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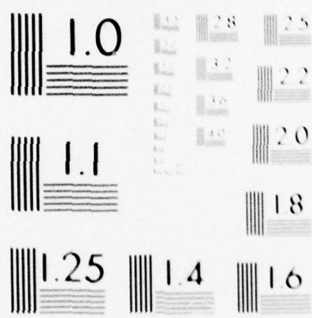

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AGARD ADVISORY REPORT No. 123

Technical Evaluation Report on the 51st (B) Specialists' Meeting of the Propulsion and Energetics Panel on Seal Technology in Gas Turbine Engines

by

B. Wrigley

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Advisory Report No.123

TECHNICAL EVALUATION REPORT

on the

51st (B) Specialists' Meeting

of the

PROPULSION AND ENERGETICS PANEL

on

SEAL TECHNOLOGY IN GAS TURBINE ENGINES

by

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The Proceedings of the 51st (B) Specialists' Meeting of the Propulsion and Energetics Panel which was held at Church House, Westminster, London, UK, on 6 and 7 April 1978, will be published as AGARD Conference Proceedings CP 237, July 1978.

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TECHNICAL EVALUATION MEMORANDUM

by

B. Wrigley

CONCLUSIONS

- In-service performance deterioration is a serious problem for Commercial Operators and Air Forces, particularly in view of the developing fuel situation.
- Seal wear is a major factor in performance deterioration and there is therefore a significant financial incentive to improve sealing technology.
- Useful research is in progress particularly for advanced seal design, but in the field of rubbing and erosion research has been insufficiently systematic and has generally had to wait for the initiative given by service problems.
- Useful measurement techniques already exist.
- The conference was clearly necessary, in fact over-due. The quality of papers and participation was of a high standard. The general awareness of the problems and the relevance of the papers is in itself remarkable.

RECOMMENDATIONS

- Blade tip and labyrinth seal rubbing phenomena need further study.
- Engine demonstration of advanced sealing concepts should be encouraged.
- Relevant heat transfer phenomena should be incorporated in future discussion.
- Measurement techniques need to be improved, further.
- Resources should be provided to deal with the above recommendations.

It should be noted that in this field the resources that need to be committed are much smaller than in, for example, the primary turbomachinery fields.

- Sealing design must be integrated into the engine mechanical design and component aerodynamic design processes.
- A follow-on activity of PEP Working Group 08 which had dealt with engine deterioration in Air Force Service, is deemed necessary. It should be invited to provide data on the influence of sealing as experienced by military users.
- Solutions must be developed for existing engines and their derivatives, as these engines will consume most of the fuel up to the end of the century.

TECHNICAL EVALUATION REPORT

by

B. Wrigley

1. INTRODUCTION

The 51st meeting of the Propulsion and Energetics Panel on Seal Technology in Gas Turbine Engines was held at Church House, Westminister, England on 6th and 7th April 1978. The meeting was arranged under five main headings:

- material technology, particularly as applied to main flow path blade tip seals.
- user's view of seal technology.
- measurements of seal behaviour.
- laboratory experiments.
- design aids.

The meeting was held in four sessions, the last one incorporating a round table discussion.

The presentations were relevant, timely and well received, covering both aircraft and industrial gas turbines.

Wide ranging comment indicated the value of the meeting and suggested the need for a continuing commitment in this field.

2. SUMMARY

There are two major issues forcing the pace of sealing technology:

- the quest for improved engine efficiency, in a period of rising fuel prices.
- poor in-service reliability of seals and engine performance deterioration in the most recent generation of subsonic jet engines.

The meeting also identified the following issues:-

- A significant factor in performance deterioration is the increased clearance and aerofoil distortion caused by abrasion and erosion.
- The influence of thermal and mechanical forces on seal clearances.

  These forces are usually of a transient nature.

  Suitable techniques for measuring these effects were described.
- Current high bypass ratio engine designs have included features detrimental to achieving low seal leakage.
- A wide range of experiments has shown the potential of advanced sealing techniques for leakage reduction but this work has not yet been taken through to engine demonstration to any substantial extent, nor has the wear characteristic of such seals been adequately established.

3. RECOMMENDATIONS

- Further study is required on blade tip and labyrinth seal rubbing phenomena and should include fully representative experimental work and the development of theoretical understanding. Consideration should be given to establishing more formal relationships with machining research.
- Seal design should be thoroughly integrated into the engine design process. The mechanical designer must ensure from the preliminary design phase onwards that the engine is structurally and thermally beneficial to good seal design. The aerodynamicist must integrate sealing quality into his judgements concerning direction of research and engine design.
- Opportunity should be provided for the demonstration of advanced seals in representative engines; sufficient confidence will only be established in such seals if reliability and integrity can be demonstrated.
- User experience represented in the conference was mainly that of a major US trunk operator. Further information is required, reflecting other geographical locations, smaller operators, industrial users and particularly from military services. Referring to the successful work of PEP Working Group 08 which dealt with Aero Engine Deterioration in Air Force Service, a follow-on activity should be invited to report on experience with seals by military users.

