life standards.

Paper No. 11 by R.J.Hill discusses procedural steps for predicting the life of turbine components. The difficulties in establishing good design and life positions are increased when actual usage varies in an unknown manner from design duty cycle assumptions. The ability to determine the proper failure modes that should be considered and their interrelationship is dependent on the availability of large data bases on failure modes in similar parts. These data bases are not adequate and in most instances do not exist for today's military engines.

Session III

The response of manufacturers to user concern over current engine reliability was addressed from a design standpoint in papers No. 8, 9 and 10 and increased testing in papers 13, 14 and 15.

Paper No. 8 by J.P.Marechal discusses the CFM-56 development program and the actions being taken to insure improvement in engine reliability and maintainability. Paper No. 9 by B.L.Koff discusses the four major requirements for engine design. Simply stated the first three, performance, weight and cost are easily determined early in an engine development program. The last, reliability, of which durability and maintainability are part, is not fully known until the engine is well into service. To maximize early reliability the design must be based on an accurate definition of mission requirements and accurate trades between competing performance, weight, cost and reliability requirements. Once the optimum configuration is chosen rigorous attention to detail is required to insure proper execution in the design process. Test and evaluation programs are directed at proving the design and correcting deficiencies. Cyclic endurance testing which tax major elements of the engine have been helpful in defining weaknesses. Component test and analysis are used to backup the engine endurance testing which cannot reproduce all expected conditions in actual flight in all parts of the engine. Advanced instrumentation and special test equipment are being used to determine the actual condition of parts under operation and to accomplish special tests such as foreign object ingestion. Tracking the first engines entering service and observing the condition of parts as usage time accumulates and factoring this experience back into both correction of current problems and new engine design requirements will lead to continuing improvements in reliability and maintainability for the future.

One of the approaches to achieving higher reliability has been to utilize redundancy. Paper No. 10 by J.C.Rennesson discusses this approach and the precautions which must be taken. The requirements for redundancy in single engine aircraft are more severe than in multiengine transports. Redundant systems present difficulties in isolating faults during maintenance and produce increases in cost.

As noted in B.L.Koff's Paper No. 9, endurance testing has shown to be beneficial in helping to uncover weaknesses in the design. Paper No. 14 by B.Devoge discussed the design and results of the endurance test program on the Olympus 593 afterburner and nozzle assemblies.

Paper No. 15 by B.J.McDonnell discusses the accelerated mission testing of the F100 engine for the F-15 and progress to date. The test program was divided into four parts: (1) determination of the actual mission profile, (2) definition of test conditions, (3) accomplishment of the tests and (4) correction of problems exposed. Perhaps most significant to the writer of this report was the number of full throttle excursions which actually occurred based on measurement. This usage showed that the military qualification testing requirements were significantly out of touch with usage. The testing has been successful in accomplishing the objectives sought and in conjunction with "lead-the-force" engines has been responsible for extension of the maximum overhaul operating time limits. These tests are not the panacea to achieve good reliability but they represent a significant step forward.

Paper No. 13 by D.Dini reports on basic test work on an engine to determine its tolerance to foreign object ingestions and the need to continue such test work to determine the effect of structural damage caused by transient loads. A procedure for undertaking such transient load tests by using a gas shock tube is discussed. The need for development of test facilities capable of simulating the icing environment of helicopters is stressed.

Session IV

Engine health monitoring and engine diagnostics have been in use by commercial airlines for a considerable period as discussed by P.Chétail in Paper No. 12. The growth and success of these techniques has led to their becoming

a fundamental part of commercial airlines engine maintenance programs. Their usefulness has come from observing the trends that had been developing prior to an actual failure and then applying these lessons to corrective action on others as soon as the same symptom(s) appear. Continued success and growth of such techniques will require even closer collaboration between users and engine manufacturers. The methods currently being utilized for engine health monitoring in the French Air Force are discussed by C.Sprung in Paper No. 3. The preliminary results of T-38 on board engine health monitoring equipment test evaluations are presented by K.E.Eickmann in Paper No. 18. The results have been gratifying and continued testing is planned. A prototype activity based on hand processed trend monitoring of engine performance on a group of military transport engines has proven immensely satisfying in reducing secondary damage and maintenance cost.

Paper No. 16 discusses the results of experimental testing of an engine with known faults to determine the detectability through normally measured gas path performance parameters. Problems of fault detection and related sensor location are covered. The growing technology in electronic digital computers will bring about totally electronic fuel control systems. Such systems lend themselves to engine diagnostics and trend monitoring with minimum increases in complexity and cost. These possibilities are discussed in Paper No. 17 based on flight test experience with prototype V/STOL fighter aircraft.

5. CONCLUSIONS

The price of each new engine generation has increased with the user demands for improvements in engine performance. The performance advances have been achieved, apparently at the cost of increased complexity and reduced reliability. Today economic forces (increased fuel costs, higher operating and support costs and poorer reliability from newer engines) have produced the need for both users and manufacturers to re-evaluate their priorities on performance and engine reliability in context with long term objectives.

Comparing historical data of the major causes for engine unreliability for a variety of engines leads to the conclusion that the same types of problems are repeated in every engine type and generation. Comparison of users data on major causes for unscheduled removals for the same engine and aircraft combination show that certain users have problems not being experienced by others. These data suggest that variations in operational usage, environment, engine age or detailed maintenance practices must also be considered as contributing to engine unreliability.

Actual military engine usage differs substantially from that used as the basis for design. Recent studies, both reported during this conference and underway in the United States, show that major thermal cycles in actual engine operation are as much as 10 times higher than originally considered in the design process or controlling military specifications. Certainly, precise definition of the way engines are actually used is needed to properly address low cycle fatigue and stress rupture. Data of actual engine thermal cycles in each aircraft type on different missions are needed to update engine specifications and design criteria.

In discussing engine reliability the engine is frequently considered alone and not as a part of a propulsion system. If detailed historical studies had been accomplished, it is the writer's belief that subsystems elements such as starters, oil system components, ignitors, instrumentation, air bleed valves, etc., are often major sources of line maintenance problems, aborts, cancellations or delays, Growth in overall system reliability will be contingent on improvements in these areas also.

Comprehensive data feed back to manufacturers of engine and part failure information including part time/cycles, mode of failure and primary or secondary involvement is needed to improve engine reliability after entry into service. All too often, redesign action can be initiated on the basis of too little information. Comprehensive research into the causes for unreliability covering many years and many engines, particularly for the military services, will be needed to understand what changes in specifications, regulations, operating procedures, design practices and maintenance programs are required. Certainly the determination of the cost to the users of poor reliability is a first step.

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14. Abstract

This Advisory Report contains the Technical Evaluation Report as well as the Technical Evaluation Memorandum of the 49th (B) Specialists' Meeting of the Propulsion and Energetics Panel on 'Power Plant Reliability' held in the Hague, Netherlands on 31 March and 1 April 1977.

The meeting was organized to review and discuss engine reliability from four aspects:

- the reliability of current civil and military engines as experienced by the users,
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This report contains the conclusions drawn from the meeting and offers recommendations.

The papers presented at the meeting, together with the discussions and the ad hoc organized Round Table Session are published as AGARD Conference Proceedings CP 215.

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