TP 13929E

CVR EXPLOSION ANALYSIS TECHNIQUE
Development and Evaluation

Prepared for
Transportation Development Centre
Transport Canada

by
Wayne Jackson, Ed.

May 2002

TP 13929E

CVR EXPLOSION ANALYSIS TECHNIQUE
Development and Evaluation

by
Wayne Jackson (Editor), Ottawa
and
Steve Hall, Structural Disaster Diagnosis Canada Inc.
Frank Slingerland, Structural Disaster Diagnosis Canada Inc.
Kevin Sharpe, Defence Evaluation and Research Agency, UK
Stuart Dyne, Institute of Sound and Vibration Research, University of Southampton
Elias Politis, Institute for Aerospace Research, National Research Council Canada
Mike Poole, Transportation Safety Board of Canada

May 2002

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 13929E	2. Project No. 9795	3. Recipient's Catalogue No.
4. Title and Subtitle CVR Explosion Analysis Technique: Development and Evaluation		5. Publication Date May 2002
		6. Performing Organization Document No.
7. Author(s) Wayne Jackson (ed.), Steve Hall, Frank Slingerland, et al.		8. Transport Canada File No. ZCD2450-B-294
9. Performing Organization Name and Address Wayne Jackson, Consultant 2200 Elder Street Ottawa, Ontario K2B 6N1		10. PWGSC File No. XSD-9-01751
		11. PWGSC or Transport Canada Contract No. T8200-9-9565/001/XSD
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer H. Polsuns

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by Transport Canada and the U.S. Federal Aviation Administration

16. Abstract

Investigation agencies believe that a detector that can discriminate between structural failures and explosions as the cause of in-flight break-ups would result in substantial improvements in the quality and efficiency of the investigation of such events. This project continued the development and evaluation of the Cockpit Voice Recorder (CVR) Explosion Analysis (CVREA) technique, which is based on the analysis of spectrograms from CVRs. Activities included the automation of the technique, the collection and analysis of data from a ground test, and an evaluation that included reviewing the development history and theoretical basis, conducting a training course and blind test, and soliciting the opinion of other experts.

While the evaluation identified a number of areas of agreement among the experts, it was concluded that the CVREA technique is not suitable for use by investigation agencies. It is recommended that research focussed only on the CVREA technique no longer be supported unless convincing evidence on the validity of the technique is presented. After a review of all available information on the structural response of aircraft to explosions and rapid decompressions, consideration should be given to several suggestions for continuing research toward finding methods of determining the cause of in-flight break-ups.

17. Key Words Aircraft, explosion, accident investigation, cockpit voice recorder, CVR, cockpit area microphone, CAM, in-flight break-up, spectrographic analysis	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xviii, 34	Shipping/ Handling

Transports Canada | Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 13929E	2. N° de l'étude 9795	3. N° de catalogue du destinataire
4. Titre et sous-titre CVR Explosion Analysis Technique: Development and Evaluation		5. Date de la publication Mai 2002 6. N° de document de l'organisme exécutant
7. Auteur(s) Wayne Jackson (ed.), Steve Hall, Frank Slingerland, et al.		8. N° de dossier - Transports Canada ZCD2450-B-294
9. Nom et adresse de l'organisme exécutant Wayne Jackson, Consultant 2200 Elder Street Ottawa, Ontario K2B 6N1		10. N° de dossier - TPSGC XSD-9-01751 11. N° de contrat - TPSGC ou Transports Canada T8200-9-9565/001/XSD
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet H. Posluns

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par Transports Canada et la Federal Aviation Administration des États-Unis

16. Résumé

Les organismes d'enquête estiment que la qualité et l'efficacité des enquêtes sur les ruptures explosives en vol d'aéronefs seraient grandement améliorées s'il existait un détecteur capable de déterminer la cause de ces explosions : défaillance structurale ou bombe. Ce projet consistait à parachever le développement et l'évaluation de la technique d'analyse d'explosions au moyen de l'enregistreur de conversation du poste de pilotage (CVREA), fondée sur l'analyse de spectrogrammes produits à partir des signaux enregistrés par le CVR. Il comprenait les activités suivantes : automatisation de la technique, collecte et analyse des données d'un essai au sol, évaluation de la technique (y compris de sa genèse et de son fondement théorique), organisation d'un cours de formation et d'un essai aveugle, et consultation d'experts extérieurs au projet.

Malgré le consensus auquel sont arrivés les experts sur un certain nombre de questions, la conclusion à retenir de l'évaluation est que la technique CVREA ne se prête pas à l'utilisation que voudraient en faire les organismes d'enquête. Il est donc recommandé de cesser d'appuyer la recherche uniquement concentrée sur la technique CVREA, à moins que des preuves convaincantes de la validité de la technique soient présentées. Pour l'avenir, il y aurait lieu, après examen de l'information disponible sur la réponse des structures d'aéronefs aux explosions et décompressions rapides, d'examiner les projets soumis pour la poursuite de la recherche sur les techniques de détermination des causes des ruptures explosives en vol.

17. Mots clés Aéronef, explosion, enquête sur accident, enregistreur de conversation du poste de pilotage, CVR, microphone d'ambiance, CAM, rupture explosive en vol, analyse spectrographique	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xviii, 34	Port et manutention

CDT/TDC 79-005
Rev. 96

Canada

ACKNOWLEDGEMENTS

The significant contributions of Mr. Frank Slingerland toward this research over the past fifteen years are recognized. Mr. Slingerland continues to pursue the objectives of this project with ingenuity, energy and determination. The effort and dedication of people such as Mr. Slingerland continue to challenge us all to expand our knowledge and understanding of complex technical issues, to the benefit of the whole aerospace community.

Transport Canada and the U.S. Federal Aviation Administration sponsored this research and development project. Additional financial support was provided by the Transportation Safety Board of Canada and the Canadian Police Research Centre.

The following individuals and organizations participated in or supported this project:

Project Review Committee

Howard Posluns (Co-Chair)	Transportation Development Centre, Transport Canada
Nick Cartwright (Co-Chair)	Canadian Police Research Centre
Lyle Malotky	U.S. Federal Aviation Administration
Marcel Faivre	Security Operations, Transport Canada
Barry Gaudette	Canadian Police Research Centre
Elias Politis	Institute for Aerospace Research, National Research Council Canada
John Garstang	Transportation Safety Board of Canada
Mike Poole	Transportation Safety Board of Canada
Jim Cash	U.S. National Transportation Safety Board
Peter Sheppard	U.K. Air Accidents Investigation Branch
Wayne Jackson	Consultant, Transportation Development Centre, Transport Canada

Structural Disaster Diagnosis Canada Inc. (SDDC) Project Team

Steve Hall
Frank Slingerland
John Miner
Dr. Nabih Abdelmalek
Alina Sintu
Anne Taylor
Nicole Boivin
Owen Lawrence

DERA/ISVR Project Team

Kevin Sharpe	Defence Evaluation and Research Agency
Stuart Dyne	Institute of Sound and Vibration Research

Technical Working Group

Rick Burdette	U.S. Federal Aviation Administration
Bob Hoyle	Transportation Safety Board of Canada
Brian Maranda	Canadian Department of National Defence
Nick Cartwright	
Wayne Jackson	
Elias Politis	

Tucson Data Collection

Richard Allen	Defence Evaluation and Research Agency
Stuart Dyne	
Kevin Sharpe	

The following FAA staff kindly approved, coordinated and assisted in the Tucson data collection:

Rick Burdette
Nelson Carey
Howard Fleisher
Ken Hacker
Lyle Malotky
Bill Morgan
Ray Schillinger

The following SDDC staff assisted in the Tucson data collection

Steve Hall
Frank Slingerland

Validation Test Coordination Group

Stuart Dyne
Wayne Jackson
Elias Politis
Mike Poole
Kevin Sharpe

The U.S. National Transportation Safety Board, the U.K. Air Accidents Investigation Branch, France’s Bureau d’Enquêtes et d’Analyses, the Transportation Safety Board of Canada and National Research Council Canada’s Institute for Aerospace Research provided the event recordings that were used for the validation, training and blind test.

Elias Politis collected and stored the event recordings.

Training Course Presenters

Steve Hall
John Miner
Frank Slingerland

Training Course Participants

Anna Cushman	U.S. National Transportation Safety Board
Sebastien David	Bureau d’Enquêtes et d’Analyses of France
Richard James	U.K. Air Accidents Investigation Branch
Philippe Plantain de Hugues	Bureau d’Enquêtes et d’Analyses of France
Greg Smith	United States Air Force
Stuart Dyne	
Bob Hoyle	
Wayne Jackson	
Elias Politis	
Kevin Sharpe	

Gerry Marsters, president of AeroVations Inc., provided many valuable comments and suggestions on the content and structure of this report.

EXECUTIVE SUMMARY

This report presents the activities, results, recommendations and conclusions of the Cockpit Voice Recorder (CVR) Explosion Analysis (CVREA) project. The objective of this project was to continue the development and evaluation of the CVREA technique, which could potentially determine the nature and location of an event that caused an in-flight break-up.

In some accidents, it has been difficult for investigators to determine whether an explosion or a structural failure caused an in-flight break-up. Air safety investigation and law enforcement agencies believe that any method that could provide this discrimination early in the investigation would result in substantial improvements in the quality and efficiency of the investigation of this type of accident.

The CVREA technique has been under development by Frank Slingerland since 1985 and is based on the interpretation of spectrograms generated from the recordings of cockpit area microphones (CAM). The CVREA technique has the advantage of using only the CAM/CVR equipment that already exists on most aircraft. Other proposed solutions to this problem would require the installation of new sensors and thus could take several years before being widely available.

Based on a proposal from Structural Disaster Diagnosis Canada Inc. (SDDC), the Transportation Development Centre of Transport Canada awarded a contract to SDDC to develop a computerized version of the CVREA technique.

At the beginning of this project, SDDC felt that the CVREA technique had been perfected and used successfully by Mr. Slingerland in the analysis of a number of aircraft crash investigations. However, it soon became evident that other experts, who had examined the technique closely over several years, were not convinced that the technique had been satisfactorily demonstrated as a tool suitable for use by air safety investigation and law enforcement agencies.

In view of these conflicting opinions and the potential benefits of the CVREA technique, it was decided to conduct an independent evaluation of the technique in addition to developing the computerized version of the technique. A Validation Test Coordination Group (VTCG) was formed to conduct the independent evaluation, and a contract was awarded to the UK Defence Evaluation and Research Agency (DERA) and the Institute of Sound and Vibration Research (ISVR) of the University of Southampton to assist in the evaluation.

The project began in September 1997 and was completed in January 2002. Major project tasks were conducted by SDDC, DERA, ISVR and the VTCG.

The project included three major activities: CVREA system development, collection and analysis of data from a ground trial, and independent evaluation of the CVREA technique.

At the beginning of the project, SDDC published two reports authored by Mr. Slingerland on the history of development and the theoretical basis of the CVREA technique.

In the past, Mr. Slingerland had found that the application of the CVREA technique was both tedious and time-consuming, and that optimization of Fast Fourier Transform parameters was not practical. The data interpretation itself involved laborious graphical measurements and hand calculations. SDDC proposed that computer automation would assist a trained practitioner to rapidly apply the technique. The PRC believed that an automated system would also facilitate the blind test.

During the system design phase, SDDC conducted a review of data processing and smoothing algorithms to identify the most suitable algorithms and smoothing techniques for the CVREA technique. SDDC produced operational concept and design documents for the CVREA system. A technical working group reviewed the technical documentation produced by SDDC. The CVREA system was built and tested by SDDC.

In September 1999, the U.S. Federal Aviation Administration (FAA) conducted a full-scale explosion trial in Tucson, Arizona, as part of an effort to characterize aircraft vulnerability to damage. Data was collected at this trial by DERA and ISVR with assistance from the FAA and SDDC. This data was used by SDDC for the validation of the CVREA technique and system, and by SDDC and ISVR for detailed analyses of the explosion signatures.

