ELECTRONIC RELIABILITY PREDICTION: A STUDY OVER 25 YEARS.

By

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My thanks also go to my colleague, Paul Roberts, who has been very generous with his time in reading and re-reading the draft and making useful suggestions to correct spelling, grammar and structural problems. I also must thank him for his contributions, in a number of discussions, about the overall direction that the thesis should take.

Jeff Jones.

Declaration

The work contained in this thesis is the candidate's own work except for certain sections where the work was carried out as part of collaborative research. This collaborative work is evident from the text and the fact that the published work presented herein contains the names of the collaborators. Statements about the proportion of the work that was carried out by the author are supplied by the collaborators where possible.

This work has not been submitted for any other degree at any other university except where some of the published documents refer briefly to work on the setting up and administration of a database carried out at Loughborough University which formed part of a MPhil submission to that University.

Signed

Jeffrey Alun Jones

Abstract

This thesis describes research work that the author has undertaken and published in the field of electronic reliability prediction techniques over the last 25 years. Reliability prediction is an important area since it has been part of the backbone of reliability engineering in one form or another for over fifty years.

The author has over 45 publications that are within the area of reliability prediction and 13 of these have been selected for review in this thesis. In order to show how the author's work has contributed to the field of reliability prediction this document also contains information on the history of reliability prediction. This allows the author's work to be placed in context with general developments in the field.

The contributions to knowledge and innovations that have been made in reliability prediction include the development of statistical models for lifetime prediction using early life data (i.e. prognostics); the use of non-constant failure rates for reliability prediction; the use of neural networks for reliability prediction, the use of artificial intelligence systems to support reliability engineers' decision making; the use of a holistic approach to reliability; the use of complex discrete events simulation to model equipment availability; demonstration of the weaknesses of classical reliability prediction; an understanding of the basic behaviour of no fault founds; the development of a parametric drift model; identification of the use of a reliability database to improve the reliability of systems; and an understanding of the issues that surround the use of new reliability metrics in the aerospace industry.

Table of Abbreviations and Acronyms

TABLE 1: Table of Abbreviations and Acronyms

Acronym	Meaning
ASPIRE	Aerospace Process Insertion of Reliability
BT	British Telecom
CALCE	Computer Aided Life Cycle Engineering
CNET	Centre National d'Etudes des Telecommunications
CORD	Component Reliability Database
DIA	Danish Engineering Academe
DIRAC	Database for Interbroadband component Reliability Calculations
DOD	Department of Defense
ECSS	European Collaboration on Space Standardisation
ESA	European Space Agency
ESR	Equivalent series resistance
FFOP	Failure Free Operating Period
FMEA	Failure Mode, Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FRDR	Field Reliability Data Report
HAST	Highly Accelerated Stress Testing
HRD	Handbook of Reliability Data
I2R	IERI Information Resource
IEC	International Electro technical committee
IEE	Institute of Electrical and Engineers
IEEE	Institute of Electrical and Electronic Engineers
IERI	International Electronics Reliability Institute
IRIS	Integrated Reliability Information System
IRPH	Italtel Reliability Prediction Handbook
Ltd	Limited
MEA	More Electric Aircraft
MFOP	Maintenance Free Operating Period
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MOD	Ministry of Defence
MSC	Master of Science
MTBF	Mean Time Between Failures/ Mean Time Before Failure
MTTF	Mean Time to Failure
NFF	No Fault Found
NN	Neural Networks
PCB	Printed Circuit Board
PoF	Physics of Failure
R&M	Reliability and Maintainability

Acronym	Meaning
RAC	Reliability Analysis Center
RACE	R&D in Advance Communications technologies in Europe
RADC	Rome Air Development Center
RAMS	Reliability and Maintainability Symposium
RCA	Radio Corporation of America
RDF	Recueil de Données de Fiabilité
REMM	Reliability Enhancement Methodology and Modelling
RIAC	Reliability Information Analysis Center
SWOT	Strengths, weaknesses, Opportunities and Threats
TC	Technical Committee, (Only used as IEC TC/56)
UK	United Kingdom
URA	Ultra Reliable Aircraft
URAM	Universal Reliability and Availability Modeller
US(A)	United States(of America)
UTE	Union Technique de L'Electricite

1. Introduction

This thesis describes a set of work that has taken place in the field of electronic reliability prediction techniques since 1984. Reliability prediction is one of those core tasks that have played a large part in the development of reliability engineering over the last fifty years. It has moved from being leading edge, to being routine, to being discredited and almost obsolete, and finally to resurgence using new methods which again are leading edge but generally have little resemblance to those that were used in the earliest days.

This document sets out the work carried out by the author in the reliability prediction field, and shows how it fits into the overall development of that field. In doing so via a comprehensive time-line it highlights the development of reliability prediction techniques, the slow process of erosion by criticism that finally led to the sweeping away of the 'standard' techniques of prediction and the development of new ideas and metrics that are now used to give a measure of the future reliability of systems.

Over the time this work was carried out the author has moved from being a research assistant to a principal investigator, but throughout has usually been part of a team that has worked together to develop the ideas, techniques and principles. The "team" has varied in this time from supervisors, to people open for discussion of ideas , to essential support in software programming, and finally to close collaboration. The make up of the team has varied from being all academic to being all industrial, save the author, and all places in between.

This document contains information on the history of reliability prediction, presented as Table 2 in the beginning of Chapter 2. This table allows the author's work to be placed in context with general developments in the field of reliability prediction. Chapter 3 presents the author's contribution to reliability prediction work; it describes projects the author has been involved with and the published papers presented as evidence of contribution to knowledge. Chapter 4 draws this work to a conclusion and the appendix contains a full bibliography of all the author's papers and citation information.

2. Electronic Reliability Prediction – The Work in Context

This section will attempt to put the various developments in reliability prediction into a historical context and show where the work performed and presented as part of this thesis fits in. It does this with the presentation of a time line, Table 2, which contains important developments in the field of reliability prediction. This includes publication and updates of handbooks (where significant), important papers by title and citation [aaaa, xxxx], the author's published work by title and number reference [xxxx] (emboldened), the presented work (emboldened and enlarged), by title and citation [PWx], and projects the author worked on. (emboldened)

TABLE 2: Timeline of Major Events in Reliability Prediction

Date	Document/Work	Comment
1950, December	AD Hoc group on reliability of electronic equipment formed with purpose to enhance reliability of electronic tubes.	This group was formed because the reliability of valve based systems was so poor that something had to be done.
1952	Emergence of Advisory Group on Reliability of Electronic Equipment, (AGREE)	This is generally considered to be the start of the reliability discipline.
1954	Start of RAMS (Reliability and Maintainability Symposium) conference.	This has grown to be the premiere world-wide conference. It is organised by the IEEE. It has addressed the subject of reliability prediction in one form or another every year until the present time.
1955, April	Reliability Factors for Ground Electronic Equipment.	This document described the actions that need to be taken into account when assessing reliability of electronic equipment. [Henney, Lopatin, Zimmer, Adler & Naresky, 1955]
1956, November	TR-110 - Reliability Stress Analysis for Electronic Equipment.	This contained the first formal statement of prediction which amongst other things presented mathematical models for predicting reliability. [Connor, 1956]
1957, April	VITRO report no 7 - Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability.	This document formed the first application based method for reliability prediction. It later evolved in to MIL-HDBK 217. [Vitro, 1957]
1959	Martin Titan Handbook.	This was the first prediction standard to suggest the use of multiplication factors, here called s-factors that later were adopted by MIL-HDBK 217 as π-factors. This handbook was also the first to suggest the use of failure per 10^6 hours

Date	Document/Work	Comment
		as a standard metric and the use of the exponential distribution. [Lockhead Martin, 1959]
1961	Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability – TR133-NAVSHIPS 93820.	This is an update of the 1957 Vitro publication and is the first military approach to performing reliability prediction. [Stokes, 1961].
1961	The Erles Report - Reliability Application and Analysis Guide.	This Report summarised the content of the TR133- NAVSHIPS 93820 for an academic audience. [Erles, 1961]
1962	MIL-HDBK 217 "Reliability Prediction of Electronic Equipment".	This is the first publication of probably the most influential and important document in reliability prediction. This was based in part on the NAVSHIPS document of 1961. This document was a standard imposed by the military and was often used in specification and requirements documents for work in the military field and increasingly outside. The document was a collection of models for specifying the reliability of components under varying conditions and a methodology for combining the component rates into a rate for the overall system. [RADC, 1962]
1962	Failure Rates.	This paper defined failure rate for technical equipment and then described the use to which such a metric could be put. [Erles & Edins, 1962]
1963	MIL-STD-756A - Reliability Modeling and Prediction.	This standard establishes procedures for predicting the reliability of aircraft, missiles and related assemblies, including electronic equipment, throughout all the development phases. It was intended as a high level document to specify the use of MIL-HDBK 217 for use in specific areas. [US DOD, 1963]
1963	Component Fault Data from a Data Processing Equipment.	This document was the first UK based document that included failure rates from commercial equipment. [ATEC, 1963]
1966, January	Reliability in Linesman/Mediator,	This document was a UK document that contained failure rates for military equipment. [Ashton, 1966]
1968	Reliability Prediction—Help or Hoax?	This was the first direct criticism of the reliability prediction process as defined in MIL-HDBK 217. [Codier,1968]
1974	MIL-HDBK 217B- "Reliability Prediction of Electronic Equipment".	This update added a number of models for newer component types such as integrated circuits which was based on work carried out at Boeing, and added models that reflected new technology in other component types. A noticeable trend was the rise in complexity of the models that were in use but the most complex models, those of reliability physics or physics of failure (PoF) were not incorporated and models that leant too far in that direction were simplified before inclusion. [RADC, 1974]
1974	Siemens SN29500 "Reliability Prediction".	This Siemens document was first published as an internal document. Note that this document

Date	Document/Work	Comment
		comprises separate parts, each of which is updated independently by different groups within Siemens and associated companies. [Siemens, 1974]
1974, January	Italtel Reliability Prediction Handbook (IRPH) Version 1.	Italtel is the Italian national telecommunication body. This was the first European equivalent to MIL-HDBK 217. This edition introduced the failure rate values in reference conditions (part count procedure). [Italtel, 1974]
1975	Bellcore TR-TSY-000332 ”Reliability Prediction Procedure for Electronic Equipment” – Version 1.	This document from Bell labs was originally developed by modifying MIL-HDBK 217 to reflect better the conditions of interest to the telecommunication industry. [Bellcore, 1975]
1976, June	Italtel Reliability Prediction Handbook (IRPH) Version 2.	This edition of the Italtel approach introduced the parts stress procedures. [Italtel, 1976]
1977, April	British Telecom - Handbook of Reliability Data for Components used in Telecommunications Systems – Version 1.	First release of handbook by the UK’s Telecommunication company. [British Telecom, 1977].
1979	MIL-HDBK 217C - Reliability Prediction of Electronic Equipment.	This update added support for newer technologies and the larger integration sizes of the older technologies. [RADC, 1979]
1979, March	Italtel Reliability Prediction Handbook (IRPH) Version 3.	This edition introduced new classification of component categories.
1980, May	British Telecom - Handbook of Reliability Data for Components used in Telecommunications Systems - Version 2.	Raw data grading quality revised. [British Telecom, 1980]
1980	The Failure Rate Function Estimated from Parameter Drift Measurements.	This paper suggested that the study of parametric drift could provide useful insight into the reliability of systems. This was the basis of the later research project into this topic. [Møltøft,1980]
1982, January	MIL-HDBK 217D - Reliability Prediction of Electronic Equipment.	An update of models and underlying data. [RADC,1982]
1982, December	Standard Reliability Table for Semiconductor Devices, Nippon Telegraph and Telephone Public Corporation.	The Japanese national Telecoms known as the NTT Standard. [NTT, 1982]
1982, July	Bellcore TR-TSY-000332 ”Reliability Prediction Procedure for Electronic Equipment” – Version 2.	Version 2 rolls up a number of updates to version 1 which were issued between 1977 and 1982. [Bellcore 1982]
1983	Reliability Assessment and Screening by Reliability Indicator Methods.	This paper proposed an early version of prognostics, called here “reliability indicators”. These ideas fed into the CORD project. [Møltøft,1983]
1983, January	Recueil de Données de Fiabilité du CNET (RDF)	This is the French national telecommunication company’s reliability prediction handbook. It contains the most complex of the models to date and is partially based on the physics of failure of those devices. [National Centre for Telecommunications Studies, 1983]
1984, January	British Telecom - Handbook of Reliability Data for Components	New component categories and appendices with failure rate models added. [British

Date	Document/Work	Comment
	used in Telecommunications Systems - Version 3.	Telecom, 1984]
1984,July	Bellcore Technical Advisory TA-000-23620-84-01, " Reliability Prediction Procedure for Electronic Equipment".	This was a re-issue of the renamed Bellcore TR-TSY-000332 document. [Bellcore, 1984]
1984	**Start of CORD Project at Loughborough University.**	The Component Reliability Database or CORD project was a data collection exercise for a variety of system types from military communications to desktop computers. The purpose of the study was to identify the electronic component types that were causing failures in electronic equipment, to examine which environments led to these failures and to investigate the failure mechanisms. In order to carry this out this study undertook to build a component reliability database, (CORD). This database proved to be an enabler that allowed many forms of analysis and innovation to take place in this field. See Section 3.1 for further details.
1984	**Start of Parametric Drift Project at Loughborough University.**	This project was to take components which were identified as troublesome by the CORD project and investigate how their reliability could be modelled, with a particular focus on the development of reliability indicators. The author was employed to work on this project. See Section 3.2 for further details.
1986	Start of the Computer Aided Life Cycle Engineering (CALCE) Institute at the University of Maryland, USA	CALCE became the chief advocate for the Physics of Failure approach to reliability engineering. [Watson, 1992]
1986, October	MIL-HDBK 217E - Reliability Prediction of Electronic Equipment.	A further update to underlying data and models. [RADC, 1986]
1986	Siemens SN-29500 "Reliability and Quality Specifications Failure Rates of Components".	An update to a number of sections of SN-29500. [Siemens, 1986]
1986	Reliability Indicators.	This paper further developed the ideas of "reliability indicators". These ideas fed into the CORD project. [Jensen & Møltøft, 1986]
1986	Reliability Prediction: A state of the Art Review.	This paper provided a review of the state of the art in reliability prediction and developed many arguments that O'Connor would use later to criticise the technique. [O'Connor & Harris, 1986]
1986	Formation of International Electronics Reliability Institute (IERI) at Loughborough University.	The component reliability projects at Loughborough had expanded sufficiently to allow the formation of a research institute. After this date the work done at Loughborough is attributed to IERI.
1986	The Highs and Lows of Reliability Predictions.	This paper addresses some of the problems of prediction. [Spenser, 1986]
1987	**End of Parametric Drift Project.**	The parametric drift project finished and the author took over as manager of the CORD project.
1987,	British Telecom - Handbook of	New component categories and user guide

