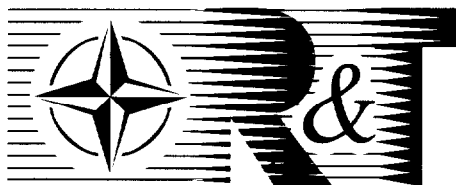


NORTH ATLANTIC TREATY ORGANIZATION



RESEARCH AND TECHNOLOGY ORGANIZATION

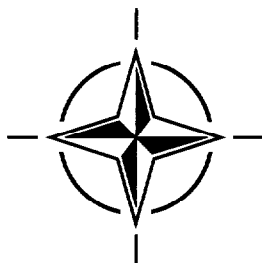
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

RTO LECTURE SERIES 211

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems

(la Conception intégrée des compresseurs multi-étage à haute performance)

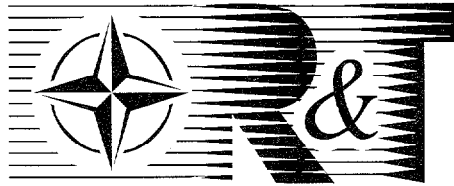
The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.



Published September 1998

Distribution and Availability on Back Cover

NORTH ATLANTIC TREATY ORGANIZATION



RESEARCH AND TECHNOLOGY ORGANIZATION

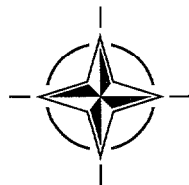
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

RTO LECTURE SERIES 211

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems

(la Conception intégrée des compresseurs multi-étage à haute performance)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.



The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by 6 Panels, dealing with:

- 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

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.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced directly from material supplied by RTO or the authors.



Printed on recycled paper

Published September 1998

Copyright © RTO/NATO 1998
All Rights Reserved

ISBN 92-837-1000-2



*Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7*

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems

(RTO EN-1)

Executive Summary

Today's aircraft gas turbine engines have remarkable performance characteristics. They provide thrust and avoid flame-out during the most demanding manoeuvres. There is also, amongst other attributes, a permanent improvement in fuel economy. Future aircraft will exceed by far today's performance envelopes.

These improvements have been made possible principally due to compressor performance. This Lecture Series covers the recent advances in the process of performing integrated design of high performance multistage compressors.

The purpose is to broaden the compressor designer's understanding beyond traditional fluid dynamics and to include the multidisciplinary systems approach required by modern gas turbine engines for longer life, lower acquisition and maintenance costs.

The design process requires an optimization of the entire machine, which may be significantly different from the best aerodynamic design of each stage or blade row. In addition, many modern engines are simultaneously increasing compressor performance, and reducing machine length, which reinforces the fluid and structure interactions. Finally, in order to reduce both production and maintenance costs, manufacturing constraints have to be taken into account in the initial phase of the design process.

The Lecture Series will underline the role of computational fluid dynamics, as well as solid mechanics and vibration simulations. The need for compressor designs to consider and model mechanical interactions and manufacturing concerns will be a central focus.

Keeping engine development ongoing and joining forces with the Nations is of utmost importance because tomorrow's engines can no longer be developed with today's simulation tools. It must also be seen that present reductions in research oriented budgets endanger the further development. This is another reason for bringing the latest state of the art information to the development engineers of as many NATO Nations as possible and to give them a forum for exchange and discussion, enabling them to further the development with coordinated forces.

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.

La conception intégrée des compresseurs multi-étage à haute performance

(RTO-EN-1)

Synthèse

Les turbomoteurs modernes ont des caractéristiques de performance remarquables. Ils fournissent la poussée nécessaire et évitent l'extinction du réacteur même pendant les manoeuvres les plus difficiles. Parmi d'autres qualités, ils permettent de faire des économies durables au niveau de la consommation du carburant. Les enveloppes de performances d'aujourd'hui seront largement dépassées par les avions de combat de demain.

Ces améliorations sont principalement dues aux performances des compresseurs. Ce cycle de conférences couvre les avancées récentes dans le domaine de la conception intégrée de compresseurs multi-étage à hautes performances.

La conférence a pour objectif de permettre aux concepteurs de compresseurs d'élargir leurs connaissances, traditionnellement axées sur la dynamique des fluides, vers les systèmes pluridisciplinaires dans le but d'augmenter la durée de vie des turbomoteurs modernes et de diminuer les coûts d'acquisition et de maintenance.