While the principal effort in the independent evaluation would be the training course and blind test, the VTCG understood that Mr. Slingerland and others had evaluated the CVREA technique on a number of previous occasions. The VTCG included these previous results in the evaluation, where possible. The VTCG used the following evaluation methods:

- review the history of development,
- participate in the training course,
- conduct a blind test,
- analyse data from a ground test,
- review the theoretical basis of the technique, and
- solicit comments from all interested safety and criminal investigation agencies.

Based on a comprehensive review of the documents published by SDDC and Mr. Slingerland, and discussions among SDDC and other experts, the following areas of agreement were identified:

- The best use should be made of existing CAM/CVR systems.
- Vibrations originating from explosions and rapid decompressions are recorded by the CVR following their transmission along the fuselage to the CAM.
- Fuselage vibration waves arrive at the CAM well before the corresponding acoustic waves travelling in air.

- The predominant features of recorded signatures of explosions and rapid decompressions are normally repeatable, implying that they are not random signals, although they are very complex.
- CAM/CVR systems are not designed for precise measurement of fuselage vibrations.
- Fuselage vibrations are not quantitatively consistent with thin cylinder theory.
- The SDDC guidelines for the placement of curves on spectrograms are based primarily on heuristic laws derived from Mr. Slingerland's previous analysis of recordings.

The same review identified the following major areas in which experts could not come to a consensus with respect to the CVREA technique:

- the mechanism that initiates the vibration of the fuselage for both explosions and rapid decompressions,
- the aircraft producing a vibration response leading to simple coherent radial dispersive vibration waves,
- the clarity of successive reflections of vibration waves from the front and rear pressure bulkheads,
- the placement of curves on the spectrograms consistent with the presence of coherent radial dispersive vibration waves, and
- the changes in nose frequencies indicating the nature of the event.

The VTCG found that the CVREA technique was not demonstrated in a substantial and convincing manner, such as would be required by potential users. Based on the evaluation, the CVREA technique is not considered suitable for use by air safety investigation and law enforcement agencies. The following were identified as the main areas of concern by the VTCG:

- the lack of independent verification of Mr. Slingerland's previous results,
- little evidence of the successful application of the technique by anyone other than Mr. Slingerland,
- the lack of a satisfactory demonstration by Mr. Slingerland of the analysis of any of the cases he had previously analysed,
- the inability of the training course participants to analyse any case using the guidelines provided by SDDC,
- the disappointing results of the blind test,
- the lack of acceptance and support for the validation of the technique from other experts, and
- the lack of a quantitative theoretical basis for the CVREA technique.

While no other techniques based on existing flight recorders were found to be usable for determining the nature and location of an event causing an in-flight break-up, some potential techniques based on existing and new sensors were identified.

The following recommendations are offered based on the results of this project:

- Research that is focussed only on the CVREA technique should no longer be supported unless substantial and convincing evidence on the validity of the technique is presented.

- Before conducting any further research with respect to the investigation of in-flight break-ups, all available information on the structural response of aircraft to explosions and rapid decompressions should be reviewed. This review should include information available from research conducted by ISVR, DERA, SDDC and Mr. Slingerland.

- Depending on the results of the review, a number of research suggestions from SDDC, ISVR and DERA should be considered. These suggestions include the study of the vibration response of thin braced cylinders using relatively inexpensive coupons, the use of regression analysis on CAM recordings, the construction and systematic analysis of an archive of all available CVR recordings, the development of a mathematical model for response prediction, the possible use of existing recorders and sensors, and the possible use of new types of sensors (such as pressure transducers).

SOMMAIRE

Ce rapport présente les activités, résultats, recommandations et conclusions du projet Analyse d'explosions au moyen de l'enregistreur de conversation du poste de pilotage (CVREA). Ce projet avait pour objectif de parachever le développement et l'évaluation de la technique CVREA, qui pourrait éventuellement servir à déterminer la nature et l'emplacement d'un événement à l'origine d'une rupture explosive en vol.

Lors d'enquêtes sur certains accidents, il a été difficile pour les enquêteurs de déterminer si la rupture de l'aéronef en vol avait pour cause une explosion ou une défaillance structurale. Les organismes responsables de la sécurité aérienne et de l'exécution de la loi estiment que s'ils disposaient d'une technique qui leur permettrait de départager ces causes tôt dans l'enquête, cela améliorerait grandement la qualité et l'efficacité de leur travail.

La technique CVREA, sur laquelle Frank Slingerland travaille depuis 1985, est fondée sur l'interprétation de spectrogrammes produits à partir des enregistrements du microphone d'ambiance du poste de pilotage (CAM). Cette technique a pour avantage de n'utiliser que du matériel (CAM et CVR) dont sont déjà équipés la plupart des aéronefs. Les autres solutions proposées pour résoudre ce problème exigeraient l'installation de nouveaux capteurs et il faudrait donc attendre plusieurs années avant que leur emploi soit généralisé.

En réponse à une proposition reçue de Structural Disaster Diagnosis Canada Inc. (SDDC), le Centre de développement des transports de Transports Canada a attribué un contrat à cette firme visant le développement d'une version informatisée de la technique CVREA.

Lorsqu'elle a entamé ses travaux, SDDC croyait que la technique CVREA avait été perfectionnée et utilisée avec succès par M. Slingerland dans l'analyse d'un nombre appréciable d'enquêtes sur des accidents d'aéronefs. Mais elle a vite appris que d'autres experts, qui avaient examiné attentivement la technique pendant plusieurs années, estimaient qu'il n'avait pas été démontré de manière satisfaisante qu'elle pouvait se prêter à l'utilisation que voulaient en faire les organismes d'enquête et d'exécution de la loi.

Au vu de ces opinions divergentes et compte tenu des avantages que pouvait représenter la technique CVREA, il a été décidé de mener une évaluation indépendante de la technique, en plus de mettre au point sa version informatisée. Un groupe de coordination de l'essai de validation (GCEV) a été créé aux fins de l'évaluation indépendante et un contrat a été attribué à la UK Defence Evaluation and Research Agency (DERA) et à l'Institute of Sound and Vibration Research (ISVR) de l'Université de Southampton pour une assistance à l'évaluation.

Le projet a débuté en septembre 1997, pour se terminer en janvier 2002. Les principales tâches associées au projet ont été réalisées par SDDC, la DERA, l'ISVR et le GCEV.

Le projet comportait trois grandes activités : développement du système CVREA, collecte et analyse des données d'un essai au sol et évaluation indépendante de la technique CVREA.

Au début du projet, SDDC a publié deux rapports rédigés par M. Slingerland sur la genèse et le fondement théorique de la technique CVREA.

Par le passé, M. Slingerland avait constaté que l'application de la technique CVREA était longue et fastidieuse et qu'il n'était pas pratique d'optimiser les paramètres de la transformée de Fourier rapide. La seule interprétation des données exigeait des mesures graphiques et des calculs à la main laborieux. SDDC a proposé d'informatiser la technique, de façon qu'un praticien spécialement formé puisse l'appliquer rapidement. Le CRP estimait qu'un système automatisé faciliterait également l'essai aveugle.

Aux fins de la conception du système, SDDC a examiné les algorithmes de traitement et de lissage des données, afin de déterminer ceux qui convenaient le mieux à la technique CVREA. Elle a ensuite produit les documents de définition conceptuelle et opérationnelle du système CVREA, documents qui ont été soumis à l'examen d'un groupe de travail technique. La firme a finalement construit et mis à l'essai le système CVREA.

En septembre 1999, la U.S. Federal Aviation Administration (FAA) a mené un essai d'explosion en vraie grandeur à Tucson, Arizona, dans le cadre de travaux visant à caractériser la vulnérabilité des aéronefs à l'endommagement. La DERA et l'ISVR ont colligé les données d'essai, appuyés par la FAA et SDDC. Ces données ont été utilisées par SDDC pour la validation de la technique et du système CVREA, et par SDDC et l'ISVR, pour des analyses détaillées des signatures d'explosions.

L'évaluation indépendante consistait principalement en un cours de formation et un essai aveugle. Mais le GCEV ayant appris que M. Slingerland et d'autres avaient déjà évalué la technique CVREA à quelques reprises, il a décidé d'intégrer les résultats de ces travaux antérieurs à sa propre évaluation, dans la mesure du possible. Le GCEV a eu recours aux méthodes suivantes pour mener son évaluation :

- examen de la genèse de la technique,
- participation au cours de formation,
- réalisation d'un essai aveugle,
- analyse des données d'essai au sol,
- examen du fondement théorique de la technique,
- sollicitation de commentaires de la part de tous les organismes d'enquête de sécurité et d'enquêtes criminelles intéressés.

Au terme d’une revue exhaustive des documents publiés par SDDC et par M. Slingerland, et de discussions entre SDDC et d’autres experts, les consensus suivants sont ressortis :

- Il faut tirer le meilleur profit possible des systèmes CAM/CVR existants.
- Les vibrations engendrées par les explosions et les décompressions rapides sont enregistrées par le CVR après qu’elles se sont propagées dans le fuselage jusqu’au microphone d’ambiance.
- Les ondes de vibration du fuselage atteignent le microphone d’ambiance bien avant les ondes acoustiques correspondantes, qui voyagent dans l’air.
- Les caractéristiques prépondérantes des signatures des explosions et des décompressions rapides enregistrées sont normalement répétables; il ne s’agit donc pas de signaux aléatoires, même s’ils sont très complexes.
- Les systèmes CAM/CVR ne sont pas conçus pour permettre une mesure précise des vibrations du fuselage.
- Sur le plan quantitatif, les vibrations du fuselage ne concordent pas avec la théorie des profils minces.
- Les lignes directrices de SDDC pour le tracé de courbes sur les spectrogrammes découlent principalement des lois heuristiques dérivées d’analyses antérieures des enregistrements par M. Slingerland.

La même revue a aussi permis de mettre au jour les principales questions sur lesquelles les experts divergent, concernant la technique CVREA :

- Le mécanisme qui déclenche la vibration du fuselage, tant dans le cas d’une explosion que d’une décompression rapide.
- La production par l’aéronef d’une réponse vibratoire menant à de simples ondes de vibration cohérentes à dispersion radiale.
- La clarté des réflexions successives des ondes de vibration sur les cloisons étanches avant et arrière.
- Le tracé de courbes sur les spectrogrammes concordant avec la présence d’ondes de vibration cohérentes à dispersion radiale.
- Les changements de fréquence dans la section avant du fuselage indiquant la nature de l’événement.

Le GCEV a conclu que la validité de la technique CVREA n’a pas été démontrée de façon sérieuse et convaincante, comme l’exigeraient des utilisateurs potentiels. Selon les résultats de l’évaluation, la technique CVREA ne convient pas à une utilisation par des organismes d’enquête de sécurité et d’exécution de la loi. Voici les grandes questions qui demeurent en suspens, selon le GCEV :

- l’absence de vérification indépendante des résultats antérieurs de M. Slingerland,
- le peu de preuve d’une application réussie de la technique par qui que ce soit d’autre que M. Slingerland,
- le défaut de M. Slingerland de démontrer de façon satisfaisante l’analyse de l’un ou l’autre cas analysé par lui dans le passé,

- l’incapacité des participants au cours de formation d’analyser un cas à l’aide des lignes directrices fournies par SDCC,
- les résultats décevants de l’essai aveugle,
- l’absence d’acceptation et de soutien à la validation de la technique de la part des experts extérieurs au projet,
- l’absence de fondement théorique quantitatif de la technique CVREA.