Date	Document/Work	Comment
January	Reliability Data for Components used in Telecommunications Systems – Version 4.	added. Quality level definitions and some tables revised. [British Telecom, 1987]
1987, September	Italtel Reliability Prediction Handbook (IRPH) Version 4.	This edition introduced new models of integrated circuits and of component categories.[Italtel, 1987]
1987	The Organization of a Study of the Field Failure of Electronic Components.	This paper described the organisation of the CORD project. It describes the procedures around the database and the reasons they were implemented. [Campbell, Hayes & Hetherington, 1987]
1987	**Reliability Behaviour of Electronic Components as a Function of Time.**	This paper described the parametric drift project and was focused on using early life measurements to predict the lifetime of capacitors. [RJ1]
1987	GJB/Z 299a – Chinese Military Standard for Reliability Prediction.	First Chinese military standard on prediction. It is loosely based on MIL-HDBK 217 but has adaption for the Chinese environment and level of technology. [Chinese National Military Standard, 1987].
1988	Reliability Prediction: A Constructive Critique of MIL-HDBK 217E.	This paper addressed some of the observed problems of MIL-HDBK 217 and suggested ways to correct and improve the shortcomings. [Blanks, 1988]
1988	A Critique of Mil-HDBK 217E Reliability Prediction Methods.	This paper examines the use of MIL-HDBK 217 and highlights where it has failings. [Pecht & Kang, 1988]
1988	On US Mil-HDBK 217 and Reliability Prediction.	This paper was a critique of prediction in general and of MIL-HDBK 217 in particular. [Leonard, 1988]
1989	Failure Prediction Methodology Calculations can Mislead: Use Them Wisely, Not Blindly.	This paper attempts to advise users of MIL-HDBK 217 on how to best use it to avoid the potential problems in the data and procedure. [Leonard & Pecht, 1989]
1989	The Analysis of Electronic Component Reliability Data. Reliability Data Collection and Use in Risk and Availability Assessment.	This paper discusses the CORD database and presented a large number of constant failure rate statistics for different component types. [Marshall, J. Hayes, J, Campbell, D & Bendell A., 1989.]
1990	AT&T Reliability Manual.	A general reliability procedures handbook that contains some failure rate data and prediction models. Unique in that it uses Weibull-based prediction for early failure periods. [AT&T,1990]
1990	An Analysis of the Field Failure of Passive and Active Components.	This paper sets out the principles of analysis used in the CORD project. It provides some early data and analysis results. [Campbell & Hayes,1990]
1990	What is Wrong with the Existing Reliability Prediction Methods?	This paper describes what appears to be wrong with MIL-HDBK 217. [Wong, 1990]
1990	Reliability Prediction: Help or Hoax?	This paper describes the methods of reliability prediction, questions the validity and logic of the process and proposes a top down approach to prediction. Note that this paper has the same title as the one published in 1968 by Codier, this was intentional to show that little

Date	Document/Work	Comment
		had changed in the intervening years. [O'Connor, 1990]
1990	**Electronic Component Reliability Data Generation, Collection and Analysis.**	This paper described the new, updated organisation of the CORD project. It also outlined the analysis types. This paper was resented as a tutorial at the Uk based Component Engineering, Reliability and Test (CERT) conference. [RC2]
1991	New Methods for Specification and Determination of Component Reliability Characteristics.	This paper describes the M(t) approach to analysis of component lifetimes. [Møltøft,1991]
1991	MIL-HDBK 217F - Reliability Prediction of Electronic Equipment.	An update of MIL-HDBK 217E with new component types added. [RADC, 1991]
1991	**Start of DIRAC (Database for Interbroadband component Reliability Calculations) Project.**	This project was funded by the European Union's RACE project (R&D in Advance Communications technologies in Europe). It included as partners many of the telecommunications companies in Europe, many of whom had their own prediction systems. DIRAC was an attempt at pooling the data that supported these separate handbooks and standardizing on a single prediction system across Europe. [RACE, 1992] See Section 3.3 for further details.
1991	**Reliability Behaviour of Electronic Components as a Function of Time.**	This paper reports the work done initially on failure intensity analysis. [RC3]
1991	**Failure Intensity Analysis of Resistors and Capacitors.**	This paper describes the failure intensity analysis results for passive electronic components. [RC4]
1992, July	MIL-HDBK 217F - Reliability Prediction of Electronic Equipment Notice 1.	Updates to a number of sections. [RADC,1992]
1992	**Reliability Behaviour of Electronic Components as a Function of Time.**	**This paper readdresses the work carried out on failure intensities and extends it to all device types.[PW3, also cited as [RJ1]]**
1992	British Telecom - Handbook of Reliability Data for Components used in Telecommunications Systems – Version 5.	This was the final version of the BT handbook. This was based on many of the principles learned on the DIRAC project and the data values published were based on data obtained from BT, CNET and Italtel using a data sharing agreement set up during the DIRAC project. [British Telecom, 1992]
1992	Bellcore TR- TSY-000332 "Reliability Prediction Procedure for Electronic Equipment" – Version 5.	A roll up of minor updates. [Bellcore Labs, 1992]
1992	**Failure Intensity Analysis of Electronic Components.**	This paper presented the failure intensity analysis of capacitors and resistors to a specific audience at a conference related to the above devices. [RC5]
1992	**The Comparative Reliability of Resistor Types under HAST.**	This paper is not concerned with reliability prediction, rather it is about Highly Accelerated Stress Testing (HAST) of devices. [RC6]

Date	Document/Work	Comment
1992	A survey of Reliability Prediction Procedures for Microelectronic Devices.	This paper survey the different reliability prediction models for microelectronic devices and compares the results. [Bowles, 1992]
1993	A Change in Direction for Reliability Engineering is Long Overdue.	This paper focused on moving the reliability engineering industry away from prediction based practices. [Wong, 1993]
1993	**End of DIRAC Project.**	This project finished for political reasons before the goal could be completed. A database was developed and procedures put in place but the database was never populated. This early curtailment of work meant that no publication was issued on this project.
1993, April	Italtel Reliability Prediction Handbook (IRPH) version 5.	Complete revision, first public release. This document also used the shared data agreed by the DIRAC project. [Italtel, 1993]
1993	Recueil de Données de Fiabilité (RDF) du CNET.	Known as RDF'93. This document also used the shared data agreed by the DIRAC project. [National Centre for Telecommunications Studies, 1993]
1993	DEF-STAN –00-42 (part 3/1): Reliability and Maintainability (R&M) Assurance Guidance, Part 3: R&M Case.	This document describes the reliability and maintainability cases that are to be used in procurement. For MOD equipment [UK MOD, 1993].
1993	**Evaluation of Reliability Prediction Methodologies.**	This paper describes the initial work carried out to compare different prediction methodologies using the CORD data on systems. [RC7]
1993	Is It Time for a New Approach?	This paper suggested that the entire approach to reliability engineering, based on prediction, was wrong and should be replaced by more logical systems. [Knowles, 1993]
1994	Perry Memorandum.	This government memorandum had the effect of cancelling any future updates of MIL-HDBK 217. [US Secretary of Defense, 1994]
1994	**Use of a Field Failure Database for Improvement of Product Reliability.**	This paper described the advantages of collecting very high quality data and the methods that can be used to achieve that. [RC8]
1994	**Estimation of System Reliability Using a Non-Constant Failure Rate Model.**	This paper describes the early work on attempting to use failure intensity analysis as a prediction method. [RC9]
1995, February	MIL-HDBK 217F Notice 2 - Reliability Prediction of Electronic Equipment.	Updates to a number of sections. [RADC, 1995].
1995	**End of CORD project.**	The CORD project finished and the database was mothballed.
1995	**Investigation of the No Fault Found Phenomena in Electronic Equipment.**	This paper describes the early work looking at the No Fault Found problem. [RC10]
1995	**Start of BSRIA Project.**	This project used thermography to inspect electrical distribution systems in buildings to identify when maintenance was required to avoid failure. The main sponsor (BSRIA) would not allow any publication since they produced their own report: "Safe thermal imaging of electrical systems (up to 1000V A.C.)". BSIRA Application Guide 17/97. [BSRIA,1997] See

Date	Document/Work	Comment
		Section 3.4 for further details.
1996	**IEC-601709–"Electronic Components - Reliability - Reference Conditions for Failure Rates and Stress Models for Conversion" standard.**	This international standard is not about reliability prediction for systems rather it described some models for the transformation of failure rate at component level between environmental conditions. The author was part of the development committee for this standard [IEC 1996]
1996	R&M in an Era of Acquisition Reform [Reliability and Maintenance].	This paper describes in detail the effect the Perry Amendment had on reliability engineering. [Caroli, Fennell, Gorniak & Reilly, 1996]
1997	Criteria for the Assessment of Reliability Models.	This paper describes how a reliability model, in particular for prediction, should be selected. In doing so it shows many shortcomings with prediction methodologies. [Pecht, Shukla, Kelkar & Pecht, 1997]
1997	**Use of a Field Failure Database for Improvement of Product Reliability.**	**This paper summarises the lessons learned on the CORD project. [PW6 Also cited as [RJ2]]**
1997	Setting the Requirements for the Royal Air Force's Next Generation Aircraft.	This paper looks at the user based metrics that can be used for reliability work. In particular, it focused on the MFOP/FFOP metric. [Hockley & Appleton, 1997]
1997	**Reliability Prediction Techniques for Commercial Components.**	This paper describes the basic principles of the IEC61709 standard. [NC1]
1997	First Release of PRISM.	PRISM was a repackaging by RADC of the MIL-HDBK data with non-electronic data. This is a software based prediction system. [RAC, 1997],
1997	**End of BSRIA Project.**	This project finished with the production of the BSRIA guidance document.
1998	Release of GJB/Z 299b.	This was an update to GJB/Z 299a – Chinese military standard for reliability prediction. [Chinese national military standard 1998]
1998	Dissolution of IERI.	IERI closed at Loughborough University when the author, who was the last active researcher, moved to Warwick University.
1998	**Start of Reliability Enhancement Methodology and Modelling (REMM) Project.**	The main objective of this project was to develop a methodology which provided pertinent reliability information to designers and programme managers at the time that they are best able to make use of it. The overall goal of REMM was to produce a holistic reliability assessment tool that could take input from all stages of the product life cycle to provide a reliability assessment. See Section 3.7 for further details.
1998	**Start of Aerospace Process Insertion of Reliability (ASPIRE) Project.**	This project came out of the Ultra Reliability Aircraft (URA) group which was formed from a number of aerospace suppliers to look at developing the reliability technology that would support the next generation of aircraft. The brief of the ASPIRE project was to examine a number of disparate reliability practices and

Date	Document/Work	Comment
		was to identify best practice and to search for improvements. See Section 3.5 for further details.
1998	IEEE-1413-1998 - Standard Methodology for Reliability Prediction and Assessment for Electronic Systems and Equipment A standard and the associated guide.	This standard and guide is a description of how IEEE thinks reliability prediction should be performed. It is a methodology firmly routed in the physics of failure approach since CALCE made a large contribution in its development. [IEEE 1998a] [IEEE 1998b]
1998	A Critique of the Reliability-Analysis-Center Failure-Rate-Model for Plastic Encapsulated Micro-Circuits .	This paper criticises the failure rate model used in MIL-HDBK 217 for a particular device encapsulation type. [Sinnadurai, Shukla & Pecht, 1998]
1999	Maintenance-Free Operating Periods—The Designer's Challenge.	This paper described the MFOP metric and outlines how a designer might deal with using it. [Relf , 1999]
1999	**A Comparison of Electronic-Reliability Prediction Models.**	**This paper was an update of the work carried out on the comparison of prediction method and reported in [RC7]. [PW1 Also cited as [RJ4]]**
1999	**A Toolkit for Parametric Drift Modelling of Electronic Components.**	**This paper was an update of the work carried out on the parametric drift project and reported in [RC1]. Here the work was extended and repackaged as a toolkit for general use. [PW2 Also cited as [RJ3]]**
1999	**Start of Universal Reliability and Availability Modelling Project (URAM).**	**The URAM project was started to develop a simulation tool for complex systems under complex operating and maintenance scenarios. The aim of the simulation was to be able to predict the availability of systems in order to test the ideas behind the MFOP/FFOP metric. See Section 3.6 for further details.**
1999	**Reliability Prediction Techniques for Commercial Components.**	This paper was a description of the IEC61709 standard aimed at space application for the European space agency. [NC2]
2000	**Reliability Enhancement Methodology and Modelling Tool.**	This paper outlines the principles of the REMM methodology and describes the work to be done during the project. [RJ5]
2000	Norme UTE C80-810 (Août 2005) : Recueil de Données de Fiabilité Modèle Universel pour le Calcul de la Riabilité Prévisionnelle (Version Anglaise).	This is the RDF 1992 standard converted in to a French telecommunication national standard. [Centre National d'Etudes des Telecommunications, 2000]
2000	**Reliability Enhancement Methodology and Modelling,**	This paper describes the structure of the REMM programme and reports preliminary work. [RC11]

