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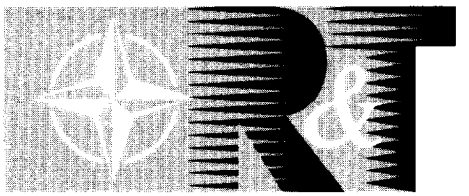

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Gas Turbine Engine Combustion, Emissions and Alternative Fuels

(la Combustion dans les turbomoteurs, les émissions et les carburants de remplacement)

Papers presented at the Applied Vehicle Technology Panel (AVT) Symposium (organized by the former AGARD Propulsion and Energetics Panel (PEP)), held in Lisbon, Portugal, 12-16 October 1998.

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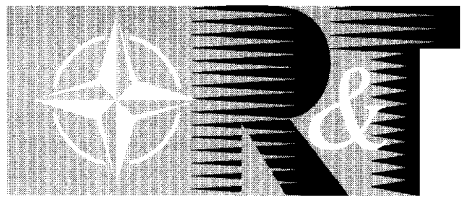

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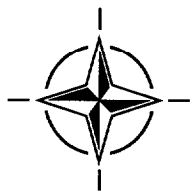

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- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine
- NSPG NATO Simulation Policy Group (Modelling and Simulation)

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

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Gas Turbine Engine Combustion, Emissions and Alternative Fuels

(RTO MP-14)

Executive Summary

NATO efficiency in the future will depend largely on air superiority, long range deployment capacity and rapid response both on land and at sea. The gas turbine engine will remain the power source of choice, and fuel efficiency, fuel availability and exhaust emissions will drive its design. The combustor is one of the crucial engine components and combustion system problems have traditionally contributed to well over half of the engine service problems in most air forces. The symposium focused on and addressed the key challenges for reducing fuel consumption, lowering emission levels and burning alternative fuels as requirements concurrent with improved performance and operation.

Widening the narrow standards of today's fuels offers a short term solution to scarcity but has detrimental effects on combustor life and emission levels. New fuels, such as liquid hydrogen and methane, offer some potential advantages but also pose new combustion problems. The contribution of military engines to emissions is of major concern today and will continue to be in the future. There are additional requirements for military engines such as higher combustion temperatures which are needed for superior efficiency but at the same time low exhaust temperatures and low exhaust volumes to reduce the infrared signature. Operability (blow-out stability and wind milling re-ignition, throttle response, etc.) must be enhanced as the aircraft flight envelope and manoeuvrability are expanded. Component durability must be maintained in an increasingly adverse environment. Combustor design, active control of flame stability, control performance and exhaust gas composition as well as operating procedure optimisation are the aims. Tools for combustion simulation and experimental validation are under continual elaboration to save on development and life cycle costs through better design.

Scientists and engineers met military and civil operators, and discussion concentrated on the customer's future needs and constraints. A review of current R&D activities and formulation of specific research resulted from the Symposium, for which there is no known competing event. Universities, government laboratories, industry and some agencies of the military services were represented and presented their knowledge and advice. The correct makeup of participants was indeed achieved. All papers presented were of good quality and covered new advances in many important areas.

Highlight topics for future AVT symposia in this field would seem to be as follows: gaseous and particulate emissions at altitude, optical diagnostics at elevated pressures in near-real combustors, and active combustion control all of which can crucially contribute to the military usefulness of engines.

La combustion dans les turbomoteurs, les émissions et les carburants de remplacement

(RTO MP-14)

Synthèse

L'efficacité des forces de l'OTAN à l'avenir dépendra largement de la supériorité aérienne, de la capacité de déploiement à grande distance et de l'intervention rapide terrestre et maritime. Le turbomoteur restera le propulseur de choix et sa conception sera guidée par des considérations d'émission de gaz polluants, ainsi que par des questions de rendement et de disponibilité du carburant. La chambre de combustion est l'un des composants clés du moteur et l'expérience montre que plus de la moitié des problèmes d'entretien des moteurs, rencontrés par la majorité des forces aériennes sont liés aux systèmes de combustion. Le symposium a privilégié les défis clés de la diminution de la consommation du carburant, l'atténuation des niveaux d'émission de gaz polluants et l'utilisation de carburants de remplacement en vue d'améliorer les performances et le fonctionnement des turbomoteurs.

Bien que l'assouplissement des normes restrictives qui s'appliquent aux carburants modernes offre une solution à court terme aux problèmes de pénurie, elle s'accompagne d'effets indésirables pour la durée de vie des chambres de combustion et les niveaux d'émission de gaz polluants. Les nouveaux carburants, tels que l'hydrogène liquide et le méthane, s'ils offrent quelques avantages possibles, posent en même temps des problèmes nouveaux de combustion. La contribution des moteurs militaires aux émissions polluantes est, et restera, un sujet de préoccupation majeur. En plus, les moteurs militaires ont des caractéristiques spécifiques, à savoir, des températures de combustion élevées, pour assurer une meilleure efficacité, avec en même temps des températures et des volumes de gaz d'échappement moindres, pour permettre de réduire la signature infrarouge. L'exploitabilité (stabilité en cas de surpression, réallumage en autorotation, réponse du moteur, etc.) doit être améliorée au fur et à mesure de l'augmentation de la maniabilité et de l'élargissement des domaines de vol. Il s'agit également de conserver la longévité des composants dans un environnement de plus en plus contraignant. La conception des chambres de combustion, le contrôle actif de la stabilité de la flamme, les performances en matière de contrôle, la composition des gaz d'échappement et l'optimisation de la procédure d'exploitation sont les objectifs en vue. Les outils de simulation et de validation expérimentale de la combustion sont en évolution permanente dans le but de réaliser des économies sur les coûts de développement et de possession par l'amélioration de la conception.