Aucune autre technique fondée sur les enregistreurs de vol existants ne s’est avérée utilisable pour déterminer la nature et l’emplacement d’un événement causant la rupture explosive en vol d’un aéronef. Mais on peut penser à des techniques fondées sur des capteurs existants et de nouveaux capteurs.

Le projet a débouché sur les recommandations suivantes :

- La recherche portant uniquement sur la technique CVREA ne doit plus être appuyée, à moins que des preuves sérieuses et convaincantes de la validité de la technique soient présentées.

- Avant de mener quelque autre recherche visant à faciliter les enquêtes sur les ruptures explosives en vol, il faudra revoir toute l’information disponible sur la réponse de structures d’aéronefs lors d’explosions et de décompressions rapides. Cette revue devrait englober l’information obtenue au terme des travaux menés par l’ISVR, la DERA, SDDC et M. Slingerland.

- Selon les résultats de la revue, une attention devrait être accordée aux propositions de recherche soumises par SDDC, l’ISVR et la DERA. Ces propositions comprennent l’étude de la vibration induite dans des cylindres à l’aide de coupons relativement peu coûteux, l’application de l’analyse de régression aux enregistrements du microphone d’ambiance, la constitution et l’analyse systématique d’une base de données d’archives comprenant tous les enregistrements de CVR disponibles, le développement d’un modèle mathématique de prédiction des réponses vibratoires, le recours aux enregistreurs et capteurs existants, et le recours à de nouveaux types de capteurs (comme les capteurs de pression).

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY

AAIB	Air Accident Investigation Branch of the UK
CAM	Cockpit Area Microphone
CVR	Cockpit Voice Recorder
CVREA	CVR Explosion Analysis
DERA	Defence Evaluation and Research Agency of the UK
FAA	Federal Aviation Administration of the US
FDR	Flight Data Recorder
FBI	Federal Bureau of Investigation of the US
FFT	Fast Fourier Transform
FPB	Front Pressure Bulkhead
IAR	Institute for Aerospace Research of NRC
ISVR	Institute of Sound and Vibration Research of the University of Southampton
NRC	National Research Council Canada
NTSB	National Transportation Safety Board of the US
PRC	Project Review Committee
SDDC	Structural Disaster Diagnosis Canada Inc.
TSBC	Transportation Safety Board of Canada
TDC	Transportation Development Centre of Transport Canada
TWG	Technical Working Group
VTCG	Validation Test Coordination Group

1. INTRODUCTION

This report presents the activities, results, recommendations and conclusions of the Cockpit Voice Recorder (CVR) Explosion Analysis (CVREA) project, which was conducted on behalf of Transport Canada and the U.S. Federal Aviation Administration (FAA).

1.1 Project Objective

The objective of this project was to continue the development and evaluation of the CVREA technique, which could potentially determine the nature and location of an event that caused an in-flight break-up.

1.2 Background

In some accidents, it has been difficult for investigators to determine whether an explosion or a structural failure caused an in-flight break-up. Air safety investigation and law enforcement agencies believe that any method that could provide this discrimination early in the investigation would result in substantial improvements in the quality and efficiency of the investigation of this type of accident.

Based on a proposal from Structural Disaster Diagnosis Canada Inc. (SDDC), the Transportation Development Centre (TDC) of Transport Canada awarded a contract to SDDC to develop a computerized version of the CVREA technique. This technique had been under development by Frank Slingerland (one of the principals of SDDC) since 1985 and is based on the interpretation of spectrograms generated from the recordings of cockpit area microphones (CAMs). The CVREA technique has the advantage of using only the CAM/CVR equipment that already exists on most aircraft. Other proposed solutions to this problem would require the installation of new sensors and thus could take several years before being widely available.

At the beginning of this project, SDDC felt that the CVREA technique had been perfected and used successfully by Mr. Slingerland in the analysis of a number of aircraft crash investigations. However, it soon became evident that other experts, who had examined the technique closely over several years, were not convinced that the technique had been satisfactorily demonstrated as a tool suitable for the use of air safety investigation and law enforcement agencies. While they appreciated Mr. Slingerland’s capabilities, determination and effort, and agreed that the potential benefits were significant, they:

- had seen no independent validation of the technique,
- were unable to duplicate Mr. Slingerland’s results,
- were unable to understand some important aspects of the technique, and
- questioned some of the assumptions on which the technique was based.

In view of these conflicting opinions and the potential benefits of the CVREA technique, it was decided to conduct an independent evaluation of the technique in addition to developing the computerized version of the technique. A Validation Test Coordination Group (VTCG) was formed to conduct the independent evaluation and a contract was awarded to both the UK Defence Evaluation and Research Agency (DERA) and the Institute of Sound and Vibration Research (ISVR) of the University of Southampton to assist in the evaluation.

1.3 Report Organization

Section 2 provides an overview of this project. Section 3 discusses the operational requirement for the CVREA technique and Section 4 describes the technique itself. Section 5 outlines the activities at SDDC in developing the CVREA technique and system. Section 6 summarizes the Tucson data collection and analysis. Section 7 provides the results of an independent evaluation of the CVREA technique. Section 8 outlines some additional development activities by SDDC after the training course and Sections 9 and 10 provide the project conclusions and recommendations, respectively.

2. PROJECT OVERVIEW

The project began in September 1997, and was completed in January 2002. Major project tasks were conducted by SDDC, DERA, ISVR and the VTCG. This report reflects the contributions of all of these participants.

TDC provided a research project officer to manage the project. An international project review committee (PRC) was convened to monitor the work and provide overall project direction. Several organizations participated in the project, including the following:

- Transport Canada
- the U.S. Federal Aviation Administration (FAA)
- the National Research Council Canada's (NRC) Institute for Aerospace Research (IAR)
- the Transportation Safety Board of Canada (TSBC)
- the Canadian Police Research Centre (CPRC)
- the US National Transportation Safety Board (NTSB)
- the Canadian Department of National Defence
- the US Federal Bureau of Investigation (FBI)
- the UK Air Accident Investigation Branch (AAIB)
- the United States Air Force
- the Bureau d'Enquêtes et d'Analyses of France
- AeroVations Inc. of Canada

The project included three major activities: CVREA system development, collection and analysis of data from a ground trial, and independent evaluation of the CVREA technique.

At the beginning of the project, SDDC published two reports on the history of development [1] and the theoretical basis [2] of the CVREA technique. Frank Slingerland, the originator of the technique, authored these reports.

During the system design phase, SDDC conducted a review of data processing and smoothing algorithms to identify the most suitable algorithms and smoothing techniques for the CVREA technique. SDDC produced operational concept [3] and design [4] documents for the CVREA system. A technical working group (TWG) reviewed the technical documentation produced by SDDC. The CVREA system was built and tested by SDDC.

In September 1999, the FAA conducted a full-scale explosion trial in Tucson, Arizona, as part of an effort to characterize aircraft vulnerability to damage. Data was collected at this trial by DERA and ISVR with assistance from the FAA and SDDC. This data was used by SDDC for the validation of the CVREA system and technique, and by SDDC and ISVR for detailed analyses of the explosion signatures.

The independent evaluation featured a review of the history of development and the theoretical basis of the technique, a training course, a blind test, analysis of data from a ground test, and comments from other experts. The project and the CVREA technique were discussed with many interested parties during several presentations, meetings and workshops.

3. OPERATIONAL REQUIREMENT

It is intended that air safety and law enforcement agencies would use the CVREA technique in conjunction with other investigative techniques. The technique could potentially be used to determine the nature and location of the event leading to an in-flight break-up. This determination could be made soon after the recovery of the CVR. Mr. Slingerland has suggested [2] that with a little further development, the CVREA technique may also be able to be used to determine the size of the perforation area and the mass of the explosive. After more extensive development, the technique may be able to be used to determine whether the event was a missile (mechanical penetration plus blast) or a wing event.

An early determination of the nature and location of the event causing the break-up would enable the investigation to be more efficient, resulting in improved findings, and substantial savings in both the time and cost of the investigation.

When the wreckage falls into a hostile or inaccessible environment such as oceans, remote locations or mountainous regions, the wreckage recovery team could set priorities more quickly on which parts of the wreckage to recover first. Investigators need to recover the most important items of wreckage before the hostile environment (e.g., salt water) destroys evidence.

If the break-up is the result of a structural failure, air safety investigators could focus their attention more rapidly on the safety implications and appropriate remedial actions to improve aviation safety.

If the break-up is the result of an explosive device, law enforcement agencies could focus their investigation more rapidly on the collection of criminal evidence and the pursuit of justice.

In previous major accidents, costly and high-profile lawsuits have often been initiated during the investigation against aircraft manufacturers, airlines, airport authorities, regulators, etc. A more rapid determination of the cause of the accident could lead to a reduction in the number of such lawsuits.

4. THE TECHNIQUE

A brief overview of the CVREA technique, its history of development, and its theoretical basis [1,2, 5-8] is provided in this section.

The technique requires that, following an impulsive structural event, dispersive vibration waves:

- emanate from the source of the event through the fuselage,
- are reflected back and forth a few times between the front and rear pressure bulkheads,
- are sensed by the CAM on each passage, and
- are recorded on the CVR.

These signals are analysed with the aid of a spectrogram (three-dimensional plot of the frequency and amplitude content of the signal over time). A sample spectrogram is shown in Figure 1. Curves are placed on the spectrogram passing through (or close to) the amplitude peaks to reveal the passage of the dispersive waves past the CAM. Parametric values derived from the curves are then used to determine the nature (rising nose frequencies means an explosion and falling nose frequencies means a rapid decompression) and longitudinal location (relative time of arrival of the waves at the CAM) of the event. In Figure 1, the nose frequencies are rising, which indicates an explosion. It can then be determined whether the event occurred in the passenger or cargo compartment by examining the initial polarity of the fastest travelling vibration mode (sometimes referenced as mode 0, ring mode or breathing mode).

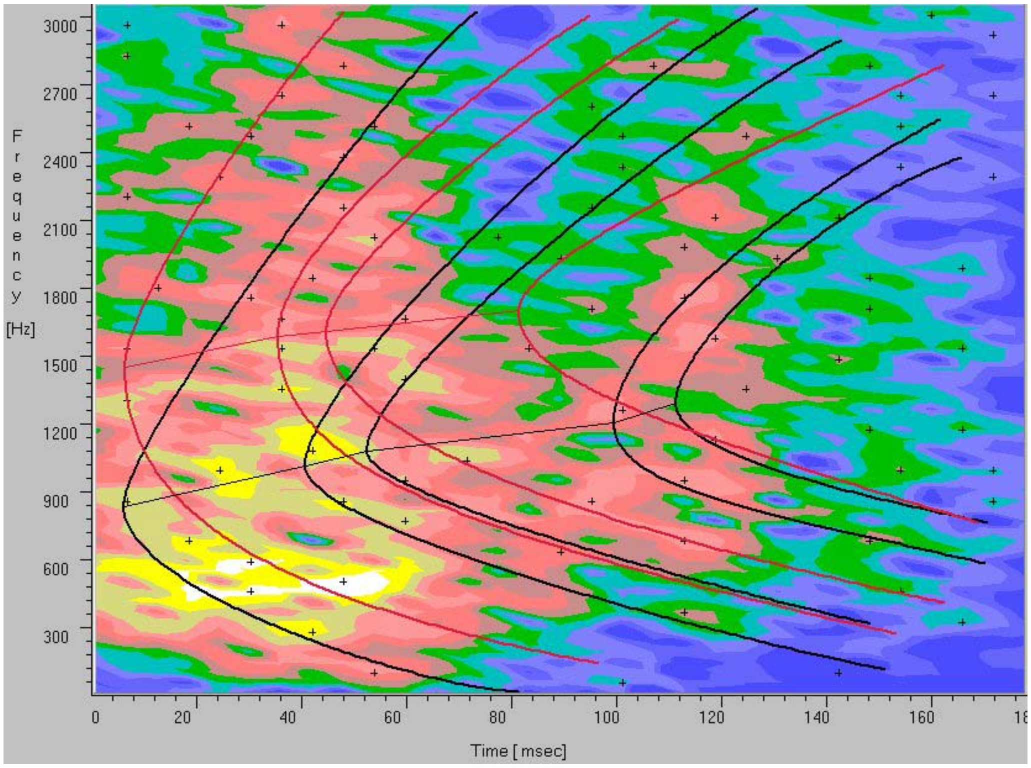

Figure 1 Sample Spectrogram

Mr. Slingerland first developed the CVREA technique during the period from 1985 to 1991, while working at NRC [1]. The development of the technique was based on his analysis of five events, and his knowledge of:

- blast and expansion waves,
- vibrations and acoustics,
- thin cylinder shell dynamics, and
- signal processing techniques.