Date	Document/Work	Comment
2000	**An Event Based Database for the Support of a Holistic Reliability Assessment Tool.**	This paper describes principles behind the REMM events database. It outlines the theory behind the structure. [RC12]
2000	**An Expert System for Constructing a Reliability Case.**	This paper outlines the thinking behind using expert systems for delivering a reliability case. [NC3]
2001, May	Telcordia SR-332 – version 1.	This is a reissued Bellcore TR-332 Version 6. Renamed since SIAC bought Bellcore. [Telcordia, 2001]
2001	**Investigation of the Occurrence of No-Fault-Founds in Electronic Equipment.**	**This paper revisits the NFF problem and summarises the work and findings to date. It is based on work reported as [RC10] in 1995. [PW4 Also cited as [RJ6]]**
2001	**Estimation of System Reliability using a Non-Constant Failure Rate Model.**	**This paper revisits the failure intensity analysis work and describes how it can be used as a prediction methodology. It is based on work reported in [RC9] in 1994. [PW5 also cited as [RJ7]]**
2001	**The Use of a Discrete Event Simulation to Model the Achievement of Maintenance Free Operating Time for Aerospace Systems.**	**This paper outlines the basics of the URAM simulation. [PW13 also cited as [RC14]]**
2001	**Understanding Reliability through Analysis of Event Histories – A Case Study from the Aerospace Industry.**	This paper describes the sorts of analysis for which event based data can be used. [RC13]
2001	**Reliability Enhancement Methodology and Modelling.**	This paper describes the REMM methodology and reports on progress. It is targeted at aerospace engine manufacturers. [NC4]
2001	**Using the REMM methodology.**	This paper describes the REMM methodology and reports on progress. It is targeted at the avionics industry. [NC5]
2001	**State Space Representation Using Path-sets.**	This paper describes the use of path sets for representation of the state spaces within the URAM simulation. [NC6]
2001	**Lessons in Distributing a Large Simulation.**	This paper describes the issues in creating a large simulation such as URAM. [NC7]
2001	**Integrating Design and Operational Models for Evaluating Logistics Systems.**	This paper examines how to integrate design and operational models of systems to allow evaluation of logistics systems. [NC8]
2002	**Reliability Enhancement Methodology and Modelling - The REMM Project.**	**This paper describes and summarises phase one of the REMM project. It outlines the methodology and describes all the elements. This paper was the winner of the Aeronautical society's SIMS prize for the best paper in the electronics field in 2002. [PW7 also cited as [RJ9]]**

Date	Document/Work	Comment
2002	**Using Neural Networks for Reliability Prediction.**	**This paper describes the use of neural networks to predict reliability of systems. [PW11 also cited as [NC9]]**
2002	**An Analysis of the Effect of a Reliability Paradigm Shift on Leading British Aerospace Companies.**	**This paper describes an analysis of the effect of a reliability paradigm shift on leading British aerospace companies. [PW12 also cited as [RJ8]]**
2002	**Modelling of maintenance Within Discrete Event Simulation.**	This paper describes how maintenance is modelled within the URAM simulation. [RC15]
2002	**Integrated Modelling of System Functional, Maintenance and Environmental Factors.**	This paper describes how systems function, environmental factors and maintenance actions are integrated within the URAM simulation. [RC16]
2002	**Enhancing Product Reliability using REMM.**	This paper describes how REMM can be used for enhancement of product reliability. [RC17]
2002	**Maintenance Free Operating Periods – A New Reliability Challenge.**	This invited paper describes the use of MFOP and explains at a high level how it can be achieved. [NC10]
2002	**A Methodology to Assess and Select a Suitable Reliability Prediction Method for EEE Components in Space Applications.**	This paper describes the methodology used in the ECSS-Q-30-08A standard and describes A methodology to assess and select a suitable reliability prediction method for EEE components in space applications. [NC11]
2003, February	Italtel Reliability Prediction Handbook (IRPH).	Complete revision of models and failure rates. [Italtel,2003]
2003	**An Event Based Database for the Support of a Holistic Reliability Assessment Tool.**	**This paper revisits the work on the event database for the REMM project described in [RC12] and outlines the changes that had to be made to implement a theoretically sound database in a company based environment, [PW8 also cited as [RC19]]**
2003	**Development of an Expert System for Reliability Task Planning as Part of the REMM Methodology.**	**This paper revisits the work on the experts system for the REMM project described in [NC3] and outlines what changes had to be made to implement the expert system in an industrial setting. [PW9 also cited as [RC18]]**
2003	**S**tart of FIDES project.	This is a mainly French project funded by the French DRA that is to develop a standard approach to reliability prediction and associated tasks. [Charpenel et al, 2003
2003	**Derivation of Technical Reliability and Maintenance Requirement.**	This paper looks at how technical and maintenance requirements can be derived. [RC20]
2003	**Representing Complex Systems within Discrete Event Simulation.**	This paper looks at how complex systems can be represented efficiently in simulations such as URAM. [RC21]
2003	**A Business Model for Reliability.**	This paper describes the ASPIRE business model for reliability. [RC22]

Date	Document/Work	Comment
2003	**A framework for Documenting and Analyzing Life-Cycle Costs using a Simple Network Based Representation.**	This paper looks at the trade offs between costs and benefit in reliability work. [RC23]
2003	**How to Achieve Assured Operation with Complex Systems.**	This RAMS tutorial describes how to achieve assured operation with complex systems. [RC24]
2003	**REMM Workshop at RAMS 2003.**	REMM took over a session at the conference to promote the REMM approach. RAMS is the première reliability conference.
2004	**End of Universal Reliability and Availability Modelling Project (URAM).**	The URAM simulation was completed and was passed to QinetiQ for evaluation.
2004	**The Reliability Case in the REMM Methodology.**	**This paper describes how the REMM expert system allows the generation of a reliability case for a system. [PW10 also cited as [RC26]]**
2004	**End of Reliability Enhancement Methodology and Modelling (REMM) pProject.**	The REMM project ended and the tools that were developed were passed to the industrial partners for evaluation and implementation.
2004	**End of Aerospace Process Insertion of Reliability (ASPIRE) Project.**	The ASPIRE project finished and best practice guides were supplied to the industrial partners.
2004	IEC62380-TR – “Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment” Technical report.	This is the international standard version of the CNET RDF2003 document. [IEC, 2004]
2004	**How to Achieve Assured Operation with Complex Systems.**	This RAMS tutorial describes how to achieve assured operation with complex systems and is an update of the previous years session [RC25]
2004	**An Analysis of the Drivers in the Philosophy of Reliability Practice over the Last 50 Years.**	This paper was invited for the 50th anniversary of the RAMS conference. It identified some of the drivers that had caused change in the reliability engineering field over the last 50 years. [RC27]
2005	**Perils and Pitfalls of Weibull Life-Data Analysis.**	This paper looked at the perils and pitfalls of performing Weibull analysis on life and test data [RC28]
2005	**Universal Reliability and Availability Modelling (URAM).**	This invited paper for the ESRA newsletter described the use of URAM for reliability improvements. [NC12]
2005	Publication of Fides Procedure.	The Fides approach takes a partial physics of failure approach to prediction and is partially based on the models in UTE C80-810 It should be noted that the FIDES handbook also addresses some of the wider aspects of reliability practice, such as recommendations for reliability process control and audits.
2006	Prognostics and Health Management of Electronics.	This paper proposes prognostics as a useful technique in the electronics field. [Vichare & Pecht, 2006]
2006, May	217Plus produced.	217Plus is the Reliability Information Analysis Center (RIAC) replacement prediction

Date	Document/Work	Comment
		methodology for MIL-HDBK 217, it supersedes the PRISM. [RIAC, 2008]
2006, October	Telcordia GR-332 – version 2.	Revised tables of generic device failure rates and 40 new devices have been added. Confidence limit calculation has been added.
2006	**ECSS-Q-30-08A – Components Reliability Data Sources and their Use**	The space industry developed this standard to deal with the lack of MIL-HDBK 217. The approach was to recommend the handbook methods only as a last resort after field data and manufacturers' data. It contained procedures for selecting prediction models that could be used to support a R&M case The author was part of the development committee for this standard. [ECSS, 2006]
2006	**Practical Evaluation of the REMM Process.**	This paper reported on the final outcome of the REMM project and described how many of the partners had implemented the system and what benefit they realised from it. [RC29]
2007	**Discrete Event Simulation for Reliability Prediction, in Encyclopedia of Statistics in Quality and Reliability.**	This book chapter described discrete event simulation and it use for reliability prediction. [BC1]
2007	**Revision of IEC-61709 started for release in 2010.**	This international standard is being updated as part of the IEC maintenance cycle. The Author is the IEC project leader for this document and is responsible for the updating of the technical content
2007	**Start of Polynoe Project.**	This project is looking at the use of physics of failure models for the prediction of lifetime and reliability of MEMS devices. See Section 3.9 for further details.
2008	Formation of working group to produce the VITA 51 – reliability prediction standard.	This is an attempt to create a new version of MIL-HDBK 217 with new data and models. [Vita, 2008].
2008	Update of 217plus.	This is the newest update to this software. [RIAC, 2008]
2008	**No Fault Found in "Encyclopedia of Quantitative risk Assessment and analysis".**	This book chapter looked at the problems of NFF in systems. [BC2]

3. Contributions to the Field of Reliability Prediction

This section sets out the author's contribution to the field of reliability prediction. It does this by first setting out the projects that author has worked on and then by discussing the published works presented with this document.

3.1 Major Research Projects

Over the years covered by this document the author has worked on a number of research projects that have led to the papers presented. This section gives details of these projects, summarising what they did, why they did it and what the author's contribution was. It is worth noting that for completeness all the major projects that the author has worked on are listed even if they did not produce relevant publications.

3.1.1 The CORD Project [1984-1995]

The Component Reliability Database or CORD project was started in 1984 because a number of concerns about reliability prediction were beginning to be made known within the industry. The project was funded by the UK MOD and involved a number of UK and Danish engineering companies from a variety of industries. It also included the Danish Engineering Academe (DIA) as an academic partner.

Apart from the Codier paper [Codier, 1968] most of the concerns were anecdotal but they were becoming a significant issue. The basic problem was three fold:

1. There was little faith in the failure rates that were being stated in the handbooks. This was because they were only derived from real field data in a few cases; many rates were from test data or from extrapolation from other data sets. Even when they were derived from field data there was little confidence that this underlying data was reliable.
2. There was some concern in the assumptions that were made. In particular the assumption that failure rates were constant. Many engineers had observed that for many components this was just not true.
3. There was a lack of confidence in the acceleration or π-factors used in the prediction methodology. These π-factors were used to convert between environments and in some cases there was little or no evidence, or theoretical justification the levels set. This was particularly noticeable for plastic encapsulations where the π-factors were such that it was impossible to use plastic parts in some military applications where MIL-HDBK 217 was a prerequisite and yet these parts were observed to be very reliable in similar non-military systems.

The CORD project set out to investigate these problems. Its remit was to collect failure and population data for a large number of systems operating in different environments and to produce a high quality set of failure rate figures for different environments for as many components as possible. The project also had scope to extend the analysis types available to reliability engineers, so the project was an enabler that allowed other goals to be achieved such as the use of proportional hazards models as documented by Marshall [Marshall, Wightman & Chester,1990] This is demonstrated by figure 1, which also shows the presented work.

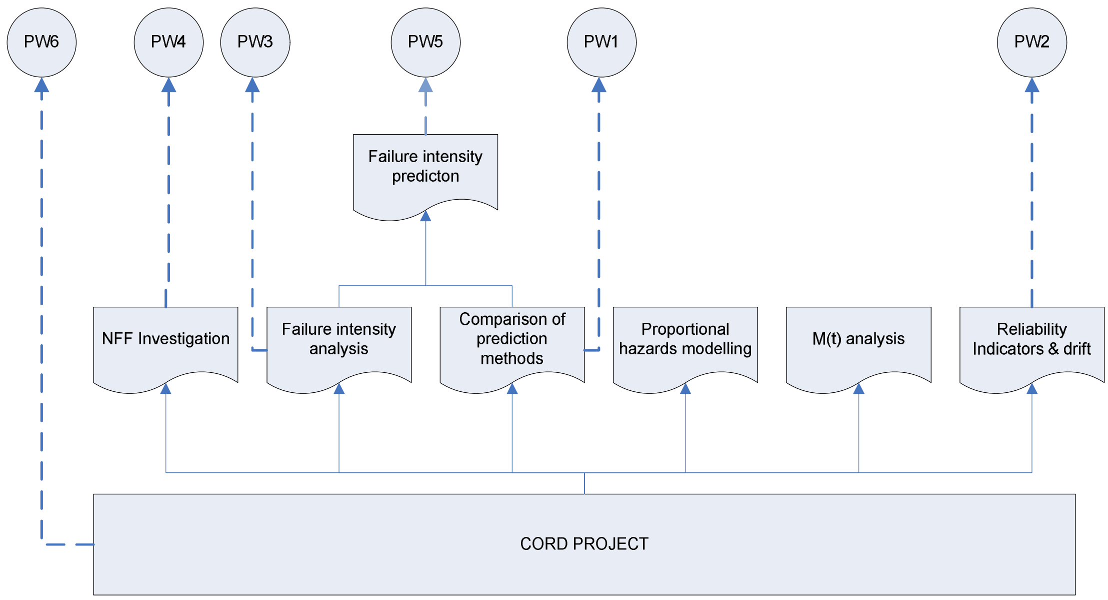

FIGURE 1: Relationships between Presented Work, Research and the CORD Project

In order to ensure that the data was high quality, very tight requirements for traceability of parts, complete data validation for incoming data, and regular re-screening of existing data were implemented. The major contribution of the core CORD project to reliability engineering lies in this area. It has been a benchmark for data collection exercises ever since.

