PUBLICATION OF THESES

Please complete in block capitals

NAME: TIMOTHY KEVIN MANNERS

DEPARTMENT: CENTRE FOR ENVIRONMENTAL RESEARCH

TITLE OF THESIS: THE DEVELOPMENT OF LIFE CYCLE AND RISK ASSESSMENT METHODOLOGY USING DATA FROM AWE ALERMASTON

PLEASE COMPLETE EITHER PART A OR PART B

A. I agree that the abstract of my thesis may be published by the University without further reference to me.

In accordance with the University's Handbook of Procedures, the Head of Library Services may allow my thesis to be copied in whole or in part without further reference to me. Such Authority shall apply only to single copies made for study purposes and shall be subject to normal conditions of acknowledgement.

(See notes overleaf)

Signature: T K Manners

Date: 28/6/04

If you have completed Part A please return this form direct to the University Library.

B. I request that my thesis be held under confidential cover in the University Library for a period of years for the following reasons:

____

Once the period of confidentiality has expired, I agree that the conditions set down in Part A will apply without further reference to me.

Signature: ____________________

Date: ________________________

Please pass this form to your supervisor who should sign below indicating his/her agreement to the retention of the thesis under confidential cover.

Signature of Supervisor: ____________

Additional comments: _____________

Part B, when complete, should be returned to the Senior Assistant Registrar.

For the attention of candidates who have completed Part A

i) Attention is drawn to the fact that the copyright of a thesis rests with its author.

ii) A copy of a candidate's thesis is supplied to the University Library on condition that anyone who consults it is understood to recognise that its copyright rests with its author and that no quotation from the thesis and no information derived from it may be published without the prior written consent of the author or University, as appropriate.

Requests for such permission should be addressed in the first instance to the Head of Library Services.

Brunel University
Centre for Environmental Research

The Development of Life-Cycle and Risk Assessment Methodology Using Data From AWE Aldermaston

T. K. Manners M.Sc

A thesis submitted for the Degree of Doctor of Philosophy

January 2004

To Moose, -

"May the road rise before you,
And may the wind be always at your back"
- Long.

ABSTRACT

The research described in this thesis further develops Life-Cycle Assessment (LCA) methodology to include radiological releases to air, water and as waste. A new methodology has been developed to characterise radioactive aspects based on known effects to man and behaviour in the environment. Equivalency factors have been developed for nine radioisotopes (^{241}Am, ^{137}Cs, ^{60}Co, ^{239}Pu, ^{241}Pu, ^{3}H, ^{234}U, ^{235}U and ^{238}U). A new LCA valuation method is developed for weighting environmental impacts in an Environmental Management System (EMS). A detailed LCA inventory of environmental burdens has been compiled from data from AWE Aldermaston and used as a case study to develop and demonstrate the methodologies developed in this work. As part of the research, the links between environmental aspects and impacts has been investigated using LCA, based on the high hazard facilities at AWE Aldermaston, which is a major industrial site. The case study also includes the contribution from vehicle use in the impact assessment.

The results of this work have clearly identified which facilities and hence which processes are causing the most damaging environmental impact.

New risk assessment methods are developed to quantify environmental accidents, that include revised consequence definitions that can be applied without the need for modelling and thus offer an economical alternative to existing methods. A new six-step screening methodology is presented to identify potential major accidents to the environment (MATTE) and to comply with the COMAH Regulations 1999. A method to prioritise MATTE scenarios has also been developed.

The research has revealed that the current approach to significance assessment does not provide enough sophistication for sites as complex as AWE Aldermaston. The impacts of most concern are environmental irradiation, the generation of all categories of waste and global warming. The impacts associated with radioactive discharges (to air, water and as waste) are given the highest weighting largely reflecting the concern of the major stakeholder groups (local community, regulatory bodies and pressure groups). The methods proposed can be readily applied to any nuclear or chemical site.