The development began when Mr. Slingerland received a copy of the CVR tape from the Air India crash off the coast of Ireland in June 1985. He was asked to examine the recording for any evidence that might be useful in the investigation. Initial inspection of the recording showed a signal that appeared to be nothing but random noise. In attempting to remove the noise, Mr. Slingerland was surprised to discover that the first part of the signal was not random, but consisted of six almost pure sine waves. He undertook a literature review, where he found that thin cylinder theory provided a qualitative explanation of the initial sine wave.

Thin cylinder theory predicts that, subject to an impulsive force, a series of waves of different vibration modes will form around the circumference of an infinitely long and uniform cylinder and then propagate in both directions along the length of the cylinder at high speed (well in excess of the speed of sound in air). Within each vibration mode will be individual waves comprising a range of frequencies and dispersive in nature. Two vibration modes are seen in Figure 1. The different frequencies within a wave will travel at different speeds, with the speed at one particular frequency (the nose frequency) being greater than all the others above and below it. The only exception to the dispersive nature of the waves is the fastest travelling breathing mode, which is a pure sinusoid with a single group velocity. A more technical explanation of the theory behind the cylinder dispersion curves used in the CVREA technique is provided in [9].

Although thin cylinder theory could not be used to predict the exact quantitative response of an aircraft structure to an impulsive force, Mr. Slingerland postulated that the pure sine waves he had observed were the dispersive radial vibration waves predicted by thin cylinder theory. By using thin cylinder theory qualitatively, Mr. Slingerland formulated the CVREA technique.

Mr. Slingerland's main findings during the analysis of the five events [1] are listed below in chronological order.

Event 1 - Air India Flight 182 crash off the Irish Coast in June 1985 (caused by a bomb):

- noticed an almost pure sine tone at the beginning of the signal;
- based on thin cylinder theory, speculated that there would also be dispersive vibration modes;
- found two sets of dispersive waves on the spectrogram (meaning two vibration modes).

Event 2 - Japan Airline crash near Mount Otsuka, Japan, in August 1985 (caused by the burst of the rear pressure bulkhead):

- noticed a long transient with two boom noises;
- found two sets of dispersive waves;
- noted that because of the lower flight altitude, three dispersive vibration modes were observed within the CAM frequency range;
- observed equal time spacing in the first set of vibration waves;
- from a re-plot of Event 1, determined the expected duration times for the round trips of the vibration waves;
- based on the round trip duration times and the strong curvature of the waves, determined that the source was near the aft bulkhead;
- noticed a steady fall in the frequencies of the waves.

Event 3 - TWA survival of in-flight explosive detonation near Athens in April 1986:

- introduced a 39 percent correction factor for the wave speed-up over the stiff wing box;
- noticed that the waves rose and fell in frequency;
- first appreciated that the frequency shift could be used to distinguish between a bomb and a rapid decompression;
- returned to the Air India case (Event 1);

- determined that the Air India wave frequency trends indicated a bomb followed by a rapid decompression;
- determined that the Japan Airline wave frequency trends indicated a rapid decompression;
- determined that the time spacing and the initial phase of the breathing wave for Air India disclosed the horizontal and vertical location.

Event 4 - Turkish Airlines crash near Paris in March 1974 (caused by the loss of a rear cargo door):

- discerned three separate sudden events – the door opening and two separate stages of floor collapse – each accompanied by a frequency jump;
- noticed that the wave frequencies trended uniformly downward, indicating a rapid decompression.

Event 5 - Pan Am crash near Lockerbie, Scotland, in December 1988 (caused by a bomb):

- found only a very short (100 ms) vibration transient;
- found two round trips of two vibration modes;
- correctly located the event to within 2.1 m;
- confirmed the cause as an explosive charge.

5. DEVELOPMENT ACTIVITIES

5.1 Literature Review

A critical part of the CVREA technique is the analysis of spectrograms, which are generated from the break-up signature recorded by the CVR. The spectrograms themselves contain significant noise. To facilitate the analysis of the spectrograms, it is necessary to numerically filter the data to clarify the signal characteristics in critical areas. Previous work [10] undertaken by SDDC staff in 1991 had shown that the Wigner Distribution was a promising spectrogram filtering technique. Since 1991 a number of variations on the Wigner Distribution have been developed. These variations were considered to have the potential to further clarify the CVREA spectrogram. SDDC conducted a survey of the recent literature to identify suitable transforms that could be used to clarify the CVREA spectrograms [11]. Transforms reviewed included the Fast Fourier Transform (FFT), the Wavelet Transform and the Wigner-Ville distribution.

5.2 System Development

In the past, Mr. Slingerland had found that the application of the CVREA technique was both tedious and time consuming, and optimization of FFT parameters was not practical. The data interpretation itself involved laborious graphical measurements and hand calculations.

SDDC proposed that computer automation would assist a trained practitioner to rapidly apply the technique, and the PRC believed that an automated system would facilitate the blind test.

SDDC recognized that the use of the CVREA technique would always require the interpretative knowledge of a skilled analyst. Therefore, the PC-based CVREA system was designed and developed to assist a trained vibro-acoustic engineer or CVR specialist in the application of the technique. The emphasis was on providing a skilled analyst with the capability to rapidly sort, manipulate and review the CAM data. It was expected that the major benefits of the CVREA system would be:

- a reduction in the time required to analyse an incident from a few weeks to a few days, and
- the consistent application of the technique by many trained analysts.

The most significant capabilities of the CVREA system are:

- trial and error parameter adjustment at all phases of the analysis,
- identification and marking of signal trace segments (pre-event noise, breathing wave, event (at least 200 ms), and post-event noise),
- signal filtering,
- two-and three-dimensional plotting of spectrograms,
- determination and display of local maxima on the spectrogram,
- flood plane height adjustment to aid visualization,
- assistance in curve drawing,
- curve placement tools to ensure consistent dispersion characteristics,
- iterative statistical analysis to identify curve placement inconsistencies,
- determination of event location from curves, and
- report generation.

The functional requirements and overall design of the CVREA system are documented in the system concept [3] and system design [4] documents.

During the design phase, required capabilities were defined, and the hardware and off-the-shelf software were selected. Algorithms for processing and data smoothing were identified, modified as required, and validated. All system interfaces and functional capabilities (analysis, graphics and reports) were defined, and a system mock-up was developed to validate the functional requirements.

The TWG was convened by TDC to review the report on the literature review, the System Concept and System Design documents, and the system mock-up. SDDC incorporated the recommendations from this review into the system design and build.

During the design phase, established software development standards were applied by SDDC and tailored as appropriate for the development of the CVREA system. A good overview of these standards can be found in [12]. During the build phase, recognized software development standards and practices were followed, including user-oriented design, Borland Delphi programming language, documentation standards, module testing, peer review and integration testing. System documentation, including a user manual, was written.

To help ensure that the CVREA system could be used to accurately replicate the results that Mr. Slingerland had achieved previously, the system was validated by SDDC through the analysis of data from the Tucson trials and data from aircraft incidents that had been previously analysed by Mr. Slingerland.

6. TUCSON DATA COLLECTION AND ANALYSIS

Ground trials on a Boeing 727 at Tucson were conducted in support of the FAA blast-hardening program and presented an opportunity for the CVREA project to acquire CVR signatures of a large-scale pressurized explosion and two subsequent unpressurized explosions. This data was used primarily in the evaluation of the CVREA technique.

The data was collected by DERA and ISVR with assistance from SDDC and the FAA [13]. The trial aircraft was equipped with three tape-based CVRs from different manufacturers, each with identical CAMs. In addition to the CAM data, two of the CVRs recorded a stable 1 kHz tone, enabling any disruption of the tape transport mechanism (due to vibration or shock) to be monitored by modulation of the 1 kHz tone. Several other sensors were also used to record the explosion response at various locations around the fuselage. A tri-axial accelerometer was mounted on the front face of one of the CVRs to record the vibration at the CAM location. An array of twelve equally spaced accelerometers was installed in a ring around the fuselage. A vibration-compensated microphone was installed near the CAMs to monitor the same acoustic environment as the CAMs, without the influence of vibration, automatic gain control attenuation, and limitations imposed by the CAM/CVR systems. Four pressure transducers were installed at various locations in the cabin to measure the impact of the blast on the cabin wall. A detonation time reference signal was recorded to provide a common reference between the CVR recordings and the recordings of the other sensors. To meet its trial objectives, the FAA installed a variety of other instrumentation, including several high-speed video and film cameras and audio microphones.

Analysis of this data by ISVR produced a report [9] that contains the following conclusions and remarks:

> Data from the Tucson trials was analysed to find the approximate location of the explosion source by using either the difference between the structural and acoustic propagation velocities, or the difference between arrival times at sensors on either side of the charge. The accuracy depended on the sensors used. The most accurate results were obtained from pressure transducers placed on either side of the charge, in which case the position error was about one frame. Pressure transducers detected the arrival of the blast wave with greater fidelity than the CAMs.

> Pressure transducer waveforms were used to discriminate between events of different types including explosions, rapid decompressions and combinations of both.
>
> There appeared to be few features in the CAM signals, which could be used to categorise the event. There were no significant features in the CAM spectrograms that could be used to determine the distance from the charge to the CAM.
>
> None of the spectrograms revealed behaviour consistent with the dispersive properties of circumferential vibration modes predicted by thin cylinder theory. ISVR therefore inferred that these modes did not make a significant contribution to the remote vibration following the explosion.
>
> There were differences in the vibration spectrograms that depended on the distance between the charge and the sensor. However, they were not consistent with cylinder dispersion theory. It is not clear if the spectrogram features that depend on the distance were merely an artefact of the particular configuration of the Tucson trials or are generally applicable.
>
> Angular filtering of the data from the twelve accelerometers to separate the circumferential vibration modes did not reveal any further information than could be obtained from a single accelerometer.
>
> The CVR tape speed was affected by vibration, but the demodulated signal transient start time did not provide an adequate reference to locate the explosion source. ISVR believes that the demodulation technique offers the potential for synchronisation of CVR and FDR recordings if the two recorders are physically close in an aircraft subject to high amplitude vibration and are subject to periodic noise signals.

SDDC analysed the Tucson data and reviewed the ISVR analysis report [9]. The SDDC report [14] contains the following conclusions and recommendations:

> There is evidence in the data to support the existence of vibrations that travel faster than acoustic waves. Furthermore, on the pressurised test there is evidence to support the existence of a near sinusoidal wave at the beginning of the vibration, which cannot be attributed to a compression wave. These factors support the hypothesis that the response of an aircraft to an internal explosion can qualitatively be characterised using thin cylinder theory.
>
> Initial analysis suggests that while skin mounted accelerometers are very sensitive to axial compression waves, aircraft CAM/CVR systems are not. Therefore, the CAM/CVR system provides a reasonable, although not ideal, record of the radial vibration signature emanating from an event. This supports the use of the CVREA technique for the analysis of in-flight break-ups.
>
> Analysis of the Tucson data appears to support the hypothesis that there is a fundamental difference between the responses of pressurised and unpressurised aircraft to an internal explosion or decompression. If this hypothesis were correct, it would have significant implications on future tests. SDDC therefore recommends that an attempt be made to validate this hypothesis by reviewing data from all previous tests. Depending on the results, additional testing may be required to quantify the differences between

pressurised and unpressurised tests, and to evaluate the validity of using data from unpressurised tests to predict the response of pressurised aircraft to explosions and rapid decompressions.