The CORD project went through two phases. The first phase is described by Marshall in her PhD thesis [Marshall, 1990], and during this phase the author's contribution was to the data analysis projects supported by CORD. Phase two of this project was managed by the author and is described in the author's MPhil thesis [Jones, 1984]. During this latter phase the data validation process was reviewed and extended by the author to further improve the data quality and a number of new reporting processes were constructed such as the development of a reliability prediction handbook known as FRDR (Field Reliability Data Report). Also produced was a

Microsoft Windows based system known as I2R (For IERI Information Resource) that incorporated much of the data and results developed as part of the CORD project and allowed prediction using the CORD data

3.1.2 The Parametric Drift Modelling Project [1984-1987]

This project was a parallel project to CORD and its remit was to examine component drift failures and the use of reliability indicators. A reliability indicator is a parameter of the component that can be measured early in its life that by various means can then be used to predict when the device would fail [Jensen & Møltøft, 1986]. The concept of these reliability indicators came from some work on an optocoupler device in Japan [Takahashi, Todoroki & Mitani, 1979] and work done on Thick Film Resistors [Pranchov & Campbell, 1984] and [Kasukabe & Tanaka, 1981]. In the project it was hoped to be able to extend this to many other device types. This project contribution to reliability engineering was to examine a number of techniques for lifetime and failure prediction using reliability indicators and to develop a statistical model for prediction. It should be noted that this project was very much ahead of its time in that it was studying what are now called prognostics measurements. The author’s contribution to this project was to run the underlying experiments, which included designing test rigs and measurement software, to select and implement, in software, the various drift models that were examined and to develop the “Loughborough model” for drift reliability prediction.

3.1.3 The DIRAC Project [1992-1993]

The Database for Interbroadband component Reliability Calculations or DIRAC project was a project funded by the European Union's RACE (R&D in Advance Communications technologies in Europe) project. It included as partners many of the telecommunications companies in Europe, such as a BT, CNET, Italtel, Siemens etc. many of whom had their own prediction systems. DIRAC was an attempt at pooling the data that supported these separate handbooks and standardizing on a single prediction system across Europe [RACE, 1992]. The role of Loughborough University in this project was to host and operate the database and to manage the data collection and merging exercise in the first instance, and later when the database was populated to develop new methods of reliability analysis using the data. However, the project was terminated prematurely for political reasons, after the database infrastructure had been built and before it was populated. The author's role in this was as data manager and as such was responsible for database design, data coding, data validation design and all operational processes. Because of the termination of this project there were no publications based on this work but the major contribution to reliability prediction was in the data coding (in particular component type coding) and data sharing agreement set up between the European telecommunication companies as part of this project which led to changes in their respective prediction handbooks.

3.1.4 The BSRIA Project [1995-1997]

This project was jointly funded by the DTI and by the Building Services Research and Information Agency (BSRIA). It was to examine the use of thermography for prediction of failures in electrical switchgear so that maintenance could be scheduled. It involved a number of UK switchgear manufacturers and building operators. The work was done to produce a guidance document [BSRIA, 1997] to be published by BSIRA and there was an embargo on further publication from this project for ten years after project completion. The author's role in this project was as the main researcher.

3.1.5 The ASPIRE Project [1998-2004]

The Aerospace Process Insertion of Reliability or ASPIRE project was funded by the DTI out of the Ultra Reliability Aircraft (URA) group, which itself was part of the Society of British Aerospace Companies (SBAC). The purpose of the URA group was to look at developing the reliability technology that would support the next generation of aircraft [Bottomley 1999]. The purpose of the ASPIRE project was to enable the UK aerospace industry to design more reliable equipment and systems, predominantly mechanical, by finding innovative methods of using in service reliability data.

The two most important areas where ASPIRE had the most influence were firstly, the development of a business model for reliability and secondly, alternative reliability metrics. The author's role in this project was as the main researcher which involved building the business model and investigating the ways in which companies would use MFOP.

3.1.6 The URAM Project [1999-2004]

In general terms a customer is interested in how much use he can make of a product before it fails and has to be repaired. These needs can be encapsulated in the metrics Failure Free Operating Period (FFOP) and Maintenance Free Operating Period (MFOP). These metrics describe the time a system will operate, in the first case for systems where no failure is permitted and in the second for systems that can fail and be repaired. The Universal Availability and Reliability Modelling or URAM project developed a discrete event simulation model that allows a system designer to investigate whether or not a system can meet a defined MFOP specification. It did this by taking into account the reliability of the system, the mission profile that the system has been tasked with and the maintenance regime that has been implemented to support the system. This simulation was the first, and still is the only, simulation model to look at reliability with this level of detail. It made a major contribution to reliability knowledge in two distinct ways. Firstly, when applied by QinetiQ and the partner companies it allowed them to perform what-if analyses on their design and maintenance regimes under a MFOP paradigm, and this is still not possible with any other simulation. Secondly, it developed new methods of efficient handling of reliability data in a discrete event simulation. The author's role in this project was to design and build the component failure models, the underlying simulation clocks and component aging mechanisms, the system structure handling, the environmental factor handling, the database access and the user interface. The maintenance and operational leg scheduling were completed by a colleague.

3.1.7 The REMM Project [1998-2004]

The Reliability Enhancement Methodology and Modelling or REMM project was sponsored by the UK DTI and involved a large number of industrial partners. Its focus was to establish new methods and tools, and the interactions between them, for the enhancement and estimation of electronics equipment reliability within the aerospace field with particular attention to the More Electric Aircraft (MEA) project. The MEA project was an attempt in the aerospace market to move to electrical actuation of control surfaces and systems rather than hydraulics to save weight.

The main objective of the REMM project was to develop a system which provides pertinent information to designers and programme managers. This system was called IRIS for "Integrated Reliability Information System". To carry out this task the REMM project looked at diverse areas of reliability engineering with the intent of integrating them to generate a holistic approach. REMM generated new knowledge in each area addressed by providing new methodologies and techniques or by providing best practice guidance on how to better carry out the technique. The reliability areas examined in the REMM project included:

- Overall REMM process development (Production of demonstrator system)
- Statistical Modelling (Bayesian based analysis)

- Effective use of system reliability tools (Fault Tree Analysis and Failure Mode Effect and Criticality Analysis)
- Effective use of reliability enhancement testing (HAST), Environmental Stress Screening (ESS), manufacturing process monitoring (MPM) and statistical process control (SPC)
- Data collection
- Development of artificial Intelligence for decision making
- Mechanical systems reliability
- Systems that include software
- Cost effectiveness
- Investigation of no fault found (NFF) events on despatch reliability

The author's contribution was to the data collection, development of artificial intelligence and the overall REMM process development although contributions were made to other areas, in particular, the system reliability tools and NFF areas.

The REMM project has been judged a great success. The work done within some parts of it was ground breaking and the processes championed by it (the use of expert judgement and previous results to predict reliability, and the justification elements that feed a reliability case) have had a far reaching effect on the companies that were involved, each company taking what they wanted from the project, but none taking everything. The REMM approach is specified in various parts of the UK MOD when dealing with reliability assessment, as in fact has been done in the Polynoe project [see section 3.1.8] which is partly UK MOD funded.

3.1.8 The Polynoe Project [2008-2010]

This project is looking at the reliability of MEMS devices. The focus of the project is to be able to predict their reliability and lifetimes using physics of failure based modelling approaches [Foucher, B, 2008]. The current approach is to use fault tree analysis to build a top down reliability assessment and to build upwards from the basic physics to meet this at appropriate points. Experimental work is also proceeding to characterise the devices. The outputs of this work are to be fed into the French Fides methodology and into the UK's REMM based approach. This is an ongoing a project at the time of writing (November 2008) and so far there are no publications from this project.

3.2 Presented Work.

This section describes the papers that are presented with this thesis.

3.2.1 A Comparison of Electronic-Reliability Prediction Models[1]

This paper describes work that was done as part of the CORD project to examine the accuracy and repeatability of some of the more popular reliability handbook prediction systems. This work was done because it was becoming anecdotally obvious that there were problems with the prediction systems that were in common use.

This led to a very important piece of work which examined the available prediction handbooks to see how they compared against known good data. This was a worthwhile exercise since the CORD team was absolutely confident that the data contained in the database was of the highest possible quality and so it could provide a benchmark against which other data handbooks could be tested. The author limited the work to a small number of handbooks, mainly because these were easily available and the CORD database contained data on equipments that were similar to the data from which the handbook had been derived.

To do the analysis six pieces of equipment were chosen based on the ability of the original data providers to provide the extra information required and the match with handbook types. The methodology was to predict the reliability of the systems from

[1] J.A.Jones & J.A.Hayes, IEEE transaction on reliability, 48(2), 1999, pp 127-134.

the handbooks and then to compare this with the observed failure rates seen from the field.

This work showed that the handbook systems were not good at providing accurate prediction. It had often been commented by the partners that this would be the case, but that the state of affairs was satisfactory since it was known that certain handbooks were either too pessimistic (predicting a higher than experienced failure rate) or optimistic (predicting a lower than experienced failure rate) and so the companies used adjustment factors to account for this deviation. However, the work performed at Loughborough not only showed that the predictions were poor in terms of accuracy but that in some cases a handbook might prove pessimistic and in other cases optimistic, so a standard adjustment factor would not work.

The author then decided that further analysis was necessary and so another set of work was done to explore the sensitivity of the different models to the various factors that are used. This showed that the models were sensitive to different factors in different, sometimes non linear, ways and so were not to be trusted in any event.
This work was first published as a conference paper [RC7] and then rewritten and extended for publication as a journal paper [PW2].

The author's role in this work was to direct the technical aspect of it. A programmer wrote the code to extract data from the database and the associated lecturer negotiated with the companies to collect the data. The author designed and directed the methodology, selected the prediction models, performed the prediction and presented the results.

3.2.2 A Toolkit for Parametric Drift Modelling of Electronic Components[2].

This paper came out of the parametric drift project and is included because it summarises the majority of the work done on this project and was an early treatment of the use of prognostics, before the term was coined for what traditionally were known as reliability indicators. The work is also about predicting lifetimes and not just failure rates, a method that has also become more prominent albeit from a physics of failure point of view rather than the statistical treatment in this paper.

The work on parametric drift failures began by looking at a particular sort of electrolytic capacitor where it had been reported [Rhoads & Smith, 1984] that electrolytic capacitors' equivalent series resistance (ESR) drifted with time and could be linearised by taking the reciprocal. To generate data 5000 capacitors were put on test at a number of different temperatures and measurements of ESR were carried out regularly. Meanwhile work was undertaken to investigate a number of different drift models. Many were examined but the choice of models taken forward was driven by what the sponsor felt would be reasonable for use in a production situation and that their engineers could understand and implement. This meant that the simpler models were chosen. Each model was identified in the literature and then converted into an algorithm that could be coded as software. The models examined included a linear model, based on a least squares fit to the ESR data, which

[2] J.A.Jones, Reliability Engineering and System Safety, 63, 1999, pp99-106

was included because the sponsor felt that it could be implemented easily on a portable calculator. The concept behind all the models was to look at early drift measurements and by trending the data or by examining probabilities, decide when the ESR value had exceeded some predefined failure limits. The linear model looked solely at average trend while the probabilistic models tried to predict the probability of exceeding the limits given the current and starting conditions. The most successful model was the model developed by Professor Jorgen Møltøft whilst he was a visiting research fellow at Loughborough in the years preceding the start of this study [Møltøft, 1980]. The author also developed a model using the best elements of the available models in combination and this model was the second best performer. This latter model became known as the "Loughborough model" and was a good compromise between prediction performance and solution time which met the sponsor's requirements.

Using modern reliability thinking, what had been developed in fact was a prognostic measurement [Vichare & Pecht, 2006]. The tools that were developed here would be easily transferable to the modern paradigm. Hence, the contribution to reliability knowledge of this work is a series of methods that can be applied to prognostic development.

The author's contribution to this work was to design and run the experimental phase, identify the candidate statistical models and, when the short list was agreed with the sponsor, develop the software necessary to carry out the analysis. The presentation of the results and development of the Loughborough model was also done by the author.

This work was originally written up as a conference paper [RC1] in the electronic components sector where the focus was on the prediction of electrolytic capacitor lifetimes. The work was generalised as a toolkit for prediction of component lifetimes with the examples of application to capacitors and was published as [PW1].

3.2.3 Reliability Behaviour of Electronic Components as a Function of Time[3]

This paper came out of the CORD project. It was based on the idea that since good quality data was available it was possible to look at one of the underlying assumptions of a lot of prediction work, the constant failure rate. This was only possible and credible because of the very high data quality of the data in the CORD project. This paper is included since it reports on this ground-breaking work to provide concrete evidence of non-compliance to the constant failure rate assumption.

It has been known for many years that many components types do not have a constant failure rate period: typical examples being mechanical and electro-mechanical components, but it was generally assumed that most other components did follow the model, at least approximately, and if they didn't then it would only be by a small variation that could easily be ignored or dealt with by some multiplier. The work done at Loughborough would provide evidence that very few components exhibited such a constant failure rate.

The applicability of constant rates was examined by looking at the failure intensity (also known as hazard rate) of the component. Most analysis that uses this metric does so by looking at it cumulatively, but in this case the work was to look very closely at changes in the data and to make them more obvious when viewed by

[3] D. S. Campbell, J.A.Hayes, J.A.Jones & A. P. Schwarzenberger, *Quality And Reliability Engineering International,* 8, 1992, pp 161-166.

engineers. It was found that for the vast majority of components the failure rate was almost never constant [RC4], [Stennet & Hayes, 1991]. This demonstration had profound implications for the future of reliability prediction since it demonstrated that the premise of constant failure rate was not true and the variation from the assumption was so great as to make any pretence that it could be ignored absurd. This also led to the development of the M(t) analysis method [Møltøft, 1991] that was spearheaded by the DIA who were partners in the project and which was to become central to the DIRAC database analysis system.

The author’s contribution to this paper was the original idea to explore the failure rate behaviour and to develop the methodology, specify the programming tasks for the programmer and to interpret the results.

3.2.4 Investigation of the Occurrence of No-Fault-Founds in Electronic Equipment[4]

This work was done as part of the CORD project. The paper is included here since it was seminal in the analysis of the No Fault Found problem. The paper presented is a rewrite of the earlier conference paper [RC10] and was further developed in the REMM project [James, Lumbard, Willis & Goble, 2003] and finally adapted as a chapter in the Encyclopedia of Quantitative Risk Analysis and Assessment which was published in 2008 [BC2].