LIST OF CONTENTS

LIST OF APPENDICES

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS

ALARP	As Low As Reasonably Practicable principle – An international principle for reduction of radiation dose and risk
AWE	Atomic Weapons Establishment
Alpha	Type of weak radiation emitted during radioactive decay
BAT	Best Available Technique
Be	Beryllium and Beryllium compounds
Beta/Gamma	Type of penetrating radiation emitted during radioactive decay
BNES	British Nuclear Energy Society
BNFL	British Nuclear Fuels Limited
BOD	Biochemical Oxygen Demand
BPEO	Best Practicable Environmental Option
BPM	Best Practicable Means
Bq	Becquerel – the Standard International unit for the quantity of radioactivity = 1 disintegration per second
CFC	Chloroflurocarbons
Ci	Curie – the old unit for radioactivity named after Marie Curie who discovered it. 1 Ci = 3.7 x 10^{10} Bq
COMAH	Control Of Major Accident Hazard Regulations 1999
CHIP	Chemical Hazard Identification and Packing for Supply Regulations 1994
CREA	Corporate Register of Environmental Aspects – database of all AWE contributions to corporate aspects
DALY	Disability Adjusted Life Years
DCF	Dose Coefficient Factor
DO	Dissolved Oxygen
Drigg	The shallow land burial site for LLW in Cumbria – operated by BNFL
DU	Depleted Uranium
EA	Environment Agency
EAL	Environmental Assessment Level
EF	Equivalency Factor
EI	Environmental Increment
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EQ	Environmental Quotient
EQS	Environmental Quality Standard
ERA	Environmental Risk Assessment
FREA	Facility Register of Environmental Aspects - database of specific facility contributions to corporate aspects
GBq	Gigabecquerel (one thousand million Becquerels)
GOCO	Government Owned Contractor Operated
GWP	Global Warming Potential
Gy	Gray - the Standard International unit for radiation dose
HAZOP	Hazard and Operability study - a structured methodology using nodes and guidewords to identify fault scenarios in a process, activity or operation. A HAZOP is run as a brainstorming session with key staff

	involved with the operation, facilitated by safety or environmental professionals
HBFC	Hydrobromofluorocarbons
HC	Hydro-carbon
HCFC	Hydrochlorofluorocarbons
HEPA	High Efficiency Particulate Air
HEU	Highly Enriched Uranium
HLW	High Level Waste (Radioactive)
HGV	Heavy Goods Vehicle
HSE	Health and Safety Executive
HTO	Tritiated water
ICRCL	Interdepartmental Committee for the Redevelopment of Contaminated Land
ICRP	International Commission of Radiological Protection
IEI	Integrated Environmental Index
ILW	Intermediate Level Waste (Radioactive)
IPC	Integrated Pollution Control
IPPC	Integrated Pollution Prevention & Control
ISO	International Standards Organisation
LCA	Life-Cycle Analysis / Assessment
LCIA	Life-Cycle Impact Assessment
LLW	Low Level Waste (Radioactive)
LNR	Local Nature Reserve
Man.Sv	Man. Sievert – this is the collective dose to a group of individuals
MAH	Major Accident Hazard
MAPP	Major Accident Prevention Policy
MATTE	Major Accident To The Environment
mbgl	Meters Below Ground Level
MEL	Maximum Exposure Limit
MeV	Mega electron volt - a measure of the ionising potential of radiation
µSv	Microsievert (one millionth of a Sievert)
mSv	Millisievert (one thousandth of a Sievert)
MoD	Ministry of Defence
NII	Nuclear Installations Inspectorate
Nirex	Nuclear Industry Radioactive Waste Executive
NNR	National Nature Reserve
NOx	Oxides of Nitrogen (NO, NO_2 and N_2O)
NRPB	National Radiological Protection Board
OBT	Organically Bound Tritium
ODS	Ozone Depleting Substances
PAH	Poly Aromatic Hydrocarbon
PCB	Poly-Chlorinated By-phenol
PM10	Particulate Material less than 10µm in diameter
POCP	Photochemical Ozone Creation Potential
PSA	Probabilistic Safety Assessment
PRA	Probabilistic Risk Assessment
Pb	Lead
R/A	Radioactive
R & D	Research and Development