While successive tests on an individual fuselage are logistically practical and cost-effective, there is evidence in the Tucson data to suggest that the cumulative damage from each test may have significantly affected the subsequent response of the aircraft. Therefore, aircraft explosive response trends identified from successive tests on an individual specimen need to be reviewed carefully to ensure that they have not been skewed by the cumulative damage sustained from preceding tests.

The method of supporting the aircraft appears to have noticeably affected the data. It has not been possible to quantify the significance of these effects from the limited data available. Again, this is an area for more research, initially through a review of all existing data, and ultimately through some purposely-instrumented tests.

While the analysis by ISVR has suggested that the Tucson data is not compatible with thin cylinder theory, no alternative explanation for the cause of the vibration signature observed in the test data is proposed. SDDC believes that the only theory that comes close to reconciling all the data from the Tucson tests is a qualitative application of thin cylinder theory.

SDDC conducted an internal blind test using the seven CVR recordings from the three Tucson shots. For each of these recordings, Mr. Slingerland attempted to locate the source using the CVREA technique, and thus identify one of the three shots. Mr. Slingerland correctly identified five of the seven Tucson shots.

ISVR provided the following additional comments after reviewing the SDDC report:

SDDC makes a very compelling case for the existence of vibration waves, which propagate faster than sound waves in air following an explosion. ISVR agrees with this.

SDDC shows some evidence to support the existence of breathing waves as predicted by thin cylinder theory, although SDDC stresses the need to treat this analysis as qualitative. In doing this, SDDC may be placing an interpretation on the data, which is not entirely justified, and which only further experimental work (or analysis of records from other trials) would be able to resolve. In any case, there clearly are vibration waves travelling at speeds between the speeds of sound in aluminium and in air. If it were possible to present a quantitative analysis showing consistency between mathematical models for the propagation speeds and hence arrival times, and for the frequency of the possible breathing wave, that would help. However, ISVR understands the difficulty of producing and validating such a model at present, and hence the lack of a quantitative interpretation.

When SDDC refers to ‘the characteristics of multi-frequency signals typical of axially propagating, radial dispersive, vibrations”, ISVR is inclined to be sceptical. This is only one possible explanation of the observed waveform, which is indeed multi-frequency. However, the waveform could also be due to the complex nature of the excitation of the structure and to non-dispersive propagation mechanisms. We simply do not know. ISVR’s experience is that accelerometer responses to remote explosions on most structures have a complex multi-frequency form, which is normally not related to axially propagating, radial dispersive waves.

SDDC infers rather a lot about the effects of pressurised versus unpressurised shots. Many of the differences mentioned by SDDC are possibly better explained by the fact that the charge for the pressurised shot was much closer to the cockpit than for the unpressurised shots. Explosion effects depend upon a critical parameter called the scaled distance (i.e. actual distance divided by the 1/3 root of the charge yield). For example, to achieve the same blast pressure at twice the distance, the explosion yield would need to be 8 times greater. Thus, distance from the charge is a most crucial parameter and likely to be much more significant than the effect of pressurisation. Accordingly, ISVR believes that there is insufficient evidence from the Tucson trials to support the SDDC hypothesis. Previous experience with a large number of trials has enabled ISVR to produce validated mathematical models for the amplitude of the vibration response (transmitted vibration and local blast wave excitation) due to remote charges in aircraft. These models could be used to determine the likelihood of observing the arrival time of the fuselage vibration at the CAM.

Mr. Slingerland provided the following additional comment:

With respect to the ISVR comment on the absence of a quantitative analysis of the frequency of the possible breathing wave, a Rayleigh-Ritz analysis of breathing wave frequency for a Boeing 747 may be found in [5]. This report shows excellent agreement with observed values on two of the events previously analysed by Mr. Slingerland.

7. INDEPENDENT EVALUATION

7.1 Introduction

A VTCG (with members representing NRC/IAR, TSBC, DERA, ISVR and TDC) was convened to conduct an independent evaluation of the CVREA technique.

As identified in the validation test procedures [15], the objectives of the evaluation were to:

- demonstrate the capabilities of the CVREA technique and system for a representative set of both explosion and decompression events;
- determine the extent of consistency and the level of accuracy achievable by the developer and by several analysts, who had been trained on the CVREA technique and system; and
- identify any limitations in the CVREA technique, theory, methodology, system and training.

While the principal effort in the evaluation would be the training course and blind test, the VTCG understood that Mr. Slingerland and others had evaluated the CVREA technique on a number of previous occasions. Where possible, the VTCG included these previous results in the evaluation. The VTCG used the following evaluation methods:

- review the history of development,
- participate in the training course,
- conduct a blind test,
- analyse data from a ground test,
- review the theoretical basis of the technique, and
- solicit comments from all interested safety and criminal investigation agencies.

SDDC fully supported this independent evaluation by:

- conducting internal evaluations of the technique as part of the development activities,
- providing many constructive suggestions for the independent evaluation,
- publishing the history of development, the theoretical basis, and other documents,
- inviting other experts to submit their concerns and responding to all comments,
- working closely with ISVR and DERA,
- participating in presentations, meetings and workshops,
- assisting in the gathering and analysis of the Tucson data,
- conducting the training course, and
- participating in the blind test.

7.2 History of Development

The history of development [1] (as summarized in Section 4) provides valuable insight into the rationale that led to the development of the technique, as it describes the development from Mr. Slingerland's perspective.

In the analysis of the five events, Mr. Slingerland claimed to have made one blind determination of the cause of the break-up (Event 1) and three blind determinations of the location (Events 1, 3 and 5). For all other determinations, he had prior knowledge of the cause and the location of the event from other investigators.

Understanding Mr. Slingerland's analysis of these five cases is very significant to the independent evaluation of the CVREA technique, since that analysis is the basis for the belief that the CVREA technique had been perfected and applied successfully.

While the report [1] describes some of Mr. Slingerland's attempts to validate the technique, it does not add significantly to the independent validation of the technique. The single blind determination of a bomb for Event 1 does not appear compelling because the analysis was done three years after the event, and after the cause of the event had been published. Mr. Slingerland has recently offered that his determination of the location of Event 1 (aft cargo) ran counter to other findings at the time (forward cargo), but was subsequently confirmed by the results of several other investigative techniques and was ultimately accepted as correct. The blind determination of the event locations for Events 1, 3 and 5 is somewhat compelling, although it would be more so if there were an independent verification of these results.

Although many investigators and other experts have tried over several years to reproduce and understand the placement of the curves and produce the results obtained by Mr. Slingerland, no one has been able to do so.

While respecting Mr. Slingerland’s claims, it is difficult for the VTCG to conclude from the report [1] that the CVREA technique had been perfected and used successfully. The VTCG would agree only that the technique had been developed and trained on these five events.

7.3 Training Course

A three-day training course [16] was conducted by SDDC in January 2000. The purpose of the course was to train a number of air safety investigators in the use of the CVREA technique and system for participation in the blind test.

During the course, SDDC presented and demonstrated the principle and theory of the technique, the methods of applying the technique, guidelines for the application of the technique, and the use of the CVREA system. Mr. Slingerland demonstrated the application of the technique using a few previously analysed recordings. The participants were given the opportunity to analyse a few cases.

The training course was well received by all participants, who gave a high rating for the overall benefit of the course, the quality of the training material, the suitability of the facilities, the presentations, and the course organization.

Unfortunately, no training-course participant was convinced that Mr. Slingerland had successfully demonstrated the technique, even with the cases previously analysed. Additionally, using the CVREA system and the guidelines, the participants were unable to correctly, consistently or confidently place curves on the spectrograms. The participants felt that the guidelines were inadequate. After the course, the participants had little confidence in being prepared for the blind test.

The CVREA system was presented by SDDC during the training course and used by all participants to apply the CVREA technique. It was clear to the participants that the system helps a trained practitioner produce accurate spectrograms and computations based on the placement of the curves. The software is fully satisfactory in all respects. The system facilitates the application of the CVREA technique in several ways, including the placement of curves and the understanding of the technique.

While the CVREA system on its own does not add to the validity of the CVREA technique, the development of the system made many significant contributions to the evaluation of the CVREA technique. In an attempt to automate as many aspects of the

CVREA technique as possible, Mr. Slingerland was required to explain the technique in detail to the system developers. The automated system was instrumental in the conduct of the training course. Without the system, the participants would have learned less about the technique and it would have taken much longer. The number of events analysed by the participants during the three days of the course and by SDDC before and after the course would not have been possible without the CVREA system. The system enabled SDDC to complete Phase 1 of the blind test much more quickly and with more participants than it could have done otherwise.

7.4 Blind Test

Despite the unexpected results of the training course, it was decided to proceed with the blind test. The schedule was modified to provide SDDC with an opportunity to refine the guidelines, make some improvements to the CVREA system, and provide further training to the non-SDDC participants before their start of the blind test. The improvements to the CVREA system are discussed in Section 8.

It was agreed that the blind test would be conducted in three or four phases. It was also agreed that the plan for the blind test [15] would be reviewed at the end of each phase and, if appropriate, further improvements could be made to the guidelines and/or the CVREA system before commencing the next phase.

The VTCG managed the blind test. It was planned that the blind test participants would include representatives of SDDC and five representatives of the air safety investigation agencies who had participated in the training course.

The test cases would be blind to the participants in that the recordings would not have been seen, analysed or discussed by the participants before the test. The test cases were collected by the VTCG from various air safety investigation agencies and from ground tests. The VTCG selected the three cases for each phase of the blind test.

With the completion of all four phases, the blind test would have provided 63 blind test results. Phase 1 would have included three cases analysed by two groups at SDDC. Phase 2 would have included three cases analysed by five investigators. Phase 3 would have included three cases analysed by two groups at SDDC and five investigators. Phase 4 would have included three cases analysed by two groups at SDDC and five investigators. This number of results would have been sufficient to draw some statistically significant conclusions about the validity of the CVREA technique.

7.4.1 Phase 1

For Phase 1, two SDDC groups working independently analysed three blind cases. One group included Steve Hall and John Miner (the latter for one test case only). The other group consisted of Mr. Slingerland.

A comprehensive report was provided by SDDC for each of the three cases [17-19]. Each report included the following:

- a description of the test data,
- a description of the data processing,
- comments on the event signal,
- two FFT spectrograms (one from each group),
- two Wigner-Ville spectrograms (one from each group),
- an assessment of the consistency of the results from the four spectrograms,
- the cause of the event as determined by each group,
- the location of the event as determined by each group, and
- conclusions.

In all three cases, because of missing or poor quality speech recordings, the two groups were unable to determine whether the event was in the passenger or cargo space. The VTCG agreed with SDDC that this would not be a factor in the evaluation.

Test Case #1

The actual event was a Cranfield BAe Trident-3 ground test (shot 62) [20]. This was a rapid decompression through a passenger window 255 in. (648 cm) from the front pressure bulkhead (FPB).

Both groups incorrectly determined the cause of the event to be an explosion. Both groups incorrectly determined the location of the event to be about 550 in. (1397 cm) from the FPB.