While examining the CORD database for failures of the systems that had been predicted using the handbooks, it was noticed that the largest outcome class following removal and repair for nearly all systems was in the No Fault Found (NFF) class, termed a NFF event. A NFF event was defined by the CORD database as occurring at three distinct levels; system, board or sub-system and component. When all these NFF events were considered they accounted for between 50% and 60% of all failures for a system. In the majority of prediction systems NFF events are not considered, but the author felt that NFF events should be analysed to see if any pattern or cause could be found and a way of bringing them into reliability prediction devised.

The principle behind the NFF event investigation was to validate some of the anecdotal reasons for NFF event occurrence and to do that the author looked at various constituent components of the boards that had displayed NFF events.

[4] J.A.Jones & J.A.Hayes, IEEE transaction on reliability, 50(3), 2001, pp 289-292

Investigating system level NFF events and component level events was excluded since that would have required a return to the companies for further data about system operating environments and failure analysis details, and at this time it was felt that a board level analysis would suffice.

The analysis of NFF events began by looking at the presence of complex components and connectors, both of which had been blamed anecdotally for high incidence of NFF. In all cases no evidence could be found that linked NFF occurrence rate to any of the anecdotal factors and this was a major result in reliability engineering since there had been no study previous to this that had drawn any firm conclusions.

Since the NFF occurrence rate was not attributable to any obvious cause there was no simple way to build this into a standard reliability prediction. However, the author felt that it might be possible to build this into the prediction systems using the failure intensity analysis approach that was under development. This would calculate the NFF intensity as being the number of NFF events observed, divided by the number of components at risk in a time period. This was the approach taken in the I2R software.

The author's contribution to this work was to devise the methodology and analysis criteria, perform the statistical analysis and report the results. In this instance the data extraction from the database was also carried out by the author.

Further work in this area was undertaken by the REMM programme but there is still a large scope for improvement since industry is still reporting a large number of NFF arisings. At the time of writing (December 2008), the author is preparing a research proposal to investigate this further using the techniques developed in REMM and URAM.

3.2.5 Estimation of System Reliability Using a Non-Constant Failure Rate Model[5]

The creation of the CORD database also led to the search for new reliability prediction methods. The first of these to be investigated was prediction using failure intensity analysis. This was work based on the failure intensity work described earlier but was focused on using the failure intensity value as a prediction tool. This sort of method of prediction would not need to be bounded by the assumption that failure rate is constant over the life of the component. This work showed that non-constant failure rate prediction was possible and did not have to rely on complex mathematical models.

The prediction is carried out by making an assumption that the failure intensity is constant over a very small interval, and then by adding the failure intensities of all contributing components, the failure intensity for the system could be derived within that small interval. If this is done for a time range then the likelihood of system failure at any instant within that time range could be derived. When this was tried on a number of boards it was found that the agreement between predicted data and observed data was extremely good.

The main benefit of this approach is that there is no longer an assumption about constant failure rate, or the shapes of the hazard curve. This means that this technique can be used to combine any number of different component types,

[5] J.A.Jones & J.A.Hayes, *IEEE transaction on reliability,* 50(3), 2001 pp 286-288

whatever their underlying failure behaviours. This method of prediction was unique at the time it was developed in that all contemporary systems made assumptions about hazard curve shapes. This approach has the benefit too that if failure intensities for NFF arisings can be calculated for a system they could also be added into the prediction. This work has not been followed up or adopted by any organisation as far as is known and this is attributed to the problem of providing sufficiently good data to support the method. The prediction system was contained in a software system specified and produced by the author for the project sponsors (UK MOD) in 1995. This system was known as I2R (For IERI Information Resource) and it incorporated much of the data and results developed as part of the CORD project. It was able to perform reliability prediction using the MIL-HDBK 217 and HRD4 systems as well as using the CORD data for constant (failure rate) and non-constant (intensity & M(t)) prediction. It was also possible to substitute the CORD failure rate data into both the HRD4 and MIL-HDBK 217 methods. I2R also incorporated the failure mechanism reports and alerts that were part of the output of the CORD project. Unfortunately, although a working, deployable version of this system was supplied to the UK MOD it disappeared in the re-organisation of the MOD in the mid 1990's when the CORD project finished.

The author's contribution to this work was the initial idea that prediction could be done in this way and the basic principles of how it would work. The author also specified and wrote all the software that comprised the I2R software system.

3.2.6 Use of a Field Failure Database for Improvement of Product Reliability.[6]

This paper summarises all the work that was done on the CORD project. It mentions other work not reported in other publications such as design fault analysis and failure pattern analysis. These forms of analysis, as well as board migration analysis which is not mentioned, were routinely carried out for the partner companies and helped them improve their products. These analysis techniques looked for patterns within the failure data and attempted to look for common faults in the same locations (design faults), under similar circumstances (failure pattern analysis) and for multiple faults on line replaceable units, (Board migration analysis), as they moved between systems and through the repair process.

The paper also describes the CORD data model. The reasons for publishing this paper were to demonstrate some of the advantages in collecting and analysing field data, and to highlight the effect that CORD had had on reliability data collections and analysis.

This paper is included here since it demonstrates the wider remit of the CORD project. The author's contribution to the work reported here is mostly described in other sections but for those analysis techniques not mentioned elsewhere the author contributed the concept and the methodology and in most cases routinely ran the analysis and interpreted the results for the companies. However, the data retrieval programming was carried out by the project programmer.

[6] J.A.Jones & J.A.Hayes, , , *Reliability Engineering And System Safety,* 5, 1997, pp 131-134

3.2.7 Reliability Enhancement Methodology and Modelling - The REMM Project.[7]

This paper describes the REMM project in detail from first principles, outlining why it was started and what it is attempting to do. It then describes the REMM process and the constituent elements such as the expert systems of the project in more detail. This paper is included because it gives a high level appreciation of the REMM project and describes many of the author's contributions to the project. It should be noted that this paper won the Aeronautical society's SIMS prize for the best paper in the electronics field in 2002.

The REMM methodology was based on the fact that all reliability tasks that are carried out will provide some information that can be used to make an assessment of the future reliability of a system. These tasks are all carried out during different phases of the lifecycle of a system, from concept design to field use.. The REMM methodology contained a database to hold the basic data, which was event based data; a Bayesian model to combine this data with expert opinion; an expert system to decide what reliability tasks could be carried out with the greatest effect on reliability; a reliability case generator which could put together the evidence required to generate a reliability case; and a series of guidance documents which demonstrated best practice on the various reliability tasks that could be performed.

This work adds to reliability engineering knowledge because it proposes an integrated, coherent methodology for looking at the different aspects of reliability. It describes a process flow that allows consideration of many things learned from

[7] J Marshall, L Walls & J Jones, *The Aeronautical Journal,* 106(1058), 2002, pp195-201

previous design and manufacturing processes. The process flow is a complex one but basically is about examining the things that make a new design different from a previous design.

The author's contribution to different parts of the REMM process is described in sections that follow. However, the author's contribution to the REMM project as a whole was the process flow that forms the backbone of the entire system. This process flow was worked out in consultation with the industrial partners in a number of brainstorming sessions where data was collected about the partners' requirements. This data was analysed and the process flow developed. Elements of the process flow were carried out by other partners. For example, the work on the Bayesian model was carried out by the University of Strathclyde [Walls & Quigley, 2001], and much of the work on the guidance documents was carried out by the various industrial partners; however, even in these cases the author made major contributions. In all cases the task of integrating the parts was carried out by the author.

3.2.8 An Event Based Database for the Support of a Holistic Reliability Assessment Tool[8].

The first part of the REMM work was to design the underlying database. This database had to store information about the systems in the field, their construction, their failures, and their operating conditions. It also had to track the systems through the manufacturing process since things that happen to a system in manufacturing and testing can certainly affect the later reliability and would have to be included in the Bayesian model. This problem was solved by the use of an event-based database. This publication describes the event-based database that was developed from the REMM project. It is included since this is a fundamental part of the REMM process. This paper also formed part of an entire session devoted to the project at the RAMS 2003 conference.

An event database records everything that happens to a system as an event of various types. Hence, the entry into service of a piece of equipment is one type of event, its later failure is another, its following repair another and so on. This sort of database can also track the construction of equipment since each process that parts of the equipment pass through can also be considered an event. So PCB construction, placement of components, soldering, final assembly, testing, etc, each have an event type associated with them. These events can be recorded for each individual component or at system level, depending on what is happening to the parts at that time. The use of events means that the system can be tracked

[8] , J. A. Jones, J. M. Marshall, R. M. Newman & G. Aulak, , *49th Annual Reliability and Maintainability Symposium (RAMS),* Tampa, 27-30 January 2003, pp 429-434

completely and this allows very many different forms of data analysis to be carried out. [Walls et al. 2001].

The author carried out all work described here; the database requirements were captured by the author from the REMM partners and the database was designed and implemented by the author.

3.2.9 Development of an Expert System for Reliability Task Planning as Part of the REMM Methodology.[9]

This paper described the expert system for the REMM project; it formed part of the special REMM session at RAMS 2003. It is included here since this is an important part of the REMM process and reflects the author's research interests in the application of AI to reliability studies.

The expert system element for the REMM project was based on the idea that when changes are made to a system, perhaps by moving to another environment, or by adding functionality, a reliability engineer would only carry out reliability tasks that targeted things that had changed on the system. The REMM expert system tried to encapsulate rules that would tell the engineer what to analyse. When a designer was designing a new system, which is mostly based on an existing system - in REMM known as the "base system" - that had extra functionality added or parts removed or swapped, the design changes or "delta" that created this "derived system" and the reasons for them would be captured as a series of facts. The expert system would then examine these facts and suggest what reliability tasks should be performed and in what way. These suggested tasks were generated into a report, called a reliability task list, and were then planned according to dependency rules. This reliability plan would contain information about the tasks that should be carried out, the likely effect the tasks would have on reliability, the typical timescales for carrying out the work based on resource availability and an indication of the probable cost of such an

[9] J.A.Jones, J. M. Marshall, R. M. Newman & G. Aulak, , 49th Annual Reliability and Maintainability Symposium (RAMS), Tampa, 27-30 January 2003, pp 423-428.

analysis path. By examining this sort of information the designer could see the effect of the design decision being considered and could then make the correct decision based upon what is trying to be achieved. The expert system would also generate a list of ‘concerns’, a concern being an aspect of unreliability, and this information, along with the mitigating effect of the reliability plan, could be passed to the Bayesian prediction tool and a prediction of the likely failure rate of the system in the field would be generated.

This paper advances the use of expert system ideas in reliability analysis, and brings the expert system closer to the designer than previously. The author’s contributions to this work were to design the expert system structure, the interface with the REMM demonstrator or IRIS, the underlying rules database and tracking systems and to outline how the expert system rules were to be generated by the partner companies. The author also produced some example rules based on previous experience with CORD and other projects and assisted the partners who undertook rule capture by facilitating an expert knowledge extraction session and then assisting with coding the rules from the domain knowledge extracted. The author also did all the programming for this application.

3.2.10 The Reliability Case in the REMM Methodology[10]

This work was part of the REMM programme and followed on naturally from the work on expert system development by taking the outcome of the latter and extending it to meet a new concept in reliability work, that of the reliability and maintainability case. This paper is included since the reliability case became a fundamental principle of REMM and this was a useful treatment of the subject generally. In particular since it analysed what should be in a case, what should be excluded and looked at the benefits and concerns of implementing a reliability case from an industrial point of view.

While the REMM expert system is making decisions about what task to carry out, the reasons for these decisions are recorded as an audit trail. This audit trail is the justification for why particular reliability tasks were scheduled. If the task was carried out and documented, then the justification and the results would form the basis for a reliability case. A reliability case, or more properly a R&M case [UK MOD, 1993], was a fairly new concept in the reliability field that came out of the safety case in the oil and nuclear industry. A reliability case was and is a reasoned argument that states why the system under consideration is reliable. Within the REMM project this was taken to mean a statement that the underlying base system is reliable (probably based on its own reliability case) and that any differences in the derived system have had reliability tasks carried out to remove the reliability concerns. Thus, a reliability

[10] Jeffrey A. Jones, Jane. Marshall & Bob Newman,*50th Annual Reliability and Maintainability Symposium (RAMS)*, LA, 26-29 January 2004, pp 25-30

case could easily be generated, based upon the results of reliability tests and analysis going right back to first principles, since a case for a complex system would be based on the reliability cases of simpler systems until at the lowest level there are simple statements about component reliability.

The work presented here examines the reliability case from a company perspective. This was done by running a number of workshop sessions with interested parties from the partners and analysing the outcome. A template for a reliability case was generated as a side product of this work and a reliability case generator system was designed and implemented. All the work described in this paper was done by the author.

3.2.11 Using Neural Networks for Reliability Prediction[11]

This work was inspired by the use of AI in the REMM project, and although not fully part of the REMM programme it was parallel to it and contributed some ideas to it. This paper is included because it is a good example of an application of novel thinking to the prediction process.

Reliability prediction can be considered a partial pattern matching exercise. When performing prediction historical data is examined and the data that best matches the current configuration is selected. Small adjustments to this historical data are made with the so called π-factors so that it is a better match to the actual configuration, environment and useage, thereby providing a prediction. There are two pattern matching elements here, the initial selection of appropriate data and the selection of the correct π-factors.

A good AI-based approach to pattern matching is the use of neural networks (NN). NN have been used in many fields for pattern matching purposes such as picture identification, credit scoring and similar [Hammerstrom, 1993] so it seemed to the author that it may be possible to use NN to perform prediction.

In order to set up the experiments data was borrowed from the REMM database. The work on NN involved deciding how to encode the data so that it could be passed

[11] J.A.Jones, Li Chong Jay Huang, & J. Marshall, The 8th ISSAT International Conference on Quality and Reliability in Design, Anaheim 7-9 August, 2002, pp 40-44

to a NN. This involved deciding on NN structure, learning algorithms, monitoring algorithms, encoding of time-based data, design of output criteria, and selection of training and test data sets. Despite best efforts the methodology had limited success; the number of factors that are important seems to be very large and it proved to be difficult to extract enough data of sufficient quality from the REMM database to address all these factors. The technique however, did show some promise if the data requirements could be met.