- Compressor and turbine aerodynamicists should work towards a better understanding of clearance sensitivity.

- In the commercial field present engines and derivatives of these engines will account for nearly the total fuel consumption up to 2000 AD (Ref.B.). Research should be directed therefore to improving the present engines and not just the so-called E^3 engines,* which may not enter service until after 1990.

- Further discussion on associated heat transfer phenomena should be organised. Future engine improvements will depend greatly on tuning the heat transfer process to reduce clearance.

4. DISCUSSION

The papers have been slightly regrouped, to allow development of the different subjects starting from the views expressed by users.

4.1 USERS VIEW OF SEAL TECHNOLOGY

Paper No.1 by L.P. Ludwig identified the effect of rising fuel price on the significance of the fuel term in DOC. Recent development to high overall pressure ratios was cited as the significant factor in causing gas turbines to be more sensitive to sealing standard. Large values for in-service performance deterioration were described, references being given for commercial and military operation.

Paper No.5 by C.R. Smith enlarged on these themes, particularly emphasising the engine suppliers' responsibility to ensure the operator gets a good return on investment. Fuel consumption was the largest factor in DOC and deterioration of specific fuel consumption therefore particularly critical, both for its direct effect and the consequences on shop loading and overhaul costs of trying to maintain the fleet at the best average level of performance. Primary gas flow path sealing was the major source of performance deterioration, although secondary flow system sealing could not be ignored. Primary flow path deteriorations were caused by tip abrasion (unshrouded HP turbine blades) and excessive erosion of static shrouds. Wear of bearing chamber carbon face seals were associated with high temperatures and long time between overhauls. The need for closer control of oil cooling of the rubbing elements was identified to prevent the coking which often occurs at long lives. The financial incentive for improvement of sealing technology was stated to be the current cost to the operator arising from sealing problems e.g. for a large US operator: $14m annually. The 'Sealing' cost might eventually reach 70% of the engine maintenance bill. An appropriate economic climate therefore exists in which to promote the necessary research, design and development effort.

4.2 SEAL MANUFACTURE, RUBBING AND EROSION

The significant causes of performance deterioration identified in 4.1 are categorised in paper No.1 by L.P. Ludwig, which surveyed the available seal lining materials and their limitations particularly with respect to environmental temperature and rub energy. Blade tips and labyrinth seal knives have required abradable static liners. Choice of liner has usually been an uncertain process not helped by ignorance of penetration rate. The balance between good abradability and erosion of the liner has been difficult to achieve. A cine-film illustrated short and repeated hot rubs, a similar phenomenon being described in ref.A with low rub penetration rates. Greater certainty was indicated for the coating of a drum rotor, usually a hard oxide abrasive. The potential benefits of ceramic or ceramic/metal shrouds for HP turbine blade tips was indicated, further research being required owing to the very high local heat transfer coefficients present.

Paper No.2 by J.G. Ferguson described testing techniques of differing sophistication for abradable linings. The debris removal mechanism was cited as a possible cause of discrepancy between rubbing tests, highlighting the requirement for truly representative testing including airflow. Method of application as well as the composition of the abradable lining have been significant factors in determining quality. Experimental techniques for testing abradables have not allowed confident selection of material for engine seals. A.R. Stetson in Paper No.3 dealt specifically with compressor vane tip abrasion. The value of an extremely sharp abrasive in minimising vane metal loss, tip distortion and temperature was clearly established. By implication increase of clearance above the pre-determined penetration was also minimised. Plasma spraying was shown to reduce the abrasiveness seriously and it was necessary to use a low temperature bond to avoid this. The coating could be easily sprayed to size and required curing. It was cleared for use at up to 700°K.

Another manufacturing technique, for an abradable felt, was described in Paper No.4 by A. Hivert. As with the abrasive material of the previous paper low thermal conductivity was a characteristic. The manufacturing process for the fibres and the moulding technique for the felt were described. A soluble bond for easier repair was available for temperatures up to 611°K. Brazing was necessary at higher temperatures.