RSA	Radioactive Substances Act 1993
SEPA	Scottish Environmental Protection Agency
SETAC	Society of Environmental Toxicology and Chemistry
SINC	Site of Importance for Nature Conservation
SMS	Safety Management System
SNF	Spent Nuclear Fuel
SSSI	Site of Special Scientific Interest
STW	Sewage Treatment Works
Sv	Sievert, the Standard International unit for measurement of radiation dose equivalent modified to reflect the differences between alpha, beta and gamma radiation.
TCA	Trichloroethane
TCE	Trichloroethene
THORP	**TH**ermal **O**xide **R**eprocessing **P**lant. A nuclear fuel reprocessing plant operated by British Nuclear Fuels Limited in Cumbria in the UK.
TWU	Thames Water Utilities
UKAEA	United Kingdom Atomic Energy Authority
UN	United Nations
US	United States of America
UV	Ultraviolet Radiation
VOC	Volatile Organic Compound
WHO	World Health Organisation

ACKNOWLEDGEMENTS

I am grateful to a number of people for their support and encouragement during the preparation of this thesis. The help and advice from Professors Susan Grimes and John Donaldson, my supervisors at Brunel University, is gratefully acknowledged. I am particularly indebted to Professor Grimes for her enthusiasm and encouragement throughout my happy association with the Centre for Environmental Research (CER). It has been a privilege to study at Brunel University.

AEA Technology Plc sponsored my first year of study and I am particularly grateful to Dr Lori Fellingham, my line manager at Harwell for all his personal encouragement and continued interest in my academic studies. Dr Chris Wilding approved the financial support and I am grateful for his help in this matter. AWE Plc and UKAEA sponsored my final years of study, and I am grateful to Tom Todd and George Burris (UKAEA) for their support and encouragement.

AWE plc allowed me to use their data for this study and I am grateful to Peter Smith for allowing access to the relevant files. The following people are "Mentioned in Despatches" as they have all helped me in my quest to finish this, the hardest and most demanding of projects: Dr Rob Macgregor (UKAEA); Dr Kevin Langley (UKAEA); Tom Turner (UKAEA); Catherine Manners; Chris Barder; Peter Booroff (AWE); Mark Patterson (AWE); Dr Chris J van der Gast (Oxford University); John Arundel; Dr Zaib Hussain (CER - Brunel University); Jeff Gledhill (WS Atkins); Colin Hunt (AWE), Craig Scarlett (AWE) and Jon Nicholls (AWE).

I owe a vote of thanks to my friend Keith Murphy (AWE) for patiently listening to my ideas and giving me so much objective, scientific and pragmatic advice in return. I am also in great debt to David Ellis (UKAEA) for challenging my approach and providing much mathematical illumination. It is my sincerest wish that the results and recommendations of this study be considered by AWE to help improve Environmental Management at Aldermaston. The methods can also be applied across the nuclear industry and at all stages of the life-cycle.

Finally I want to thank my family for all their love, support and encouragement through some very difficult times. This work is dedicated to my Dad who was right about everything.

CHAPTER 1 SUMMARY

In Chapter 1 background information on AWEs Environmental Management System (EMS) is given. A general discussion on significance testing and the importance of an Environmental Aspect Register in an EMS is presented. The need for a significance testing procedure, that gives the appropriate level of complexity for a particular organisation, is identified. Operations at AWE are described and how the existing EMS is used to control them. The aim of the research is described which is summarised as, development of methodologies to establish which processes, activities and associated impacts are causing the most environmental damage. A number of objectives are defined to achieve this aim, which, include the use of the LCA approach to quantify routine environmental impact and the development of improved risk assessment methods to measure the impact from accidental scenarios.

1 INTRODUCTION

1.1 BACKGROUND TO AWEs ENVIRONMENTAL MANAGEMENT SYSTEM

The Atomic Weapons Establishment (AWE) is currently operating an Environmental Management System (EMS) in line with the requirements of the International Standard Organisation (ISO) 14001 [1]. A fundamental requirement of the EMS is to assess the significance of impacts of the operation of the site in order to set priorities for improvement. Current methods for significance testing rely on assessing the frequency of an impact and its importance against the resulting consequence. Whilst the frequency assessment is fairly straightforward, determination of the consequence, and in turn the significance test, can be based on a wide variety of criteria including:

- Compliance with legislation;
- Business needs including cost implications;
- Environmental damage;
- Other stakeholder concerns.

Throughout this thesis reference is made to a number of environmental management terms. To avoid ambiguity of meaning these terms are defined in **Table 1-1**.