Les scientifiques et les ingénieurs qui ont assisté à la réunion ont pu rencontrer des exploitants militaires et civils et leurs discussions ont porté essentiellement sur les besoins futurs des clients et les contraintes qui leur sont imposées. Le symposium, qui est, à notre connaissance, unique en son genre, a permis de faire le point des activités de R&D actuelles et de formuler des projets de recherche spécifiques. Les universités, les laboratoires gouvernementaux, les industries et les agences militaires représentés ont exposé leurs connaissances et proposé des conseils. Du point de vue des participants, la répartition était équilibrée. Toutes les communications présentées ont été de bonne qualité, couvrant de nouvelles avancées dans bon nombre de domaines importants.

Les sujets présentant un intérêt particulier pour les futurs symposia AVT dans ce domaine pourraient être : les émissions particulaires et gazeuses en altitude, le diagnostic optique aux pressions élevées dans des chambres de combustion quasi-réelles, et la combustion active, ces sujets pouvant faire l'objet de contributions déterminantes dans le domaine des moteurs militaires.

Contents

† Paper not available at time of printing

Theme

NATO efficiency in the future will depend largely on air superiority, long range deployment capacity and rapid response both on land and at sea. The gas turbine engine will remain the power source of choice, and fuel efficiency, fuel availability, and exhaust emissions will drive its design. The symposium will focus on the combustor as the crucial engine component, and will address the key challenges of reducing fuel consumption, lowering emission levels, and burning alternative fuels. Widening the narrow standards of today's fuels offers a short term solution to scarcity but has detrimental effects on combustor life and emission levels. New fuels, such as liquid hydrogen and methane, offer some potential advantages, but also pose new combustion problems. The use of these fuels will be considered, as will the contribution of military engines to exhaust emission levels, combustor design and operating procedures, and active control of flame stability. Development tools such as combustion simulation and experimental validation will also be discussed. Scientists and engineers will meet military and civil operators and discussion will concentrate on the customer's future needs and constraints. A review of current R&D activities and formulation of specific research may result from the Symposium, for which there is no known competing event.

Thème

L'efficacité, à terme, des forces de l'OTAN dépendra en grande partie de la supériorité aérienne, ainsi que des capacités de déploiement à grande distance et de réaction rapide sur terre et sur mer. Le turbomoteur restera le propulseur de choix et sa conception sera guidée par des considérations de rendement énergétique, de disponibilité de carburant, et d'émission de gaz polluants.

Ce symposium s'attachera à étudier la chambre de combustion en tant que composant propulsif fondamental et il examinera les défis décisifs représentés par la diminution de la consommation de carburant, l'abaissement des niveaux d'émission et les carburants de remplacement. Si l'augmentation des normes actuelles qui s'appliquent aux carburants peut fournir une solution à certains problèmes ponctuels de pénurie, elle a en revanche des effets contraires sur la durée de vie des chambres de combustion et sur les niveaux d'émission. Les nouveaux carburants, tels que l'hydrogène liquide et le méthane, offrent certes des avantages possibles, mais ils posent aussi de nouveaux problèmes de combustion.

L'utilisation de ces carburants sera étudiée, ainsi que l'apport des moteurs militaires aux problèmes des niveaux d'émission des gaz d'échappement, aux procédures de conception et d'exploitation et au contrôle actif de la stabilisation de flamme. Les outils de développement, tels que la simulation de la combustion et la validation expérimentale, seront également pris en compte. Des contacts seront établis entre scientifiques et ingénieurs d'une part, et militaires et exploitants civils d'autre part, avec des échanges de vues sur les attentes futures des utilisateurs et sur les contraintes qui leur sont imposées.

Le symposium, qui est le seul à être organisé sur ce sujet à l'heure actuelle, pourrait aboutir à une mise au point des activités courantes de recherche et développement dans ce domaine, ainsi qu'à la formulation de projets spécifiques de recherche.