SDDC provided the following note after the completion of the blind test:

> As stated in the SDDC analysis, the signal provided was very challenging. First its entire length was less than 90 ms (SDDC usually work with a minimum of 200 ms) and it had some unusual dead-band areas at higher frequencies. Second, the initial breathing wave, which was sinusoidal, had an amplitude that was as large as (if not larger than) the remaining part of the signal. This effect has never been observed in any other signal that we have observed from either actual incidents, or the Tucson tests. Third, the way the decompression was simulated with the use of a bomb release mechanism was always a point of concern to SDDC. SDDC remains to be convinced that the release itself did not provide some misleading input to the fuselage. Finally, and most importantly, the magnitude of the decompression is probably the smallest SDDC has had to analyse. SDDC estimates that the magnitude of the mechanical force release from the window was of the order of one half a tonne. Previous decompressions that SDDC has reviewed have involved the release of cargo doors or failure of pressure bulkheads where the instantaneous mechanical force release ranges from tens to hundreds of tonnes. Therefore, if this was an accurately simulated decompression, there is the possibility that this case might indicate a lower bound with respect to the sensitivity of the CVREA technique. SDDC emphasises that this hypothesis would be difficult to confirm or refute without access to additional experimental data.

Test Case #2

The actual event was a Bruntingthorpe B747 ground test (shot 25) [21, 22]. This was an explosion 880 in. (2235 cm) from the FPB.

Both groups correctly determined the cause of the event to be an explosion. Mr. Slingerland correctly determined the location of the event to be about 910 in. (2311 cm) from the FPB. Group 2 incorrectly determined the location of the event to be about 1600 in. (4064 cm) from the FPB.

The VTCG felt that although the location determined by Mr. Slingerland was correct, the interpretation of the spectrogram was substantially inconsistent with the interpretation of all other spectrograms. The analysis was conducted on the part of the signal that follows the arrival of the sound blast at the CAM.

According to the training material, an attempt should have been made to place the curves on the vibration response before the arrival of the sound blast. The training material says:

> Over time, the record will contain a mixture of vibration and acoustic signals. Combined signals are complex and difficult to interpret. Fortunately, as the sound signals travel much slower than the vibration signals, there is a unique window of opportunity for separating vibration signals from sound signals, and being able to interpret the nature and location of the event from the vibration signal.

SDDC provided the following note after the completion of the blind test:

> ... while it had been anticipated that it would be difficult to see the vibration waves once the acoustic waves arrive, it does not mean that they disappear. In fact, a more detailed analysis of the Tucson data indicates that for a pressurised test the acoustic waves might be much smaller in magnitude than the vibration waves. If the trend postulated from the Tucson data were correct, this would go a long way to addressing the VTCG's concerns about Mr. Slingerland's ability to accurately determine the nature and location of the event. Also, the analysis guidelines were developed solely from in-flight events, whose noise background obscures early low-level signals. They may require modification for ground tests.

Test Case #3

The actual event was an in-flight separation of the front cargo door on a United Airlines B747. This was a rapid decompression with the cargo door being about 400 in. (1016 cm) from the FPB.

Both groups incorrectly determined the cause of the event to be an explosion. Both groups incorrectly determined the location of the event to be about 1400 in. (3556 cm) from the FPB.

7.4.2 Phase 1 Review

The VTCG thought that the Phase 1 results did not add significantly to the validation of the CVREA technique. Besides the disappointing results in the determinations of the cause and location of the three events, close examination of the spectrograms did not convince the VTCG that there were compelling reasons for the placement of the curves. There were many inconsistencies among the curves placed on the different spectrograms of the same data. However, the VTCG also recognized that the small number of test cases and the questions raised with respect to the tests suggest that little statistical significance should be attached to these results.

After the completion of Phase 1, the VTCG met with SDDC to discuss the results of Phase 1 and the plans for Phase 2.

Based on the Phase 1 results, the results of the training course, and SDDC's observation that more fundamental research would be required before improved guidelines could be provided for placing curves on spectrograms, it was decided not to continue the blind test.

SDDC provided the following note after the completion of the blind test:

> Following the training course, SDDC commenced work on addressing the three major enhancements, which the accident investigators had identified. In terms of providing better guidance for the placement of the first wave of a given mode on the spectrogram, SDDC concluded that based on their experience, they would attempt to further refine the first curve location criteria. However, it was quickly appreciated that for significant improvements in this area to be made, some limited experimental work would be required.
>
> Unfortunately, it appeared that there was still some additional fundamental research required before a consistent and reliable outcome could be predicted. Therefore, SDDC proposed that a straightforward coupon test program be considered, aimed at resolving some of the issues identified during the blind test. Once this program had been completed, the intent was to revise the software in the light of the findings of the experimental program and undertake some additional blind tests. SDDC did concur with the recommendations of the VTCG that until some of these issues were resolved, there was no point in involving the accident investigators in the blind test.

7.5 Tucson Data Analysis

Both SDDC and ISVR provided reports on their analysis of the data collected at Tucson [9, 14]. These reports are summarized in Section 6. The ISVR results that are relevant to the evaluation of the CVREA technique are included in Sections 7.6 and 7.7. The SDDC analysis of the Tucson data reinforces the areas of agreement with ISVR, which are listed in Section 7.7. The SDDC analysis also raises some significant questions about the applicability of the results of the analysis of ground tests to the analysis of in-flight break-ups, and suggests the need for additional research. While the SDDC results provide further evidence of the initial near-sinusoidal vibrations of the fuselage in the pressurized shot, they provide no evidence that the subsequent fuselage vibrations are radial dispersive as predicted by thin cylinder theory and required by the CVREA technique. The VTCG felt that the SDDC internal blind test using the Tucson recordings added little to the independent evaluation since it was not independently monitored.

7.6 Related Research by DERA and ISVR

The material in this section was extracted from a report provided by DERA/ISVR in May 2001 [23]. Except for the DERA and ISVR members, the VTCG has made no attempt to validate this material. However, it is understood that most of the DERA/ISVR work and reports have been reviewed and approved by air safety investigation agencies in the UK and the US. Some of the recommendations contained in Section 10 were derived from this DERA/ISVR report.

DERA and ISVR have worked for 10 years on the detection of explosions and rapid decompressions in civil aircraft [20-22, 24-36]. Their attempt to understand whether useful diagnostic data could be obtained from CVR recordings began with ground trials to see what the CVR does record when aircraft are subject to explosions and decompressions. These trials were conducted on several aircraft types, including Boeing 727 and 747, BAe Trident, BAC 1-11, Airbus A300, and small executive jets. The trials included over 200 shots involving both destructive and non-destructive tests, and both pressurized and unpressurized conditions. Some of the DERA/ISVR observations from these studies are listed below. Some, but not all of these observations are relevant to the evaluation of the CVREA technique.

- From an analysis of the Lockerbie recording [37], DERA/ISVR were unable to determine the nature of the event from either the CVR or the flight data recorder (FDR). Similarly, it was not possible to yield diagnostic data from recordings of other accidents where aircraft have been subject to explosions and rapid decompressions, although a considerable effort has been expended on attempts to obtain this information.

- The predominant features of signatures of explosions were normally repeatable for charges with the same yield at the same location on a particular fuselage. Rapid decompression signatures were also repeatable for similar pressure ratios and source locations. It follows that these are not random signals although they are very complex.

- Time-frequency (i.e., spectrogram) methods may be useful to discriminate between the phases of explosion response signatures, but did not appear to offer a reliable method for source location using only CAM signatures.

- Both acoustic and vibration responses were often observed in the CAM signal. Under some circumstances involving explosions, it was possible to find the distance from the source to the CAM from the CVR signature alone by exploiting the difference between the propagation speed of vibration through the fuselage structure and pressure waves through the cabin. However, in many cases the CVR record alone has not been able to locate the source. The likelihood of success was increased for blast waves, which had a relatively unimpeded path to the cockpit.

- In many of the trials, additional instrumentation (accelerometers, microphones and pressure transducers) was used and it was believed to be generally possible to locate sources and determine the nature of a source from a combination of sensor measurements. Thus, the shortcomings of flight recorders could probably be addressed by the use of additional instrumentation for violent events.

- It was generally possible to locate an explosion source using synchronized recordings of the output from pressure transducers on both sides of the source. It was also possible to locate a decompression orifice from pressure transducers on both sides of it.

- Pressure transducer recordings of explosions from devices inside baggage need to be examined to determine the effects of baggage and shipping containers on the blast wave and hence CAM signatures.

7.7 Theoretical Basis

Stuart Dyne of ISVR reviewed the theoretical and experimental basis of the CVREA technique [1-8] as well as the response from SDDC to his review. Mr. Dyne also attended the CVREA training course, and was a member of the VTCG.

The ISVR review [38] and the response from SDDC [39] have clarified that thin cylinder theory provides only qualitative guidelines for the CVREA technique. The quantitative basis for the technique is the empirical criteria determined by Mr. Slingerland during his analysis of the five events mentioned in Section 3.3 and various ground test events.

7.7.1 Thin Cylinder Theory

The following notes are extracted from the ISVR report [38]:

> ISVR agrees with SDDC that:
>
> - the CAM responds to vibration in addition to the more familiar acoustic response,
> - a vibration from a remote source on the aircraft will be recorded by the CVR following transmission along the structure to the CAM, and
> - the remote source could be an explosive device or the seat of a rapid decompression.
>
> The essential concern with the CVREA technique for air safety investigation and law enforcement agencies has been the placement of curves on the spectrograms. In spite of a large number of guidelines for curve placement, the training course participants encountered great difficulty in the placement of the curves. Typically, a confused mass

of peaks is seen on the spectrogram. No one set of possible curves can be favoured over any other set. Moreover, having reviewed solutions produced by Mr. Slingerland, other practitioners have been unable to reproduce similar results. Concern has also been expressed that significant features in spectrograms are ignored for the purposes of curve placement. Further concern has been expressed about the way in which some of the curve placement criteria have been excluded from particular sets of curves when they do not suit the data. These issues were most evident during the CVREA training course.

ISVR believes that the placement of curves on the spectrograms is doomed to failure because the spectrograms do not reveal a simple dispersive structure as required by the CVREA technique. There are several reasons for this including:

- aircraft structures are extremely complex and cannot be modelled as simple vibrating systems with a relatively small number of dispersive modes,
- the excitation produced by an explosion and/or by a rapid decompression is distributed in both time and space so that the forced vibration input cannot be treated as a point impact as required by the CVREA technique, and
- the CAM is sensitive to vibration but it is not an accurate vibration transducer.

Thus, ISVR believe that the CVREA technique is not useable by air safety and law enforcement agencies not only due to the difficulty in placing curves on spectrograms, but also due to the aircraft not producing a vibration response leading to such simple curves. That is, the problem is not just with curve placement, but with the very existence of these curves. While ISVR acknowledge that it is always possible to place curves on a spectrogram of a complex vibration response, the curves are of no significant diagnostic value, and do not reveal anything about the nature and location of the source.

ISVR's main criticism of the CVREA technique is that the placement of dispersion curves on spectrograms is not scientifically proven. In many cases, the only evidence to support aspects of the curve placement theory is in the form of interpretations of accident CVR recordings. Thus, there is no other evidence to support the applicability of some of the theory. The theory is amended to suit the data, which then (not surprisingly) supports the theory. Both are mutually supportive but could be invalid.

Some of the significant differences between thin cylinder theory and the requirements for the CVREA technique are listed below.

- The frequency range of curves produced by the CVREA technique is an order-of-magnitude higher than for corresponding thin cylinders of comparable dimensions. Moreover, in thin cylinder theory, the frequency range of these curves is independent of the order number (covering zero Hz to the 'ring frequency'). However, for the CVREA technique, the frequency range is order number dependent. No body of theory exists to explain these differences.

- Aircraft structures are not uniform along their length, and include many departures from uniform cylinders such as stiffening near the wings and engine mountings and tapering at either end. SDDC have therefore divided the structure into virtual sections and applied heuristic laws for the behaviour in these sections. The heuristic laws are inconsistent with thin cylinder theory. For example, the behaviour due to tapering is wholly inconsistent.