Cette méthode de conception, qui exige d'optimiser intégralement le propulseur peut s'avérer tout à fait différente de l'optimisation aérodynamique de chaque étage ou de chaque grille d'aubes. En outre, pour de nombreux moteurs modernes, l'accroissement des performances en matière de compression va de pair avec une diminution de la taille, ce qui a pour effet d'améliorer les interactions entre le fluide et la structure. Enfin, il faut également tenir compte des contraintes de fabrication lors de la phase initiale de conception, afin de réduire les coûts de production et de maintenance.

Ce cycle de conférences soulignera le rôle de l'aérodynamique numérique dans ce processus, ainsi que celui de la mécanique des solides et de la simulation des vibrations. La prise en compte et la modélisation des interactions mécaniques, ainsi que les aspects industriels, constitueront le thème central de la conférence.

Il est d'une importance capitale de maintenir les activités de développement des moteurs d'avion en rassemblant les efforts des différents pays de l'OTAN, car il n'est plus envisageable de développer les moteurs de demain avec les moyens de simulation d'aujourd'hui. Cependant, les diminutions actuelles des budgets de recherche risquent de compromettre ces activités. Pour toutes ces raisons, il est important de mettre les dernières connaissances techniques à la disposition des ingénieurs concepteurs du plus grand nombre des pays de l'OTAN, et de leur offrir un forum pour des discussions et des échanges, leur permettant de coordonner et de faire avancer leur travaux de développement.

Les textes contenus dans cette publication ont été présentés lors d'un cycle de conférences organisé par la commission RTO des technologies appliquées aux véhicules, sous l'égide du programme des consultants et des échanges, du 14 au 15 septembre 1998 à Lyon en France, du 17 au 18 septembre 1998 à Cologne en Allemagne, et du 22 au 23 septembre 1998 à Cleveland aux Etats-Unis.

Contents

	Page
Executive Summary	iii
Synthèse	iv
List of Authors/Speakers	vi
	Reference
Introduction and Overview on Integretaged Design of High Pressure Multistage Engine Systems by Professor F. Leboeuf	I
The Multidisciplinary Design Process by Professor H.-P. Kau	1
Recent Advances in Compressor Aerodynamic Design and Analysis by Mr. J.F. Escuret, Mr. D. Nicoud and Mr. Ph. Veysseyre	2
First Order Manufacturing Constraints & Requirements - Session 1 by Mr. M.W. Bailey, Mr. G.T. Steinmetz, Mr. R.E. Kielb, Mr. L.L. Long, Mr. J.G. Herbert and Mr. J.M. Vishnauski	3
Compressor Matching and Designing for Tip Clearance by Professor H.-P. Kau	4
Design to Cost and Manufacturing Process Considerations - Session 2 by Mr. M.W. Bailey, Mr. L.L. Long and Mr. J.G. Herbert	5
Common Geometry and Multidisciplinary Design & Optimization - Session 3 by Mr. M.W. Bailey and Mr. J.M. Vishnauski	6
Bibliography	B

List of Authors/Speakers

Lecture Series Director: Professor Francis LEBOEUF
Ecole Centrale de Lyon
Directeur de l'Administration de la Recherche
36 Avenue Guy de Collongue
BP163
69131 ECULLY Cedex

Mr. Philippe VEYSSEYRE
Compressor Aerodynamics Department
Direction Technique
SNECMA
77550 Moissy Cramayel
FRANCE

Professor Hans Peter KAU
University of Technology Munich
Lehrstuhl für Flugantriebe
Boltzmannstrasse 15
D-85747 Garching
GERMANY

Mr. Michael BAILEY
General Electric Aircraft Engines
1, Neumann Way MD A410
Cincinnati, Ohio 45213-6301
USA

Co-Authors

Mr. J.F. ESCURET
Compressor Aerodynamics Dept.
SNECMA
77550 Moissy Cramayel
FRANCE

Mr. D. NICOUD
Compressor Aerodynamics Dept.
SNECMA
77550 Moissy Cramayel
FRANCE

Mr. Jon M. VISHNAUSKI
General Electric Aircraft Engines
1, Neumann Way
Cincinnati, Ohio 45213
USA

Mr. Loren L. LONG
General Electric Aircraft Engines
1, Neumann Way
Cincinnati, Ohio 45213
USA

Mr. Jeffery G. HERBERT
General Electric Aircraft Engines
1, Neumann Way
Cincinnati, Ohio 45213
USA