Recent Publications on Propulsion and Power Systems of the Former AGARD Propulsion and Energetics Panel and the RTO Applied Vehicle Technology Panel

CONFERENCE PROCEEDINGS (CP)

Combustion and Fuels in Gas Turbine Engines
AGARD CP 422, June 1988

Engine Condition Monitoring — Technology and Experience
AGARD CP 448, October 1988

Application of Advanced Material for Turbomachinery and Rocket Propulsion
AGARD CP 449, March 1989

Combustion Instabilities in Liquid-Fuelled Propulsion Systems
AGARD CP 450, April 1989

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AGARD CP 467, October 1989

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AGARD CP 479, December 1990

Low Temperature Environment Operations of Turboengines (Design and User's Problems)
AGARD CP 480, May 1991

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AGARD CP 510, February 1992

Insensitive Munitions
AGARD CP 511, July 1992

Combat Aircraft Noise
AGARD CP 512, April 1992

Airbreathing Propulsion for Missiles and Projectiles
AGARD CP 526, September 1992

Heat Transfer and Cooling in Gas Turbines
AGARD CP 527, February 1993

Fuels and Combustion Technology for Advanced Aircraft Engines
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AGARD CP 537, March 1994

Erosion, Corrosion and Foreign Object Damage Effects in Gas Turbines
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AGARD CP 559, February 1995

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AGARD CP 571, January 1996

Advanced Aero-Engine Concepts and Controls
AGARD CP 572, June 1996

Service Life of Solid Rocket Propellants
AGARD CP 586, May 1997

Aircraft Fire Safety
AGARD CP 587, September 1997

Future Aerospace Technology in the Service of the Alliance — Sustained Hypersonic Flight
AGARD CP 600, Volume 3, December 1997

Advanced Non-Intrusive Instrumentation for Propulsion Engines
AGARD CP 598, May 1998

MEETING PROCEEDINGS (MP)

Design Principles and Methods for Aircraft Gas Turbine Engines
RTA MP-8, February 1999

ADVISORY REPORTS (AR)

The Uniform Engine Test Programme *(Results of Working Group 15)*
AGARD AR 248, February 1990

Test Cases for Computation of Internal Flows in Aero Engine Components *(Results of Working Group 18)*
AGARD AR 275, July 1990

Test Cases for Engine Life Assessment Technology *(Results of Working Group 20)*
AGARD AR 308, September 1992

Terminology and Assessment Methods of Solid Propellant Rocket Exhaust Signatures *(Results of Working Group 21)*
AGARD AR 287, February 1993

Guide to the Measurement of the Transient Performance of Aircraft Turbine Engines and Components *(Results of Working Group 23)*
AGARD AR 320, March 1994

Experimental and Analytical Methods for the Determination of Connected — Pipe Ramjet and Ducted Rocket Internal Performance *(Results of Working Group 22)*
AGARD AR 323, July 1994

Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines *(Results of Working Group 24)*
AGARD AR 332, September 1995

Structural Assessment of Solid Propellant Grains *(Results of Working Group 25)*
AGARD AR 350, December 1997

CFD Validation for Propulsion System Components *(Results of Working Group 26)*
AGARD AR 355, May 1998

LECTURE SERIES (LS)

Blading Design for Axial Turbomachines
AGARD LS 167, June 1989

Comparative Engine Performance Measurements
AGARD LS 169, May 1990

Combustion of Solid Propellants
AGARD LS 180, July 1991

Steady and Transient Performance Prediction of Gas Turbine Engines
AGARD LS 183, May 1992

Rocket Motor Plume Technology
AGARD LS 188, June 1993

Research and Development of Ram/Scramjets and Turboramjets in Russia
AGARD LS 194, December 1993

Turbomachinery Design Using CFD
AGARD LS 195, May 1994

Mathematical Models of Gas Turbine Engines and their Components
AGARD LS 198, December 1994

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems (LS-211)
published as RTO EN 1, September 1998

AGARDOGRAPHS (AG)

Measurement Uncertainty within the Uniform Engine Test Programme
AGARD AG 307, May 1989

Hazard Studies for Solid Propellant Rocket Motors
AGARD AG 316, September 1990

Advanced Methods for Cascade Testing
AGARD AG 328, August 1993

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AGARD R 745, June 1990

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AGARD R 775, June 1990

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AGARD R 824, March 1997

Impact Study on the use of JET A Fuel in Military Aircraft during Operations in Europe
AGARD R 801, January 1997

The Single Fuel Concept and Operation Desert Shield/Storm
AGARD R 810, January 1997 *(NATO Unclassified)*

Active Combustion Control for Propulsion Systems
AGARD R 820, September 1997

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Combustion chambers	Combustion efficiency
Fuel consumption	Combustion control
Exhaust emissions	Mathematical models
Jet engine fuels	Computerized simulation
Aviation fuels	Optical measurement
Availability	Emission control
Alternative fuels	Design
Aircraft engines	Ignition

14. Abstract

The symposium dealt with Gas Turbine Engine Combustion, Emissions and Alternative Fuels. Forty-six papers and a Keynote Address elucidated the role of the combustion process as a crucial factor of engine performance and operability under various conditions including non-standard, new fuels and environmental effects of civil and military interest.

There were 12 Sessions covering the following topics (some in 2 sessions):

- Gas Turbines in Land, Sea and Air Applications
- Low-Emission Combustors
- Combustion Modelling
- Optical Measurements
- Emissions
- Combustor Design
- Ignition Processes
- Active Combustion Control
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