The lack of consistency between rig and engine tests of abradable tip seals noted by J.G. Ferguson is also brought out in Paper No.14 by C.W. Elrod. In order to tackle this deficiency an engine representative rig has been designed and is currently being commissioned. A specific feature of testing will cover titanium ignition phenomena. Complementary testing with laser ignition of representative titanium alloy samples was described. The effect of air velocity, pressure and temperature on burning rate and propagation to other 'aerofoils' was examined. Fires could be extinguished by a high concentration of Argon.

* E^3 = energy efficient engine

4.3 ADVANCED SEALS AND LABORATORY EXPERIMENTS

The introductory survey by L.P. Ludwig described the use of sliding face seals for bearing chamber sealing in a high pressure environment. An example showing substantial SFC improvement compared with labyrinth seals was given.

Paper No.11 presented by E. Bollina described a range of tests undertaken on small, low rubbing speed, hydraulic face seals. Data were presented which showed the effect of rotational speed on pumping between the sliding contact faces. (The cooling flow rates appear to be generous for the size of seal and similar values for oil as the cooling medium could present difficulties with oil feed and scavenge in small gas turbines). An approach to the design of such a seal is provided by Dr B.S. Nau in Paper No.19. The interface loading in the gap between the sliding surfaces is considered and a computational model presented which allows for cavitation in the interface. When program testing is complete correlation with the results of Paper No.11 should be considered.

L.P. Ludwig's second paper (No.16) showed that some important aspects of gas turbine secondary flow system leakage can be tackled with a fair chance of success. The examination provided for pneumatic self-acting seals, showed that high enough values of pressure, rubbing speed, face run-out and temperature have already been demonstrated to allow consideration for arduous gas turbine application. Furthermore heat generation was much less than conventional carbon contact seals. Methods for dealing with steady and dynamic (seal face runout) situations were described and performance and wear characteristics in tests up to 500 hours duration were discussed. With further effort to prove reliability and in particular low wear rates over a long period, it should be possible to provide a feasible alternative to the present methods of sealing bearing chambers in high pressure environments.

Paper No.17 by Professor D. Dini again identified the advantages of the self-acting pneumatic seal as one of a range of advanced seal types proposed for modern high performance gas turbines. Inexpensive laboratory testing but at engine representative conditions has shown the low leakage potential but with some variations, which may be due to unanticipated local distortions. The paper showed the need to understand accurately the force mechanisms in such seals, if consistency and long life are to be achieved. An oil slinger seal was mentioned, which was also covered by D.C. Whitlock in Paper No.7. This type of seal is quite positive and has no rubbing parts.

Paper No.13 by H.L. Stocker considered performance development of labyrinth seals. Results were presented which showed gains from refinement of seal knife configuration and the effect of the material and construction of the static member. At 0.51 mm clearance and seal pressure ratio of 2.0 (conditions for which stepped seals are generally considered), a leakage flow range of greater than 2:1 was indicated for the full range of seals tested.

At the larger clearances the value of a honeycomb lining on a straight-through seal,and knife inclination for a stepped seal was highlighted. The data are particularly important for demonstrating the effect of rotation. It is clear that the engine designer has been provided with good labyrinth seal performance data, from which seal configurations can be selected, providing of course consideration for the mechanical and rubbing behaviour is given.

Integrity rather than engine performance was the motivation of the remaining two papers in this section. T. Boyman in paper No.8 presented data relevant to bearing chambers sealed by low pressure drop labyrinths. More accurate prediction of the failure point, defined by oil leaking from the bearing chamber through the labyrinth, should be possible from the relationship established between oil outward diffusion rate and inward airflow. H. Benckert in Paper No.9 described the theoretical and experimental examination of the pneumatic forces present with swirling flow through a labyrinth. For machines operating with high density flow the forces can be significant. Further work is in progress covering changes to the labyrinth proportions.

4.4 SYSTEM DESIGN AND MEASUREMENT TECHNIQUES

Integration of bearing chamber seals into the design of the oil system, with particular reference to venting and scavenging arrangements, was described in paper No.7 by D.C. Whitlock. Seal performance was described and assessed against the background of system integrity. Designs ranged from labyrinth sealed chambers of varying degrees of sophistication, to carbon face seals and positive hydraulic seals using the strong centrifugal fields present. Principles and criteria for chamber design, of value to the engine designer, were established.

D.A. Campbell in Paper No.18 presented an approach to the design of disc sealing and cooling systems, an important topic owing to the large disc entrained air flows on present and future high rim speed discs. Minimising the cooling air supplied to disc cavities is dependent on associated seal performance. It is important in the design of these systems that secondary flows are not reduced at the expense of disc integrity. A benefit of 0.5% SFC was quoted for halving disc sealing flows on a large transport engine.