Mr. Gregory T. STEINMETZ
General Electric Aircraft Engines
1, Neumann Way
Cincinnati, Ohio 45213
USA

Mr. Robert E. KIELB
General Electric Aircraft Engines
1, Neumann Way
Cincinnati, Ohio 45213
USA

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References RTO EN-1 AC/323 (AVT) TP/1	3. Further Reference ISBN 92-837-1000-2	4. Security Classification of Document UNCLASSIFIED/ UNLIMITED														
5. Originator Research and Technology Organization North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly-sur-Seine, France																	
6. Title Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems																	
7. Presented at/sponsored by The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel and the Consultant and Exchange Programme of RTO presented on 14-15 September 1998 in Lyon, France, on 17-18 September 1998 in Cologne, Germany, and on 22-23 September 1998 in Cleveland, USA.																	
8. Author(s)/Editor(s) Multiple			9. Date September 1998														
10. Author's/Editor's Address Multiple			11. Pages 156														
12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.																	
13. Keywords/Descriptors <table style="width: 100%; border: none;"> <tr> <td style="width: 50%;">Gas turbine engines</td> <td style="width: 50%;">Mechanics</td> </tr> <tr> <td>Aircraft engines</td> <td>Aerodynamic characteristics</td> </tr> <tr> <td>Performance</td> <td>Maintenance</td> </tr> <tr> <td>Compressors</td> <td>Manufacturing</td> </tr> <tr> <td>Design</td> <td>Vibration</td> </tr> <tr> <td>Computational fluid dynamics</td> <td>Simulation</td> </tr> <tr> <td>Optimization</td> <td></td> </tr> </table>				Gas turbine engines	Mechanics	Aircraft engines	Aerodynamic characteristics	Performance	Maintenance	Compressors	Manufacturing	Design	Vibration	Computational fluid dynamics	Simulation	Optimization	
Gas turbine engines	Mechanics																
Aircraft engines	Aerodynamic characteristics																
Performance	Maintenance																
Compressors	Manufacturing																
Design	Vibration																
Computational fluid dynamics	Simulation																
Optimization																	
14. Abstract <p>This Lecture Series covers the recent advances in the process of performing integrated design of high performance multistage compressors.</p> <p>The purpose is to broaden the compressor designer's understanding beyond traditional fluid dynamics to include the multidisciplinary systems approach required by modern gas turbine engines for longer life, lower acquisition and maintenance costs.</p> <p>The design process requires an optimization of the entire machine, which may be significantly different from the best aerodynamic design of each stage or blade row. In addition, many modern engines are simultaneously increasing compressor performance, and reducing machine length, which reinforces the fluid and structure interactions. Finally, in order to reduce both production and maintenance costs, manufacturing constraints have to be taken into account in the initial phase of the design process.</p> <p>The Lecture Series underlines the role of Computational Fluid Dynamics, as well as solid mechanics and vibration simulations. The need for compressor designs to consider and model mechanical interactions and manufacturing concerns will be a central focus.</p> <p>The subjects to be covered are:</p> <ul style="list-style-type: none"> • Flow simulations with special emphasis on three-dimensional computations and on the stage stacking and interactions in multistage compressors. • Modelling the fluid structure interactions. • First order manufacturing constraints and requirements. <p>This Lecture Series, sponsored by the Applied Vehicle Technology Panel (AVT) of RTO, has been implemented by the Consultant and Exchange Programme.</p>																	



RESEARCH AND TECHNOLOGY ORGANIZATION

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Télécopie 0(1)55.61.22.99 • Téléc 610 176

DIFFUSION DES PUBLICATIONS

RTO NON CLASSIFIEES

L'Organisation pour la recherche et la technologie de l'OTAN (RTO), détient un stock limité de certaines de ses publications récentes, ainsi que de celles de l'ancien AGARD (Groupe consultatif pour la recherche et les réalisations aérospatiales de l'OTAN). Celles-ci pourront éventuellement être obtenues sous forme de copie papier. Pour de plus amples renseignements concernant l'achat de ces ouvrages, adressez-vous par lettre ou par télécopie à l'adresse indiquée ci-dessus. Veuillez ne pas téléphoner.

Des exemplaires supplémentaires peuvent parfois être obtenus auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la RTO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus sur la liste d'envoi de l'un de ces centres.