- The CVREA technique uses changes in nose frequencies to determine the nature of the remote event. An increase in nose frequency indicates an explosion and a decrease indicates a rapid decompression. ISVR does not accept this theory because explosions do not produce a quasi-static overpressure over the fuselage surface as would be required.

- ISVR does not agree with SDDC about the nature of the vibration loading when aircraft are subject to explosions and decompressions brought about by structural failure. For both sources, ISVR maintains that the source is distributed in time and space. The CVREA technique requires that the source be effectively of short duration and effectively confined to a small part of the surface. The rationale for the ISVR view is that blast waves propagate outwards and impinge on many parts of the structure producing reflected blast, which also propagates and impinges on other parts of the structure producing a continuous, distributed force. Similarly, decompression waves travelling at the speed of sound in air propagate throughout the entire volume of the structure. The ISVR view would mean that it would not be possible to exploit dispersion characteristics to locate sources beyond first arrival at the CAM, as the arrival of energy from the multiple sources would become rapidly confused.

- The CVREA technique requires that the CAM detect successive reflections of an impulsive wave from the nose and tail pressure bulkheads of the aircraft. ISVR believes that reflections would be produced by every change in impedance (mass and/or stiffness) along the length of the structure so that it would not be possible to see the end reflections with any clarity.

In summary, although much of the material produced by SDDC has discussed the theory of thin cylinders, this theory cannot be used directly to support the placement of curves on spectrograms of CAM recordings. There is no theoretical basis for the placement of curves on spectrograms and guidelines for this are based solely upon heuristic laws developed from the analysis of previous recordings.

The following notes are extracted from SDDC's response [39]:

Accurate analysis of vibration waves in aircraft structures is the goal of the CVREA technique. Many of the points raised by ISVR are based upon reservations concerning the applicability of thin cylinder theory to the technique. SDDC concurs with ISVR that there is no established body of theory to support the CVREA technique. The technique embodies an empirical, phenomenological approach dealing with complex aircraft vibration phenomena that have not yet received adequate theoretical treatment in the literature. As SDDC cannot draw upon a body of established theory, classical thin cylinder theory has been employed with restraint to elicit qualitative observations to gain insight into the much more complex phenomena of vibration waves in aircraft fuselages.

The phenomenological approach followed in the development of the CVREA technique is based upon rational hypotheses, observed quantitative results, and a coherent plan for development and exploration consistent with normal research and development objectives. Through such efforts, it is hoped that sufficient understanding of the physical process involved will be developed to fully establish the theoretical and experimental substantiation for the CVREA technique.

Within this context, it is appropriate to report when observed results are consistent with the hypotheses. At the same time, ISVR's observation that such results do not constitute scientific proof of the method is correct.

Specifically, SDDC acknowledge that the thin cylinder theory is deficient in many ways:

- It assumes a surrounding vacuum (air mass and dampening effects are ignored);
- It assumes a thin cylinder without cross bracing, whereas a fuselage has heavy cargo and passenger floor, and a ceiling truss multiply connected to the ring frames;
- No allowance is made for mass loads, e.g. cargo, baggage, passengers and fuel; and
- Non-uniformity is limited to a few simple cases, whereas a fuselage is non-uniform in stiffness and mass distribution, both axially and circumferentially.

It follows that discrepancies between findings using the CVREA technique and the predictions of classical thin cylinder theory may well be substantial in magnitude. It would be in the best interests of all parties to undertake an experimental program to address the unknowns in the theory of vibration waves in aircraft structures.

Mr. Slingerland recently offered the following additional comments [40]:

The original explanation of the frequency rise or fall of the vibration waves was in error. However, the existence of a small zone of pressure and hull stress change will have the same effect on the waves, which scan this zone twice per round trip.

The amplitude of the waves reflected from intermediate changes in fuselage impedance will depend on the magnitude and suddenness of these changes. The only large and sudden change is at the wing root. Even this region of the fuselage occupies only 25% of the fuselage circumference, leaving the rest free to pass the incident wave. In any case, the only effect we have observed at the wing root is an increase in group velocity.

The excitation produced by an explosion cannot be adequately represented by a single impulse, as the pressure pulses are distributed in both time and space. However, the CVREA technique does not resolve closely timed signals from closely spaced sources, but provides a mean source location.

The excitation produced by a rapid decompression is not caused by the decompression pressure wave, but rather by the sudden release of mechanical force and stress caused by a sudden hull breach.

7.7.2 CAM/CVR System

The following notes are extracted from the ISVR report [38]:

> The CVREA technique requires the CAM/CVR system to be an effective vibration recording system (as opposed to simply sensitive to vibration).
>
> ISVR agrees with SDDC that since the CAM/CVR system is all that is available, it is essential that the best use be made of this resource. However, ISVR contends that these systems are not designed for this purpose and have no specifications for vibration sensitivity (beyond a recommendation that the CAM is isolated from structure connected to the aircraft skin [41]). Thus, CAM/CVR vibration recordings are likely to be non-linear and subject to frequency dependent amplitude and phase distortions. Additionally, tape saturation and automatic gain control systems could have a devastating effect upon the CAM/CVR vibration recording.

The following notes are extracted from SDDC's response [39]:

> SDDC agrees that CAMs do not have specifications for vibration sensitivity. Obviously, a CAM is a poor choice of device for precise measurement of vibro-acoustic events on aircraft. However, CAMs currently exist on current aircraft, whereas accelerometers and pressure transducers do not. It is reasonable to believe that any new devices for vibro-acoustic measurement will not be in general use on aircraft within the next twenty years. Thus, CAM recordings will probably provide the only record of vibro-acoustic events on aircraft for the foreseeable near future. This provides the rationale for attempting to develop the CVREA technique based on CAM recordings.
>
> The CVREA technique does not require the vibrations to be measured with high fidelity. ISVR have observed in the Tucson recordings that the CAM time trace signals of the same event differ from one recorder to another. However, these differences largely disappear in the spectra, which are energy spectra in which all phase information is ejected, and these spectra all lead to the same diagnosis by the CVREA technique. One reason for the robustness of the spectrograms lies in the fact that they involve an integration of the signals over time, rendering them less sensitive to recording errors. In effect, the technique uses the CAM/CVR only as a peak detector on the spectrogram, and this is a robust application. Non-linearity, wow, flutter, tape speed errors and non-flat response have negligible impact on the CVREA technique.
>
> The CAM is intentionally isolated from the vibrations caused by exterior boundary layer turbulence. The vibrations used in the CVREA technique are several orders of magnitude greater than those caused by external turbulence. They are large enough to trigger vigorous automatic gain control action in the system. They totally overcome the isolation of the CAM.

Mr. Slingerland has recently conducted a detailed theoretical analysis of vibration detection by the CAM [42], including diaphragm acceleration, dynamic pressures, feed-in from the surrounding vibrating hull surface, and cockpit reverberation. This report reveals that acceleration is the predominant effect by a factor of six to eighty, increasing with frequency. Experimental evidence of vibration waves recorded on CAMs is presented in [14].

7.8 Other Expert Opinions

As part of this project, SDDC and TDC attempted to contact all air safety investigation and law enforcement agencies and other experts with relevant experience to solicit comments with respect to the evaluation of the CVREA technique. Some representatives were invited to participate in the PRC, the TWG, the VTCG and the training course. Presentations were given to the International Society of Air Safety Investigators, EuroCAE WG-50, the NTSB and the FBI. The historical perspective and overview documents were published. A public web site was constructed by SDDC to disseminate project information.

Many experts and air safety investigation and law enforcement agencies have been aware of the CVREA technique since it was first proposed. TSBC and other agencies have attempted since then to understand and apply the technique. However, no expert outside SDDC has been identified who:

- is convinced that the validity of the CVREA technique has been established,
- has claimed to be able to apply the technique, and
- was able to offer any evidence to support the validation of the CVREA technique.

The following specific comments were received:

> The AAIB published a paper in 1998 [43] on issues related to CVRs. The report said:
>
> > Some people have a belief that the CVR can provide [a detector which will discriminate between a decompression and an explosive event], but actual cases and research at Southampton University has strongly indicated that this is inconclusive. Further research needs to be done on how a detector may be provided and recorded.
>
> The NTSB in a letter to the FAA dated January 3, 2000 stated:
>
> > As part of the continuing investigation of the TWA flight 800 accident, the Safety Board invited Mr. Slingerland to make a formal presentation concerning the CVREA technique to a panel of experts. This international panel was assembled to review and to evaluate the technique to see if any additional information could be obtained from the CVR recording.
> >
> > Although the Safety Board believes the technique, in theory, has merit and would like to see its continued development, we recognize that there are serious doubts about the technique within the accident investigation community.

The TSBC in a letter to TDC dated August 17,1999 stated:

> TSBC has been aware of Mr. Slingerland's technique since its conception a number of years ago. While we feel that the technique has potential and wish to support its development, we are also aware there is significant controversy with respect to the technique within the accident investigation community. Based on our knowledge to date, we still have some reservations about its applicability and therefore want to ensure that our formal participation will not be perceived as TSBC's endorsement of the technique at this time.

TDC and SDDC met with these agencies in an attempt to alleviate their concerns. However, at the conclusion of the project the agencies indicated that the CVREA technique was not suitable for their use and they did not wish to support its continued development.

8. ADDITIONAL DEVELOPMENT ACTIVITIES

At the completion of the training course the following improvements were suggested:

- better guidelines for placing the first wave of a given mode on the spectrogram;
- an addition to the system to automatically generate and place on the spectrogram a consistent family of curves based on the user-defined first curve;
- a method of determining whether the cause of the incident was a bomb or rapid decompression that was independent of the CVREA technique.

SDDC soon realized that some experimental work would be required before being able to provide better guidelines for the placement of the first wave of a given vibration mode on the spectrogram.

SDDC implemented an automatic curve generation technique [44]. This technique, termed the "fishbone", generates a family of curves on a spectrogram, based on the first curve for each vibration mode. The user can then adjust the curves (including the first) until they are consistent with the peaks on the spectrogram. Curving the spine of the fishbone up or down until it closely follows peaks located on the spectrogram makes a final, fine adjustment of the curves. This capability was incorporated into the software and used by SDDC during part of the blind test.

SDDC also commenced research on alternate methods of determining the nature of the event. The most promising technique found by SDDC was regression analysis. The principle behind regression analysis is that if an explosion causes an initial tightening in a fuselage and a corresponding increase in frequency trend, then the maximum points identified on the spectrogram should exhibit the same trend. Similarly, if a decompression causes an initial relaxation of the fuselage and a corresponding decrease in frequency trend, then the frequency of the maximum points on the spectrogram should show a similar trend. SDDC has found that while the principle itself is relatively straightforward, its application is not. Consequently, although under development, this technique was not available during the blind test.

While the VTCG did not consider these additional development activities in the independent evaluation of the CVREA technique, two observations are offered:

- ISVR reviewed the fishbone technique and agreed that it would be helpful. However, it would be of no value unless the first curve could be placed properly.
- SDDC has not published any of the work on regression analysis. However, ISVR has noticed a decreasing frequency during rapid decompressions in ground tests. This phenomenon may have some diagnostic potential. ISVR has not noticed a corresponding increase in frequency during explosions.

9. CONCLUSIONS

The goal of this project was to further develop the CVREA technique, automate it and evaluate it. This project accomplished that and more. Many interested parties participated in this project and much was learned about the CVREA technique and the detection of explosions and rapid decompressions.