P.E.A. Stewart and K.A. Brasnett in Paper No.10 on X-ray measurement techniques described a powerful diagnostic tool, which does not require special engine preparation other than installation in a medically safe test bed. Transient surveys have generally been made to define the timing for instantaneous X-ray photographs, of high accuracy for a wide range of metal thicknesses. Complementary methods, which can provide continuous output of clearance but which require an engine to be specially instrumented , were described in Paper No.12 by C.R. Amsbury and J.W.H. Chivers. The value of the existing techniques in understanding seal clearance behaviour was stressed. Even so the need for further development of measurement techniques was indicated.

5. ROUND TABLE DISCUSSION

Members: Mr A.J.B. Jackson (Moderator), UK
Ing Gen A. Journeau, France
Mr L.P. Ludwig, U.S.A.
Prof F. Wazelt, Germany
Mr B. Wrigley, UK

Each of the members gave their comments after which there was general discussion.

Several speakers emphasised the need to increase research and development activity. In no way was the effort thought to be equivalent to that in the primary turbo machinery areas, particularly when allowance was made for the possible return on investment. F. Mahler drew attention to the increased dependence on good sealing of the future energy efficient engines and suggested that component aerodynamic design could be dictated by sealing technology.

Attention was also drawn to the necessity for engine designs which maintain roundness and concentricity. It was suggested that positive evidence was available from the most recent large subsonic transport engines, that attention, particularly in the conceptual phase of design, to rotor and casing rigidity, will substantially reduce in-service deterioration rate.

The importance of good measurement techniques was again emphasised. Although the terms of reference of the conference were limited to seals with relative movement, some speakers used this discussion to identify leakage potential between adjacent stationary parts. The value of the conference was stressed as was the need for further meetings.

In his resume Mr Jackson again emphasised the powerful incentive for advancing sealing technology. He thought that the technology was considerably behind turbomachinery and posed a question for operators. Taking the analogy of hot end life extension by adopting 'flexible' thrust ratings, were there operating techniques which would extend seal lives?

6. CONCLUSIONS

- In-service performance deterioration is serious in its direct financial impact and also due to its effect on the maintenance and repair burden.
- Seal deterioration, particularly in the primary flowpath, contributes substantially to the performance deterioration. Although the majority of fresh evidence was from commercial operation, it is well known that the Air Forces suffer similar problems.
- Although much research in this field is in hand, the commitment of resources and money is not commensurate with either the need to fix current engines or the potential return in future energy efficient engines. It appears from an assessment of the papers, against the background of service problems, that the majority of the current research work is of a 'fire-fighting' nature. This seems to apply particularly in the fields of rubbing and erosion, where only slowly is a systematic campaign, aimed at providing a sound base for future designs, being mounted.
- An abrasive coating should be fiercely abrasive to minimise wear beyond the penetration depth and to minimise heat generation. Such coatings are feasible. Plasma spraying seriously reduces abrasiveness.
- The relationship between labyrinth seal flow resistance and clearance and lining material, has been established for a range of labyrinth configurations. However there is scope for further correlation of existing test data.
- Sealing problems generally require an understanding of clearance variation and measurement techniques are vital. Useful techniques, including X-ray measurements, have been described but the need for much more compact probes, which can provide a continuous signal, was identified.
- It appears that there is considerable variation of opinion regarding the sensitivity of compressor efficiency to tip clearance.
- Different engine companies adopt a traditional, perhaps even reactionary approach to bearing chamber sealing. This caution is a consequence of the necessity for extremely high standards of integrity in this context and the failure to provide engine demonstration of alternative approaches. The NASA work on pneumatic self-acting seals is encouraging, particularly for high pressure environments, and has the potential for overcoming some of the draw-backs of current low leakage seals.
- Heat transfer phenomena associated with clearance control was not covered adequately. The following areas are clearly important:-
  - thermal response of rotating discs
  - casing thermal response, particularly the heat transfer mechanism over blade tips
  - heat distribution during a rub
  - local effects in labyrinth seals
- Future energy efficient engines are likely to prove more demanding with respect to the standard of sealing required.

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14. Abstract

This Technical Evaluation Report on the 51st (B) PEP Specialists' Meeting on "Seal Technology in Gas Turbine Engines" surveys critically the 17 papers presented at the meeting and the final Round Table Discussion. An overview on the present status of the employed technology and its shortcomings is reached as well as an overview on the current developments in the field. It is placed within the context of engine operating and maintenance costs and engine design including its relation to the mechanical and aerodynamic performance of engines. Conclusions are drawn and recommendations are given whereto future interest should be directed.

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