The paper contributes to knowledge in reliability engineering since it proposes a number of reusable coding models for use of NN in prediction. It also highlights some of the problems that are likely to be encountered.

The author's contributions to this paper were to design the NN models, develop the coding systems and interpret the results. The actual execution of the NN and the data extraction were performed by a MSC student under the author's supervision.

3.2.12 An Analysis of the Effect of a Reliability Paradigm Shift on Leading British Aerospace Companies[12]

This work was part of the ASPIRE project and is included here since it is the first assessment of the effect of MFOP on aerospace companies published to date and is core to understanding the response of industry to the MFOP paradigm change. This paper attempts to address what effects the move to MFOP would have on an aerospace company and concludes that although the move would be possible and welcomed, there are some problems to overcome, not least the ability to design for an MFOP.

One of the main aspects of this ASPIRE work was to look at a type of metric that had first been suggested by the UK MOD [Hockley & Appleton, 1997], and later by other authors [Dinesh, Knezevic & Crocker, 1999], [Cini & Griffith, 1999] and [Relf, 1999]. The idea was to look at the availability concept through two different aspects of this metric type, "Failure Free Operating Period" – FFOP [Burckhard, 1987] and "Maintenance Free Operating Period" – MFOP [Dagg & Newby, 1998]. These are inherently similar in that they are both about availability of a system. Each asks "how long can my system operate" without any failure at all in the first case and without maintenance in the latter case.

Changes in the aerospace market required consideration of through-life costs. These changes needed to be made to support lease-based contracts using a power-by-the-hour™ paradigm. Power-by-the-hour™ is a concept first adopted and trademarked

[12] J. A. Jones & L. Warrington, *Quality And Reliability Engineering International*, 18, 2002, pp 1-8

by Rolls-Royce to describe a situation where a customer leases an aero engine while Rolls Royce keeps ownership of and maintains the system. In this instance all the customer is interested in paying for is the time when the engine is available and so MFOP is of great importance to both the customer and to Rolls Royce. [Baines, et al, 2007], [Marinai, Probert & Singh, 2004] and [Allmendinger & Lombreglia, 2005].

The industrial partners in ASPIRE were concerned since they were expecting to be soon meeting MFOP requirements and power-by-the-hour™ based contracts for new equipment, in particular in the military field, and they wanted to be ready for it.
A number of different techniques were used to investigate the effect of a change to MFOP would have on the partners, such as questionnaires and in depth interviews, but the most useful was a simple Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. The SWOT attendees were asked to think about the MFOP concept first technically and then as it would apply to their companies. The results of the SWOT were gathered and reported back to each company for further elaboration and discussion and finally were summarised, made anonymous and presented.

The contribution carried out by the author during this work was to take the output from the questionnaires, SWOT sessions and other interactions and perform the analysis. This led directly to the material presented in this paper.

3.2.13 The Use of a Discrete Event Simulation to Model the Achievement of Maintenance Free Operating Time for Aerospace Systems.[13]

This paper described the URAM simulation model. The reason for inclusion of this paper is that the work was ground-breaking. There still are no other reliability simulation tools that can do what URAM can do.

In order to examine the use of MFOP, as suggested by the ASPIRE project, what is needed is a single tool that can consider all the various parts of a system and estimate the achievability of the required MFOP. A number of people suggested various mathematical models for MFOP modelling (Dagg & Newby, 1998) but it was generally felt that the complexity of the models would be far too great.

It was therefore decided that a simulation model would be built, to be known as the Universal Reliability and Availability Modeller or URAM (also for a period known as the Ultra Reliability Aircraft Model after the parent project group). This simulation model is a complex model of a system's behaviour that is capable of simulating groups of highly complex systems through a complex operation scenario whilst being supported by a complex maintenance schedule. The simulation takes into account systems structure and interdependence, systems capability, diagnostics and prognostics abilities, maintenance support abilities and availability, maintenance planning including a look ahead facility, operational planning, operational conditions such as environmental conditions, useage factors, failure behaviour of components,

[13] J.A.Jones, L Warrington & N Davis, , *Proceeding Of The 47th Annual Reliability And Maintainability Symposium (RAMS)*, Philadelphia, 22-25 January 2001. pp 170-175

and it supports any component reliability model. The simulation outputs a list of all events that have happened to the groups of systems during the operational periods that can be analysed further.

The work on this project was shared between three developers, with input about requirements from industrial project partners. The role of the author was to collect these requirements and specify what the simulation had to achieve, develop the databases that support the simulation, develop the component failure models, the underlying simulation clocks and component aging mechanisms, the system structure handling, the environmental factor handling, the database access and the user interface.

The URAM simulation was used by partners in the project to simulate the part that Tornado played in the first Gulf War and in doing so was found to be astonishingly accurate [QinetiQ, 2002], [QinetiQ, 2003] and [QinetiQ, 2004].

Personal recognition for the work on discrete event simulation in reliability prediction led to a request for an article in the Encyclopedia of Statistics in Quality and Reliability, which was published in 2007 [BC1]. Also arising out of this work on URAM and MFOP was an invitation by the Reliability and Maintainability Symposium, known as RAMS, to present a tutorial at the 2003 and 2004 conference [RC24] [RC25]. The tutorials examined how the concept of MFOP fitted into the wider aspects of designing for reliability.

4 Conclusions

It is clear from the work that has been described that the area of reliability prediction has changed in the last 25 years. It has gone from being a tool used routinely and taken seriously, to one that is not used and is deprecated and finally to one that is making a comeback albeit in a different form.

The initial part of the author's work was about assessment of the effectiveness of reliability prediction using the existing methods and in doing so the author added fuel to the debate that led to the demise of the initial form of reliability prediction. The second part of the author's work has been looking for replacements to prediction using various different means since the task of prediction, if it could be relied upon, would be an extremely useful tool in the armaments of the reliability professional.

There has been limited success however in devising a prediction system that is both accurate and can be made to work in the real world. Many of the most accurate prediction techniques have extremely large data or high computational requirements which most companies, with consideration of costs, tend to shy away from. Even if the companies had unlimited funds to spend in these areas because of lacklustre data collection in the past, for many reasons, they would have to start afresh with precise data collection and so would be slow to see the benefits of any improved prediction, too slow perhaps to make it possible to invest in these sorts of improved data collection techniques.

It is likely that the new handbooks, such as FIDES [Charpenel et al, 2003], IEEE 1413[IEEE, 1998a], and VITA 51[VITA 2008], will demonstrate an improvement over the previous generation in that they at least do consider the physics of the devices being modelled.

Other techniques such as discrete event simulation like URAM [Jones, Warrington & Davis, 2001] and the holistic approaches of REMM[Marshall, 1999] will also come in to their own as the complexity of systems increase beyond what is possible to predict using simple handbook methods. This is most likely as the customer focus switches to the availability paradigm and the use of complex accommodation systems like prognostics handling becomes more prevalent. These latter two methods of course have a lot of synergy since the output from both of them can be fed into the other to improve the prediction potential.

The work described covers almost 25 years of work by the author in the prediction area. In that time the innovations that the author has made are:

- The application and development of statistical models for lifetime prediction using early life data.(i.e. prognostics) [PW2]
- The use of non-constant failure rates for reliability prediction. [PW5]
- The use of neural networks for reliability prediction. [PW11]
- The use of artificial intelligence systems to support reliability engineers decision making. [PW9]
- The use of a holistic approach to reliability. [PW7][PW8][PW9][PW10]

- The use of complex discrete events simulation to model equipment availability. [PW13]

The contributions to knowledge that the author has made in this field have been:

- Demonstration of the weaknesses of classical reliability prediction.[PW1][PW3]
- An understanding of the basic behaviour of no fault founds. [PW4]
- The development of a parametric drift model (The Loughborough model). [PW2]
- Identification of the use of a reliability database to improve the reliability of systems. [PW6]
- An understanding of the issues that surround the use of new reliability metrics in the aerospace industry. [PW12]

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5 References

Allmendinger G. & Lombreglia R., 2005. Four Strategies for the Age of Smart Services. *Harvard Business Review*, 83(10), pp. 131-145.

Ashton W. F., 1966, *Reliability in Linesman/Mediator*, Radar and Radio Establishment, Malvern, Internal Report, (Restricted Publication)

ATEC, 1963 Automatic Telephone & Electric Company, , *Component Fault Data from a Data Processing Equipment*, P.L.C.S. Department, Electronics Division Exchange Laboratories Internal Report.

AT&T 1990, Reliability Manual, Eds. David J. Klinger, Yoshinao Nakada, Maria A. Menendez, AT & T Bell Laboratories, Springer, 1990, ISBN 0442318480.

Baines T., Lightfoot H., Evans S., Neely A., Greenough R., Peppard J., Roy R., Shehab E., Braganza A. , Tiwari A., Alcock J., Angus J., Bastl M., Cousens A., Irving P., Johnson M., Kingston J., Lockett H., Martinez V., Michele P., Tranfield D., Walton I., & Wilson H., 2007. State-of-the-art in Product-Service Systems. *Proceedings of the Institution of Mechanical Engineers*, Part B: Journal of Engineering Manufacture, 221(10), pp. 1543-1552.

Bellcore, 1975. Bellcore Technical Reference. TR-TSY-000332: *Reliability Prediction Procedure for Electronic Equipment, no. 1*. Bell Communications Research, USA.

Bellcore, 1982. Bellcore Technical Reference. TR-TSY-000332: *Reliability Prediction Procedure for Electronic Equipment, no. 2*. Bell Communications Research, USA.

Bellcore, 1984. Bellcore Technical Advisory, TA-000-23620-84-01: *Reliability Prediction Procedure for Electronic Equipment,* Bell Communications Research, USA.

Bellcore, 1992. Bellcore Technical Reference. TR-TSY-000332: *Reliability Prediction Procedure for Electronic Equipment, no. 5*. Bell Communications Research, USA.

Blanks H. S., 1988, Reliability Prediction: A Constructive Critique of MIL-HDBK 217E, *Quality and Reliability Engineering international*, 4(3), pp227-234.

Bottomley T., 1999. The Ultra Reliable Aircraft, *Systems Reliability and Maintainability (Ref. No. 1999/189)*, IEE Seminar, pp. 7/1 - 7/11

Bowles J., 1992, A Survey of Reliability Prediction Procedures for Dinesh Microelectronic Devices. *IEEE Transactions on Reliability 41*(1): pp2–12.

British Telecom, 1977. *Handbook of Reliability Data for Components used in Telecommunications Systems, Version 1*. British Telecommunications PLC.

British Telecom, 1980. *Handbook of Reliability Data for Components used in Telecommunications Systems, Version 2*. British Telecommunications PLC.

British Telecom, 1984. *Handbook of Reliability Data for Components used in Telecommunications Systems, Version 3*. British Telecommunications PLC.

British Telecom, 1987. *Handbook of Reliability Data for Components used in Telecommunications Systems, Version 4*. British Telecommunications PLC.

British Telecom, 1992. *Handbook of Reliability Data for Components used in Telecommunications Systems, Version 5*. British Telecommunications PLC.

BSRIA, 1997, *BSIRA Application Guide 17/97 - Safe Thermal Imaging of Electrical Systems (up to 1000V A.C.)*, Building Services Research and Information Agency.

Burkhard, A. H., 1987. Deterministic Failure Prediction. *The Journal of Environmental Sciences*, 30(2), pp. 34-36.

Campbell D. S., Hayes J. A. & Hetherington D. R., 1987. The Organization of a Study of the Field Failure of Electronic Components. *Quality and Reliability Engineering International*, 3(4), pp. 251-258.

Campbell D. S. & Hayes J. A., 1990. An Analysis of the Field Failure of Passive and Active Components. *Quality and Reliability Engineering International*, 6(3), pp. 189-193.

Caroli J. A., Fennell T. L., Gorniak M. J. & Reilly, J. F, 1996. R&M in an Era of Acquisition Reform [Reliability and Maintenance]. *42nd Proceedings of Annual Reliability and Maintainability Symposium (RAMS)*, Las Vegas, NV, USA, 22-25 Jan 1996, pp.1-6

Centre National d''Etudes des Telecommunications, 2000. *UTE C 80-810: UNION TECHNIQUE DE L'ELECTRICITE, RDF 2000 : RELIABILITY DATA HANDBOOK A Universal Model for Reliability Prediction of Electronics Components, PCBs and Equipment*. Union Technique De L'Electricite, Centre National D'Etudes des Telecommunications.

Charpenel P., Davenel F., Digout R., Giraudeau M. , Glade M., Guerveno J. P., Guillet N., Lauriac, A. Male, S. & Manteigas D., 2003. The Right Way to Assess Electronic System Reliability: FIDES. *Microelectronics Reliability*, 43, pp. 1401-1404.

Chinese National Military Standard, 1987., GJB/Z 299/A, *Reliability Prediction Handbook for Electronic Equipment*. Chinese National Miltary. Beijing, China. [In Chinese]

Chinese National Military Standard, 1991., GJB/Z 299/B, *Reliability Prediction Handbook for Electronic Equipment*. Chinese National Military. Beijing, China. [In Chinese]

Cini P. F. & Griffith P., 1999. Designing for MFOP: Towards the Autonomous Aircraft. *Journal of Quality in Maintenance Engineering*, 5(4), 296-308.

Codier E. O., 1968, Reliability Prediction—Help or Hoax?, *14th Proceedings of Annual Reliability and Maintainability Symposium (RAMS)*, Chicago, IL USA 21-23 Jan 1968, pp 383-390

Connor J., 1956. PB131678 - Reliability Stress Analysis for Electronic Equipment: *TR1100* , RAC.

Dagg R. & Newby M., 1998. Optimal Overhaul Intervals with Imperfect Inspection and Repair. *IMA Journal of Management Mathematics*, 9(4), pp. 381-391.

Dinesh Kumar U., Knezevic J. & Crocker, J., 1999. Maintenance Free Operating Period - An Alternative Measure to MTBF and Failure Rate for Specifying Reliability? *Reliability Engineering and System Safety*, 64(1), pp. 127-131.