Les publications de la RTO et de l'AGARD sont en vente auprès des agences de vente indiquées ci-dessous, sous forme de photocopie ou de microfiche. Certains originaux peuvent également être obtenus auprès de CASI.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE

Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

BELGIQUE

Coordinateur RTO - VSL/RTO
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, B-1140 Bruxelles

CANADA

Directeur - Gestion de l'information
(Recherche et développement) - DRDGI 3
Ministère de la Défense nationale
Ottawa, Ontario K1A 0K2

DANEMARK

Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE

INTA (RTO/AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

ETATS-UNIS

NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076

FRANCE

O.N.E.R.A. (Direction)
29, Avenue de la Division Leclerc
92322 Châtillon Cedex

GRECE

Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ISLANDE

Director of Aviation
c/o Flugrad
Reykjavik

ITALIE

Aeronautica Militare
Ufficio Stralcio RTO/AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG

Voir Belgique

NORVEGE

Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PAYS-BAS

RTO Coordination Office
National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM Amsterdam

PORTUGAL

Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

ROYAUME-UNI

Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE

Millî Savunma Başkanlığı (MSB)
ARGE Dairesi Başkanlığı (MSB)
06650 Bakanlıklar - Ankara

AGENCES DE VENTE

NASA Center for AeroSpace
Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076
Etats-Unis

The British Library Document
Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume-Uni

Canada Institute for Scientific and
Technical Information (CISTI)
National Research Council
Document Delivery,
Montreal Road, Building M-55
Ottawa K1A 0S2
Canada

Les demandes de documents RTO ou AGARD doivent comporter la dénomination "RTO" ou "AGARD" selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants:

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de
ressources uniformes (URL) suivant:
<http://www.sti.nasa.gov/Pubs/star/Star.html>
STAR est édité par CASI dans le cadre du programme
NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
Etats-Unis

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
Etats-Unis
(accessible également en mode interactif dans la base de
données bibliographiques en ligne du NTIS, et sur CD-ROM)





RESEARCH AND TECHNOLOGY ORGANIZATION

7 RUE ANCELLE • 92200 NEUILLY-SUR-SEINE

FRANCE

Telefax 0(1)55.61.22.99 • Telex 610 176

DISTRIBUTION OF UNCLASSIFIED
RTO PUBLICATIONS

NATO's Research and Technology Organization (RTO) holds limited quantities of some of its recent publications and those of the former AGARD (Advisory Group for Aerospace Research & Development of NATO), and these may be available for purchase in hard copy form. For more information, write or send a telefax to the address given above. **Please do not telephone.**

Further copies are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO publications, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your organisation) in their distribution.

RTO and AGARD publications may be purchased from the Sales Agencies listed below, in photocopy or microfiche form. Original copies of some publications may be available from CASI.

NATIONAL DISTRIBUTION CENTRES

BELGIUM

Coordinateur RTO - VSL/RTO
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, B-1140 Bruxelles

CANADA

Director Research & Development
Information Management - DRDIM 3
Dept of National Defence
Ottawa, Ontario K1A 0K2

DENMARK

Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE

O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92322 Châtillon Cedex

GERMANY

Fachinformationszentrum Karlsruhe
D-76344 Eggenstein-Leopoldshafen 2

GREECE

Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ICELAND

Director of Aviation
c/o Flugrad
Reykjavik

ITALY

Aeronautica Militare
Ufficio Stralcio RTO/AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG

See Belgium

NETHERLANDS

RTO Coordination Office
National Aerospace Laboratory, NLR
P.O. Box 90502
1006 BM Amsterdam

NORWAY

Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PORTUGAL

Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

SPAIN

INTA (RTO/AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

TURKEY

Millî Savunma Başkanlığı (MSB)
ARGE Dairesi Başkanlığı (MSB)
06650 Bakanlıklar - Ankara

UNITED KINGDOM

Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES

NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076

SALES AGENCIES

NASA Center for AeroSpace
Information (CASI)

Parkway Center
7121 Standard Drive
Hanover, MD 21076
United States

The British Library Document
Supply Centre

Boston Spa, Wetherby
West Yorkshire LS23 7BQ
United Kingdom

Canada Institute for Scientific and
Technical Information (CISTI)

National Research Council
Document Delivery,
Montreal Road, Building M-55
Ottawa K1A 0S2
Canada

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)

STAR is available on-line at the following uniform resource locator:

<http://www.sti.nasa.gov/Pubs/star/Star.html>
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
United States

Government Reports Announcements & Index (GRA&I)

published by the National Technical Information Service
Springfield
Virginia 22161
United States
(also available online in the NTIS Bibliographic Database or on CD-ROM)



Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7