Based on a comprehensive review of the documents published by SDDC and Mr. Slingerland, and discussions among SDDC and other experts, the following areas of agreement were identified:

- The best use should be made of existing CAM/CVR systems.
- Vibrations originating from explosions and rapid decompressions are recorded by the CVR following their transmission along the fuselage to the CAM.
- Fuselage vibration waves arrive at the CAM well before the corresponding acoustic waves travelling in air.
- The predominant features of recorded signatures of explosions and rapid decompressions are normally repeatable, implying that they are not random signals, although they are very complex.
- CAM/CVR systems are not designed for precise measurement of fuselage vibrations.
- Fuselage vibrations are not quantitatively consistent with thin cylinder theory.
- The SDDC guidelines for the placement of curves on spectrograms are based primarily on heuristic laws derived from Mr. Slingerland’s previous analysis of recordings.

The same review and discussions identified the following major areas in which experts could not come to a consensus with respect to the CVREA technique:

- the mechanism that initiates the vibration of the fuselage for both explosions and rapid decompressions,

- the aircraft producing a vibration response leading to simple coherent radial dispersive vibration waves,
- the clarity of successive reflections of vibration waves from the front and rear pressure bulkheads,
- the placement of curves on the spectrograms consistent with the presence of coherent radial dispersive vibration waves, and
- the changes in nose frequencies indicating the nature of the event.

The VTCG found that the CVREA technique was not demonstrated in a substantial and convincing manner, such as would be required by potential users. Based on the evaluation, the CVREA technique is not considered suitable for use by air safety investigation and law enforcement agencies. The following were identified as the main areas of concern by the VTCG:

- the lack of independent verification of Mr. Slingerland's previous results,
- little evidence of the successful application of the technique by anyone other than Mr. Slingerland,
- the lack of a satisfactory demonstration by Mr. Slingerland of the analysis of any of the cases he had previously analysed,
- the inability of the training course participants to analyse any case using the guidelines provided by SDDC,
- the disappointing results of the blind test,
- the lack of acceptance and support for the validation of the technique from other experts, and
- the lack of a quantitative theoretical basis for the CVREA technique.

The automated CVREA system developed by SDDC was well received by the training course participants and proved valuable in helping to achieve the project objectives.

Collection and analyses of data from the FAA ground test at Tucson and discussions among the experts added to the understanding of the CVREA technique, aircraft structural responses to explosions and rapid decompressions, and the detection of these vibrations by the CAM/CVR systems and other sensors. The analysis by SDDC also raised some concerns about the applicability of some of the results from ground tests to the analysis of in-flight events.

While no other techniques based on existing flight recorders were found to be usable for determining the nature and location of an event causing an in-flight break-up, some potential techniques based on existing and new sensors were identified.

10. RECOMMENDATIONS

The following recommendations are offered based on the results of this project:

1) Research that is focussed only on the CVREA technique should no longer be supported unless substantial and convincing evidence on the validity of the technique is presented.

2) Before conducting any further research with respect to the investigation of in-flight break-ups, all available information on the structural response of aircraft to explosions and rapid decompressions should be reviewed. This review should include information available from research conducted by ISVR, DERA, SDDC and Mr. Slingerland.

3) Depending on the results of the review, the following research suggestions from SDDC, ISVR and DERA should be considered:

    a) Investigate methods with the potential of extracting useful information from existing recorders and sensors, since new types of sensors probably will not be widely available for several years.

    b) Study the vibration response of thin braced cylinders using relatively inexpensive coupons.

    c) Investigate the use of regression analysis on CAM recordings to distinguish between explosions and rapid decompressions.

    d) Search for possible explanations other than thin cylinder theory for the initial vibration sine waves seen on many recordings of explosions and rapid decompressions, since these vibration waves were the primary evidence that led to the postulation of the existence of radial dispersive vibrations on the CVR.

    e) Construct an archive of all available CVR recordings from accidents known to have been caused or suspected of having been caused by an explosion or rapid decompression.

    f) Conduct a systematic analysis of all available CVR recordings from accidents known to have been caused or suspected of having been caused by an explosion or rapid decompression.

    g) Develop a mathematical model for response prediction that could be used to improve the understanding of what is actually recorded by current CAM/CVR systems and thus the understanding of future accident recordings and the specification of devices aimed at the detection of explosions and rapid decompressions.

h) Investigate new types of sensors such as pressure transducers for their utility in distinguishing between bombs and rapid decompressions, and in determining the location of the event.

REFERENCES

[1] **F.W. Slingerland**, *Development of the CVR Explosion Analysis Technique, An Historical Perspective*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TM/98-003, Revision 001, May 1998.

[2] **F.W. Slingerland**, *Vibration Spectrograms for Aircraft Accident Investigation (an Overview)*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TR/98-002, Revision 001, April 1998.

[3] **J.W.R. Miner et al.**, CVR *Explosion Analysis System: System Concept Document*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TR/98-003, Initial issue, July 1998.

[4] **J.W.R. Miner et al.**, CVR *Explosion Analysis System, System Design Document, Volume 1: System Design Requirements and Volume 2: System Data Model and Database Design*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TR/98-004, Initial issue, July 1998.

[5] **F.W.Slingerland**, *Aircraft Damage Analysis by Vibration Spectrograms*, Laboratory technical report LTR ST 1572, National Research Council Canada, 1986.

[6] **F.W. Slingerland**, *Spectrogram Diagnosis of Aircraft Disasters*, International Pacific Aerospace Conference, Gifu, Japan, 1991.

[7] **F.W. Slingerland**, *Aircraft Damage Analysis by Vibration Spectrograms*, Journal of Sound and Vibration, 110, 1986.

[8] **F W Slingerland**, "The Use of Vibration Spectrograms in Aircraft Accident Investigation", Chapter 14 in *Forensic Investigation of Explosions*, edited by Dr. A Bevridge, Taylor & Francis, London, April 1988.

[9] **S.J.C. Dyne**, *Analysis of Recordings from Boeing 727 Trials, Tucson, Arizona, September 1999*, ISVR/SAL/99/2, DERA, December 1999.

[10] **N.N. Abdelmalek and S.R. Hall**, *A Preliminary Evaluation of the Wigner Distribution in the Analysis of Cockpit Area Microphone Data*, S&S Software Ltd., Report Number SSS/TR/0003, April 1991.

[11] **N.N. Abdelmalek**, *Frequency-Time Transforms for Use in the Analysis of CVR Generated Spectrograms, Part I – Literature Survey*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TR/98-001, Initial issue, April 1998.

[12] **ISO/IEC 122207**, *Information Technology – Software – Part1: Software Life-Cycle Process.*

[13] **S.J.C. Dyne**, *Preliminary Results from the Boeing 727 Trials, Tucson, Arizona, September 1999*, ISVR/SAL/99/1, DERA, October 1999.

[14] **S.R. Hall and F.W. Slingerland**, *CVR Explosion Analysis System: Some Observations from the Tucson Ground Explosion Tests*, SDDC Technical Report SDDC/TR/00-005, Initial Issue, December 2000.

[15] **A.W. Jackson**, Editor, *CVR Explosion Analysis – Validation Test Procedures*, 18 February 2000.

[16] **S.R. Hall et al.**, *CVREA Training Course Material*, Structural Disaster Diagnosis Canada Inc., Report SDDC/TR/00-001, Initial issue, January 2000.

[17] **S.R. Hall and F.W. Slingerland**, *CVR Explosion Analysis System: Analysis of Validation Test Case "Case # 1"*, SDDC Technical Report SDDC/TR/00-003, May 2000.

[18] **S.R. Hall and F.W. Slingerland**, *CVR Explosion Analysis System: Analysis of Validation Test Case "Case # 2"*, SDDC Technical Report SDDC/TR/00-004, June 2000.

[19] **S.R. Hall, F.W. Slingerland and J.W.R. Miner**, *CVR Explosion Analysis System: Analysis of Validation Test Case "Case # 3"*, SDDC Technical Report SDDC/TR/00-002, May 2000.

[20] **S.J.C. Dyne**, *Trident Explosion Trials CVR Recordings*, ISVR Memorandum 734, April 1994.

[21] **S.J.C. Dyne**, *Preliminary Results from the Bruntingthorpe Boeing 747 Trials in March and May 1997*, DERA/ESC/ANAREP/9748/1.0, DERA Fort Halstead, August 1997.

[22] **S.J.C. Dyne**, *An Analysis of the March and May Bruntingthorpe Boeing 747 Trials Data*, DERA/ESC/REP/9749/1.0, August 1997.

[23] **K. Sharpe and S.J.C. Dyne**, *Violent Events on Civil Aircraft*, DERA, 24 May 2000.

[24] **S.J.C. Dyne**, *Determination of the Cause of Failure of Aircraft Structures from Transducer Recordings up to the Time of Failure,* ISVR Contract Report 91/35*,* University of Southampton, December 1991.

[25] **A.B. Miller**, *Research into the Identification of the Signatures of Violent Events in Aircraft*, DERA Fort Halstead, Group Working Paper 2/92 (EC3), January 1992.

[26] S.J.C. Dyne, *Determination of the Cause of Failure of Aircraft Structures from Transducer Recordings up to the Time of Failure,* ISVR Contract Report 92/17*,* University of Southampton, June 1992.

[27] A.B. Miller, *Preliminary Visit Report Corvette Aircraft Trials, Centre d'Etudes, Gramat*, DERA Fort Halstead, CES3 Division, July 1992.

[28] S.J.C. Dyne and J.K. Hammond, "Identification of the Cause of Failure of Aircraft Structures from Cockpit Voice Recorders", *Proceedings of the Institute of Acoustics*, 15, Acoustics '93 Part 3 (book 2), Southampton, April 1993.

[29] S.J.C. Dyne, *DC-9 Final Report,* ISVR Contract Report 93/27, University of Southampton, March 1994.

[30] S.J.C. Dyne, *Corvette Explosion Trials*, ISVR Contract Report 94/15, University of Southampton, June 1994.

[31] S.J.C. Dyne, *Analysis of CVR Transient Signatures*, International Society of Air Safety Investigators*,* 28(4), ISASI 95, Seattle, September 1995.

[32] M. Moshrefi-Torbati and S.J.C. Dyne, "Time-frequency Analysis of the CVR's Signature", *Acoustical and Vibratory Surveillance Methods and Diagnostic Techniques,* Senlis, France, October 1995.

[33] S.J.C. Dyne, *BAC 1-11 Explosion Trials CVR Recordings*, ISVR Contract Report 97/08, February 1997.

[34] S.J.C. Dyne, *Cockpit Voice Recorder Transient Signatures,* ISVR Contract Report 97/07, February 1997.

[35] S.J.C. Dyne, *Preliminary Results from the Bruntingthorpe Boeing 747 Trials in July 1997*, DERA/ESC/CR9763/1.0, DERA Fort Halstead, October 1997.

[36] S.J.C. Dyne, *An Analysis of the July 1997 Bruntingthorpe Boeing 747 Trials*, DERA Report, DERA Fort Halstead, May 1998.

[37] M.M. Charles et al., *Report on the Accident to Boeing 747-121, N739PA at Lockerbie, Dumfiesshire, Scotland on 21 December 1988*, Air Accidents Investigation Branch, Department of Transport, Aircraft Accident Report 2/90, HMSO, 1990.

[38] S.J.C. Dyne, *Review by ISVR of SDDC Documents*, 31 March 2000.

[39] S.R. Hall and F.W. Slingerland, *Response to Review by ISVR*, 13 July 2000.

[40] F.W. Slingerland, *E-mail to A W Jackson*, Vibacon, October 2001.

[41] P. Mayes, Chair WG18, *Minimum Operational Performance Specification for Cockpit Voice Recorder Systems*, ED56A, EuroCAE, 1993.

[42] F.W. Slingerland, *The Role of CAM as Hull Vibration Detector*, Vibacon, December, 2000.

[43] P.F. Sheppard, *Analysing Accident Data – Are the Systems Meeting the Need?*, AAIB, England, 1997.

[44] S.R. Hall, *CVR Explosion Analysis System: Initial Implementation of Automatic Vibration Curve Generation*, SDDC Technical Report SDDC/TM/00-001, April 2000.