ECSS, 2006. *ECSS-Q-30-08A: Components Reliability Data Sources and their Use*, ECSS, European Co-Operation for Space Standardization.

Erles D. R., 1961. *Reliability Application and Analysis Guide*, Lockheed Martin Corporation.

Erles D. R. & Edins M., 1962. *Failure Rates*, AVCO Corporation.

Foucher B., 2008, Polynoe, *CANEUS Micro-Nano-Technologies Reliability Workshop,* Tolouse, France, 29-30 May 2008.

Hammerstrom D., 1993. Neural Networks at Work. *Spectrum*, IEEE, 30(6), 26-32.

Henney K., Lopatin I., Zimmer E. T., Adler L. K, Naresky J .J. 1955, *Reliability Factors for Ground Electronic Equipment*, USAF, General Engineering Laboratory, Rome Air Development Center, Griffis Air Force Base, USA. McGraw-Hill book company.

Hockley C. J. & Appleton D. P., 1997. Setting the Requirements for the Royal Air Force's Next Generation Aircraft. *43rd Proceedings of Annual Reliability and Maintainability Symposium (RAMS)*, Philadelphia, PA, USA 13-16 Jan 1997, pp. 44-49.

IEC, 1996. *IEC 61709 Ed. 1.0:1996 Electronic Components - Reliability - Reference Conditions for Failure Rates and Stress Models for Conversion.* International Electrotechnical Commission, Geneva, Switzerland.

IEC, 2004. *IEC/TR 62380 Ed. 1.0:2004 Reliability Data Handbook - Universal Model for Reliability Prediction of Electronics Components, PCBs and Equipment*. International Electrotechnical Commission, Geneva, Switzerland.

IEEE, 1998a. *IEEE1413:1998 - Standard Methodology for Reliability Prediction and Assessment for Electronic Systems and Equipment* . The Institute of Electrical and Electronics Engineers, Inc.

IEEE, 1998b. *IEEE1413.1:1998 : Guide for Selecting and Using Reliability Predictions based on IEEE 1413*. The Institute of Electrical and Electronics Engineers, Inc.

Italtel, 1974. *ITALTEL IRPH 1974. Italtel Reliability Prediction. Methods.* Italtel Quality Division. Milan Italy.

Italtel, 1976. *ITALTEL IRPH 1976. Italtel Reliability Prediction. Methods.* Italtel Quality Division. Milan Italy.

Italtel, 1987. *ITALTEL IRPH 1987. Italtel Reliability Prediction. Methods*. Italtel Quality Division. Milan Italy.

Italtel, 1993. *ITALTEL IRPH 1993. Italtel Reliability Prediction. Methods.* Italtel Quality Division. Milan Italy.

Italtel, 2003. *ITALTEL IRPH 2003. Italtel Reliability Prediction. Methods.* Italtel Quality Division. Milan Italy.

James I., Lumbard D., Willis D. & Goble J., 2003. Investigating No Fault Found in the Aerospace Industry. *49th Proceedings of Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, FL,USA , 27-30 Jan. 2003., pp. 441-446.

Jensen F. & Møltøft J., 1986. Reliability Indicators. *Quality and Reliability Engineering International* , 2(1), pp. 39-44.

Jones J. A., 1994. *The Implementation of a Field Reliability Database*, MPhil Thesis, Loughborough University.

Jones J. A., Warrington L. & Davis N., 2001, The Use of a Discrete Event Simulation to Model the Achievement of Maintenance Free Operating Time for Aerospace Systems, *Proceeding of the 47th Annual Reliability and Maintainability Symposium (RAMS)*, Philadelphia, PA, USA. 22-25 January 2001, pp 170-175.

Kasukabe S., & Tanaka, M., 1981, Reliability Evaluation of Thick Film Resistors through Measurement of Third Harmonic Index, *Electro-Component, Science and Technology*, 8, pp 167-174.

Knowles I., 1993, Is it Time for a New Approach, *IEEE Transactions on Reliability*, 42(1), pp3

Leonard C. 1988 On US Mil-HDBK 217 and Reliability Prediction. *IEEE Transactions on Reliability*, 37 (5) : pp 450–451.

Leonard C. & Pecht M. 1989 . Failure Prediction Methodology Calculations can Mislead: Use Them Wisely, not Blindly. *Proceedings of the National Aerospace and Electronics Conference,* NAECON 1989;4:1248–53.

Lockhead Martin, 1959. *Martin Titan Handbook: Procedure and Data for Estimating Reliability and Maintainability*. Lockhead Martin Corporation.

Marinai L., Probert D. & Singh R., 2004. Prospects for Aero Gas-Turbine Diagnostics: A Review. *Applied Energy,* 79(1), 109-126.

Marshall J. Hayes J., Campbell D. S. & Bendell A., 1989. The Analysis of Electronic Component Reliability Data: Reliability Data Collection and Use in Risk and Availability Assessment, *Proceedings of the 6th Euredata Conference*, Siena, Italy, March 15-17, 1989 pp. 286-309.

Marshall J., 1990. *The Organisation and Statistical Analysis of an Electronic Component Field Failure Database*. PhD Thesis, Loughborough University 1990

Marshall J., Wightman D. & Chester S., 1990. Proportional Hazards Analysis of Electronic Component Reliability Data . *Proceedings of 11th Advances in reliability technology symposium*, ARTS, Liverpool, England. April 1990. Pp. 252-271.

Møltøft J., 1980. The Failure Rate Function Estimated from Parameter Drift Measurements. *Microelectronics and Reliability,* 20, pp. 787-802.

Møltøft J., 1983. Reliability Assessment and Screening by Reliability Indicator Methods. *Electro-Component Science and Technology*, 11, pp.71-84.

Møltøft J., 1991. New Methods for Specification and Determination of Component Reliability Characteristics. *Quality and Reliability Engineering International*, 7(2), pp. 99-105.

National Centre for Telecommunications Studies, 1983. *RDF83 - Recueil de Donnees de Fiabilite du CNET, Compilation of CNET's Reliability Data, 1983*. Centre National d'Etudes des Telecommunications.

National Centre for Telecommunications Studies, 1993. *RDF93 - Recueil de Donnees de Fiabilite du CNET, Compilation of CNET's reliability data, 1993*. Centre National d'Etudes des Telecommunications.

NTT, 1985, *Standard Reliability Table for Semiconductor Devices*, Nippon Telegraph and Telephone Corporation, March, 1985.

O'Connor P. D. T. & Harris L, 1986, Reliability Prediction: A State-of-the-art Review, *IEE Proceedings Part A: Physical Science, Measurement and Instrumentation, Management and Education,* 133, Pt A, No 4, pp 202-216.

O'Connor P. D. T, 1990, Reliability Prediction: Help or Hoax?, *Solid State Technology,* 33(8) , pp 59-61.

Pecht M. G., Shukla A. A. , Kelkar N. & Pecht, J., 1997. Criteria for the Assessment of Reliability Models. *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part B: Advanced Packaging*, 20(3), pp. 229-234.

Pecht M. G & Kang W. C. 1988 A Critique of MIL-HDBK 217E Reliability Prediction Methods, *IEEE Transactions on Reliability*, 37(5), pp 453-458

Pranchov R. B & Campbell D. S., 1984, "Model for Reliability Prediction of Thick Film Resistors, *Electro-Component Science and Technology*, 11, pp 185-190.

QinetiQ, 2002. *Operational Effectiveness and Whole Life Cost Impact of Maintenance Free Operating Periods.* QinetiQ report QINETIQ/KI/CONSULT/CR021718 - Restricted, 2002

QinetiQ, 2003. *Impact of Alternative Assumptions on Operational Effectiveness and Whole Life Cost of Maintenance-Free Operating Periods.* QinetiQ report QINETIQ/KI/CONSULT/CR031722 - Restricted, 2003

QinetiQ, 2004. *Deployable, Affordable Mission Effectiveness Study*. QinetiQ report QINETIQ/KI/CONSULT/CR042873 - Restricted, 2003

RAC, 1997. *PRISM® Software Tool - RAC Project A06839*. RAC.

RACE, 1992. Project R1092 - DIRAC Database for Reliability Calculations Page A-103 *Technical Report of the RACE Programme,* Research and Development in Advanced Communication Technologies in Europe.

RADC, 1962. *MIL-HDBK 217 : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1974. *MIL-HDBK 217B : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1979. *MIL-HDBK 217C : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1982. *MIL-HDBK 217D : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1986. *MIL-HDBK 217E : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1991. *MIL-HDBK 217F : Reliability Prediction of Electronic Equipment*. Rome Air Development Center for US Department of Defense

RADC, 1992*. MIL-HDBK 217F Notice 1 : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

RADC, 1995. *MIL-HDBK 217F Notice 2 : Reliability Prediction of Electronic Equipment.* Rome Air Development Center for US Department of Defense

Relf M. N., 1999. Maintenance Free Operating Periods—The Designer's Challenge. *Quality and Reliability Engineering International,* 15(2), pp. 111-116.

Rhoads G. & Smith A., 1984. Expected Life of Capacitors with Non-Solid Electrolyte. *Proceeding of the 34th Electronic Component Conference*, New Orleans, LA, USA, pp. 156-161.

RIAC,2008. 217Plus: RIAC's Reliability Prediction Methodology. [online], http://www.theriac.org/productsandservices/products/217plus/index.swn. (17/11/2008)

Siemens, 1974. *Reliability and Quality Specifications Failure Rates of Components*, Technical Liaison and Standardisation,. Siemens AG, Munich, Germany.

Siemens, 1986. *Reliability and Quality Specifications Failure Rates of Components*, Technical Liaison and Standardisation,. Siemens AG, Munich, Germany.

Sinnadurai N., Shukla A. & Pecht M., 1998, A Critique of the Reliability-Analysis-Center Failure Rate Model for Plastic Encapsulated Microcircuits. *IEEE Transactions on Reliability* 47(2): pp110–3

Spenser J. L., 1986, The Highs and Lows of Reliability Predictions, *IEEE 32nd Proceedings of Annual Reliability and Maintainability Symposium (RAMS)*, Las Vegas, 28th -30th January, 1986, PP 156-162.

Stennet, N. & Hayes J., 1991. Connector Reliability. *The Electrical Contacts in Automotives, Aeronautical and Space Applications Proceedings*, Toulouse, France, 1991, pp. 145-150.

Stokes R., 1961. *NAVSHIPS 93820: Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability*. United States, Department of Defense.

Takahashi T., Todoroki S. & Mitani S., 1979. A New Screening Method for Optocouplers and LEDS. *17th Annual Reliability Physics Symposium,* San Diego, CA, USA , April 1979, pp. 167-170

Telcordia, 2001, Special Report *SR-332*, Reliability Prediction Procedure for Electronic Equipment (Issue. 1), *Telcordia* Technologies, Piscataway, NJ.

Telcordia, 2006, Special Report *SR-332*, Reliability Prediction Procedure for Electronic Equipment (Issue. 2), *Telcordia* Technologies, Piscataway, NJ.

UK MOD, 1993. *DEF-STA –00-42 (part 3/1): Reliability and Maintainability (R&M) Assurance Guidance, Part 3: R&M Case.* Directorate of Standardisation United Kingdom Ministry of Defence.

US DOD, 1963. *MIL-STD-756A: Reliability Prediction*. United States Department of Defense.

US Secretary of Defense, 1994. *SECDEF MEMO , Specifications and Standards - A New Way of Doing Business*. 29 Jun 94, Memorandum for Secretaries of the Military Departments, United States Department of Defense.

Vichare N. & Pecht M., 2006. Prognostics and Health Management of Electronics. *IEEE Transactions on Components and Packaging Technologies*, 29(1), 222-229.

VITA 2008, *VITA51, Reliability Prediction*, VITA Standards Organization, The VMEbus International Trade Association.

Vitro, 1957, *Vitro Technical Report no 7 - Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability*, Vitro Corporation.

Walls L. & Quigley J., 2001. Building Prior Distributions to Support Bayesian Reliability Growth Modelling using Expert Judgement. *Reliability Engineering and System Safety*, 74, pp. 117-128.

Walls L., Jones J., James I., & Marshal J., Understanding Reliability through Analysis of Event Histories – A Case Study from the Aerospace Industry, *European Safety and Reliability Conference, ESREL* 16th - 20th September 2001, Turin, Italy. pp.1353-1360

Watson G., 1992. MIL Reliability: A New Approach. *IEEE Spectrum*, 29(8), pp. 46-49.

Wong K. L., 1990, What is Wrong with the Existing Reliability Prediction Methods? *Quality and Reliability Engineering International* 5(4): pp 251–7.

Wong K. L., 1993, A Change in Direction for Reliability Engineering is Long Overdue. *IEEE Transactions on Reliability* 42: pp261.

6 Appendix 1 – Bibliographic Information

6.1 Complete list of the author's published works

(KEY: RJx are referred journal papers, BCx are book chapters, RCx are referred journals, NCx are non-referred journals.)

RJ1 D. S. Campbell, J.A.Hayes, J.A.Jones and A. P. Schwarzenberger, 1992, Reliability Behaviour of Electronic Components as a Function of Time, *Quality and Reliability Engineering International*, 8, pp 161-166.

RJ2 J.A.Jones and J.A.Hayes, 1997, Use of a field failure database for improvement of product reliability, *Reliability Engineering and System Safety,* 55, pp 131-134

RJ3 J.A.Jones, 1999, A toolkit for parametric drift modelling of electronic components, *Reliability Engineering and System Safety*, 63, pp99-106

RJ4 J.A.Jones & J.A.Hayes, 1999, A comparison of electronic-reliability prediction models, *IEEE transaction on reliability,* 48(2), pp 127-134

RJ5 J. Marshall & J.A.Jones, 2000, Reliability Enhancement Methodology and Modelling Tool, *ASQ Reliability Review*, 20(4), pp5-15

RJ6 J.A.Jones & J.A.Hayes, 2001, Investigation of the occurrence of no-fault-founds in electronic equipment, *IEEE transaction on reliability,* 50(3), pp 289-292

RJ7 J.A.Jones & J.A.Hayes,2001, Estimation of system reliability using a non-constant failure rate model, *IEEE transaction on reliability,* 50(3), pp 286-288

RJ8 J. A. Jones & L. Warrington, 2002, An analysis of the effect of a reliability paradigm shift on leading British aerospace companies, *Quality and Reliability Engineering International,* 18, pp 1-8

RJ9 J Marshall, L Walls & J Jones, 2002, Reliability enhancement methodology and modelling - the REMM project, *The Aeronautical Journal*, 106(1058), pp195-2011

BC1 Jones, J. 2007. Discrete event simulation for reliability prediction, in *Encyclopedia of Statistics in Quality and Reliability,* Ruggeri, F., Kenett, R. and Faltin, F. W. (eds). John Wiley & Sons Ltd, Chichester, UK, pp 553-558.

BC2 Jones, J, 2008, No Fault Found, in *Encyclopedia of Quantitative risk Assessment and analysis*, Melnick, E., and Everitt, B. (eds). John Wiley & sons Ltd, Chichester, UK. Pp 1163-1167.

RC1 J.A.Jones and J.A.Hayes, 1987, The Parametric Drift Behaviour of Aluminium Electrolytic Capacitors: An Evaluation of Four Models. *Proceedings of the 1st European Capacitor and Resistor Technology Symposium. (CARTS)* pp 171-179, Brighton October 1987.

RC2 J.A.Hayes, J.A.Jones, A. P. Schwarzenberger and D. S. Campbell. 1990, Electronic Component Reliability Data Generation, Collection and Analysis. *Proceedings of the 1st Components Engineering, Reliability and Test Conference (CERT)*, p246, Gatwick May 1990.

RC3 D. S. Campbell, J.A.Hayes, J.A.Jones and A. P. Schwarzenberger, 1990, Reliability Behaviour of Electronic Components as a Function of Time, *2nd European Symposium on Reliability of Electron Devices (ESREF)* 7th-10th October 1991, Bordeaux pp 41-48,

RC4. J.A.Hayes, J.A.Jones, A. P. Schwarzenberger and D. S. Campbell. 1991, Failure Intensity Analysis of Resistors and Capacitors. *Proceedings 5th European Capacitor and Resistor Technology. Symposium. (CARTS)* 30th September-3rd October, 1991., Munich, pp. 230-233,

RC5. J.A.Hayes, J.A.Jones, A. P. Schwarzenberger and D. S. Campbell, 1992, Failure Intensity Analysis of Electronic Components, *European Safety and Reliability Conference* (ESREL'92). Copenhagen June 1992. pp- 829-833

RC6. N. M. Troop, J.A.Jones and J.A.Hayes, 1992, The Comparative Reliability of Resistor Types under HAST, *6th Annual European Passive Components Symposium (CARTS),* Bruges, September 1992, pp 145-150,

RC7. M. Zahid, J.A.Jones and J.A.Hayes, 1993, Evaluation of Reliability Prediction Methodologies, *4th European Symposium on Reliability of Electronic Devices (ESREF'93),* 4th-7th October 1993, Bordeaux, pp 59-64,
RC8. J.A.Jones, M. Zahid and J.A.Hayes, 1994, Use of a field failure database for improvement of product reliability, *9th European Safety and Reliability conference. (ESREL'94),* La Baule, 30th May - 3rd June 1994, pp 1156-1164,.
RC9. J.A.Hayes, J.A.Jones and M. Zahid, 1994, Estimation of System Reliability Using a Non-Constant Failure Rate Model, *5th European Symposium on Reliability of Electron Devices (ESREF),* Glasgow, October 1994, pp 571-574,
RC10. J.A.Jones and J.A.Hayes, 1995, Investigation of the no fault found phenomena in electronic equipment, *10th European Safety and Reliability conference. (ESREL'95),* Bournemouth 1995, pp 569-580
RC11. J. Marshall, I. James & J.A.Jones, 2000, Reliability Enhancement Methodology and Modelling, *Foresight and Precaution - Proceedings European Safety and Reliability conference (ESREL) 2000,* Edinburgh, 15-17 May 2000, pp1479-1487
RC12. J.A Jones & J. Marshall, 2000, An Event Based Database for the Support of a Holistic Reliability Assessment Tool. *Foresight and Precaution - Proceedings European Safety and Reliability conference (ESREL) 2000*, Edinburgh, 15-17 May 2000, pp331-337
RC13. Lesley Walls, Jeff Jones, Ian James, & Jane Marshall, 2001, Understanding Reliability through Analysis of Event Histories – A Case Study from the Aerospace Industry, *Proceedings European Safety and Reliability conference (ESREL 2001),* Turin, 16th - 20th September 2001, pp 1353-1360
RC14. J.A.Jones, L Warrington & N Davis, 2001, The Use of a Discrete Event Simulation to Model the Achievement of Maintenance Free Operating Time for Aerospace Systems, *Proceeding of the 47th Annual Reliability and Maintainability Symposium (RAMS)*, Philadelphia, PA, USA. 22-25 January 2001, pp 170-175.
RC15. Jeffrey A. Jones, Les Warrington, & Neil Davis, 2002, Modelling of maintenance within discrete event simulation, *48th Annual Reliability and Maintainability Symposium (RAMS)*, Seattle, 28th-31st January 2002, pp 260-265
RC16. Les Warrington, Jeffrey A. Jones,& Neil Davis, 2002, Integrated modelling of system functional, maintenance & environmental factors, *48th Annual Reliability and Maintainability Symposium (RAMS)*, Seattle, 28th-31st January 2002, pp 399-403
RC17. J Marshall, L Walls, & J. A. Jones, 2002, Enhancing product reliability using REMM, *48th Annual Reliability and Maintainability Symposium (RAMS)*, Seattle, 28th-31st January 2002, pp 372-378
RC18. J.A.Jones, J. M. Marshall, R. M. Newman & G. Aulak, 2003, Development of an expert system for reliability task planning as part of the REMM methodology, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 423-428,
RC19. J. A. Jones, J. M. Marshall, R.M. Newman & G. Aulak, 2003, An Event Based Database for the Support of a Holistic Reliability Assessment Tool, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 429-434.
RC20. L. Warrington & J. A. Jones, 2003, Derivation of Technical Reliability & Maintenance Requirement, *49th Annual Reliability and Maintainability Symposium (RAMS)*,Tampa, 27-30 January 2003,pp 464-469
RC21. L. Warrington & J. A. Jones, 2003, Representing Complex Systems within Discrete Event Simulation, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 487-492
RC22. L. Warrington & J. A. Jones, 2003, A Business Model for Reliability, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003,pp 459-463
RC23. N. Davis, J. A. Jones & Les Warrington, 2003, A framework for documenting and analyzing life-cycle costs using a simple network based representation., *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 232-236
RC24. L. Warrington & J. A. Jones 2003, ,Tutorial paper - How to achieve assured operation with complex systems, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, Tutorial 6C, in Tutorial Notes. 14 Pages
RC25. L. Warrington & J. A. Jones , 2004, Tutorial paper - How to achieve assured operation with complex systems, *50th Annual Reliability and Maintainability Symposium (RAMS)*, LA, 26-29 January 2004, Tutorial 2A, in Tutorial Notes. 14 Pages

RC26. Jeffrey A. Jones, Jane. Marshall & Bob Newman, 2004, The reliability case in the REMM methodology, *50th Annual Reliability and Maintainability Symposium (RAMS)* ,LA, 26-29 January 2004, pp 25-30

RC27. Phoomphat Taksakulvith, Jeffrey. A. Jones, & Les. Warrington, 2004, An analysis of the drivers in the philosophy of reliability practice over the last 50 years, *50th Annual Reliability and Maintainability Symposium (RAMS)*, LA, 26-29 January 2004, pp 96-101

RC28. Warrington, L. & Jones, J.A , 2005, Perils and pitfalls of Weibull life-data analysis, *51st Annual Reliability and Maintainability Symposium (RAMS)*, Washington, Jan. 24-27 2005 pp 121 – 125

RC29. Jane Marshall, & Jeff Jones, 2006, Practical evaluation of the REMM process, *52nd Annual Reliability and Maintainability Symposium (RAMS)*, LA, 23-26 January 2006, Section 11D3 4 Pages.

NC1. E Schwarz, J. Jones and K Sateesh, 1997, Reliability prediction techniques for commercial components, *International workshop on electronic components for the commercialisation of military and space systems,* San Diego, February 3-5 1997, pp 1-5

NC2. J. Jones & E Schwarz, 1999, Reliability Prediction Techniques for Commercial Components, *European Meeting on Electronic Components Reliability Data and Modelling(ESTEC)* , Noordwijk, June 9, 1999

NC3. J. Marshall & J.A.Jones, 2000, An expert system for constructing a reliability case, *Avionics 2000, 14th Annual Conference and Exhibition: "Real-world avionics - meeting the customer's needs*", London, 15-16 November 2000. Pp 10.2.1 – 10.2.12.

NC4. J. Marshall, & J.A.Jones, 2001, Reliability Enhancement methodology and Modelling, *8th CEAS European Propulsion Forum: "Affordability and the environment, Key challenges for propulsion in the 21st Century",* Nottingham, UK, 26-28 March, 2001, pp 5.1-5.11

NC5 J. Marshall, Lesley Walls & Jeff Jones, 2001, Using the REMM methodology, *Avionics 2001, 15th Annual Conference and Exhibition*, Bristol, UK, 27-28 November 2001. Pp3.1.1–3.1.13

NC6. Les Warrington, J. Jones, & Neil Davis, 2001, State Space Representation Using Path-sets, *OR43, Operation research Society Annual Conference,* 4th-6th September 2001, University of Bath

NC7. Neil Davis, Les Warrington, & J. Jones, 2001, Lessons in distributing a large simulation, *OR43, Operation research Society Annual Conference*, 4th-6th September 2001, University of Bath

NC8. Neil Davis, J. Jones, & Les Warrington, 2001, Integrating Design and Operational Models for Evaluating Logistics Systems, *OR43, Operation research Society Annual Conference*, 4th-6th September 2001, University of Bath.

NC9. J.A.Jones, Li Chong Jay Huang, & J. Marshall, 1002, Using Neural Networks for Reliability Prediction, *The 8th ISSAT International Conference on Quality and Reliability in Design,* 7-9 August, 2002, Anaheim, pp 40-44

NC10. J.A.Jones, 2002, Maintenance Free Operating Periods – A new reliability challenge, *The Reliability Challenge 2002,* London, 20 September 2002

NC11. Gericke, W., Jenkins, I., Gregoris, G., Neugnot, C., Jones, J., & Lenic, J., 2002, A methodology to assess and select a suitable reliability prediction method for EEE components in space applications, *Proceedings of the European Space Components Conference, ESCCON 2002*, 24-27 September 2002, Toulouse. Compiled by R.A. Harris. ESA SP-507, Noordwijk: ESA Publications Division, ISBN 92-9092-817-4, 2002., p.73-83

NC12. J. Jones & L. Warrington, 2005, Universal Reliability and Availability Modelling (URAM), *ESRA Newsletter,* May 2005, pp6- 8

6.2 Citation data for Author's Published Works.

This data is derived from the ISI web of knowledge. (http://wok.mimas.co.uk) and was accessed on the 3/12/2008. The emboldened entries are discussed in this thesis.

Publication details	Citation count
J.A.Jones & J.A.Hayes, 1999, A comparison of electronic-reliability prediction models, *IEEE transaction on reliability,* 48(2), pp 127-134	13
J.A.Jones and J.A.Hayes, 1997, Use of a field failure database for improvement of product reliability, *Reliability Engineering and System Safety,* 55, pp 131-134	10
J.A.Jones, 1999, A toolkit for parametric drift modelling of electronic components, *Reliability Engineering and System Safety*, 63, pp99-106	5
J.A.Jones, L Warrington & N Davis, 2001, The Use of a Discrete Event Simulation to Model the Achievement of Maintenance Free Operating Time for Aerospace Systems, *Proceeding of the 47th Annual Reliability and Maintainability Symposium (RAMS)*, Philadelphia, PA, USA. 22-25 January 2001, pp 170-175.	5
J.A.Jones & J.A.Hayes,2001, Estimation of system reliability using a non-constant failure rate model, *IEEE transaction on reliability,* 50(3), pp 286-288	4
J Marshall, L Walls, & J. A. Jones, 2002, Enhancing product reliability using REMM, *48th Annual Reliability and Maintainability Symposium (RAMS)*, Seattle, 28th-31st January 2002, pp 372-378	2
N. Davis, J. A. Jones & Les Warrington, 2003, A framework for documenting and analyzing life-cycle costs using a simple network based representation., *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 232-236	1
J.A.Jones and J.A.Hayes, 1995, Investigation of the no fault found phenomena in electronic equipment, *10th European Safety and Reliability conference. (ESREL'95),* Bournemouth 1995, pp 569-580	1
L. Warrington & J. A. Jones, 2003, A Business Model for Reliability, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003,pp 459-463	1
J Marshall, L Walls & J Jones, 2002, Reliability enhancement methodology and modelling - the REMM project, *The Aeronautical Journal*, 106(1058), pp195-2011	1
J.A.Jones & J.A.Hayes, 2001, Investigation of the occurrence of no-fault-founds in electronic equipment, *IEEE transaction on reliability,* 50(3), pp 289-292	1
Jeffrey A. Jones, Les Warrington, & Neil Davis, 2002, Modelling of maintenance within discrete event simulation, *48th Annual Reliability and Maintainability Symposium (RAMS)*, Seattle, 28th-31st January 2002, pp 260-265	1
L. Warrington & J. A. Jones, 2003, Representing Complex Systems within Discrete Event Simulation, *49th Annual Reliability and Maintainability Symposium (RAMS)*, Tampa, 27-30 January 2003, pp 487-492	1
Jeffrey A. Jones, Jane. Marshall & Bob Newman, 2004, The reliability case in the REMM methodology, *50th Annual Reliability and Maintainability Symposium (RAMS)* ,LA, 26-29 January 2004, pp 25-30	1