The Environmental Aspect Register is the cornerstone of an EMS where contributions, material inventories and controls (engineered and managerial) are summarised and it is this document that needs to be scrutinised and their importance ranked to identify significant impacts. Criteria used to develop scoring systems for significance testing may include:

- Longevity of damage;
- Sensitivity;
- Reversibility;
- Geographical spread;
- Impact relative to sustainable development.

All of these criteria must be tailored to suit an individual organisation.

All management systems need to confront the problem of prioritisation or significance testing in order to make best use of the businesses resources, yield the biggest improvements and hence generate the greatest cost savings. The process of significance testing has 3 main objectives [2]:

1. To identify issues requiring further analysis or measurement;
2. To identify issues for improvement;
3. To identify issues for continued control.

The significance testing procedure will form the basis for targeting issues for improvement whilst keeping those issues that are of a lower priority still on the register and under control.

Brown [3] suggests that a good significance testing procedure should include a number of desirable attributes [3] including the following:

- Force the organisation to consider environmental impacts (as opposed to environmentally damaging activities);
- Be derived especially for that particular organisation;
- Give the level of complexity appropriate for that organisation.

Much of the data gathering required for significance testing at AWE has been completed and individual facilities on the site have been assessed and operations which, are considered to be making a significant impact, identified [5]. At AWE efforts are currently being directed at fulfilling recommendations generated during the certification process and defining a strategy for improvements against the following corporate aspects.

- Releases (to the environment);
- Resource Use;
- Land Quality;
- Ecology;
- Nuisance.

A company's environmental performance has become an increasingly important factor as organisations recognise the value of controlling environmental risk. A good environmental management system should ensure compliance with legislation, save money spent on resources and assist with formulating company strategy.

In recent years the environmental problems of immediate concern have shifted from triggering a reactive response to adoption of a proactive response and the technological innovation required to resolve these problems has had to be developed along with methods to assess them [32]. The main focus of environmental performance is no longer restricted to the control of emissions from the pipes and stacks of industrial facilities, but increased attention is given to global and regional problems including climate change, stratospheric ozone depletion, air quality, loss of habitat and biodiversity [32]. Technologies have advanced from end-of-pipe solutions to clean technology, which, not only address direct impacts but also indirect impacts. Environmental management is now moving towards an holistic approach in which the entire life-cycle of products or processes are assessed with an overall goal of developing sustainable solutions optimised on environmental, social and economic criteria [32].

Bruntland [4] originally defined sustainable development as "development, which meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainable development has also been defined as living off the Earth's interest rather than the capital, which for energy requirements puts the emphasis on renewable sources (wind, solar, geothermal and tidal) as opposed to finite fossil reserves (the capital).

It is against the requirements of improved environmental management and the overall goal of sustainable development that the research described in this thesis is being carried out. Quantifying environmental burdens and establishing impacts for contributions at AWE will facilitate decision making within the EMS by targeting those processes that are generating the greatest impact.

1.2 OPERATIONS AT AWE

The Atomic Weapons Establishment was established in 1950 forming part of the United Kingdom Atomic Energy Authority (UKAEA). In 1973 ownership and management control of the site was transferred to the Ministry of Defence (MoD).

The AWE Aldermaston site in Berkshire undertakes the design, manufacture and servicing of Trident nuclear warheads, conducts research and development into warhead technology and carries out decommissioning of redundant Chevaline nuclear warheads and associated process plants.

Manufacturing, research and decommissioning operations produce solid, liquid and gaseous radioactive wastes principally tritium, uranium or plutonium. Small quantities of radioactive waste containing cobalt and caesium are also produced from maintenance of AWE Aldermaston's HERALD nuclear research reactor, which is not operational and has been shut down for several years awaiting decommissioning.

Following delays in commissioning Trident manufacturing facilities at AWE the Government decided to introduce modern management practices at Aldermaston. The Atomic Weapons Establishment Act 1991, made provision for contractor management of the site and in 1993 a Government-Owned Contractor-Operated (GOCO) fixed term contract was awarded. Under this arrangement the contractor organisation is responsible for management of all work activities at AWE. MoD retains ownership of the sites, radioactive substances and all plant and equipment.

In July 1997 the sites were each granted a Nuclear Site Licence under the Nuclear Installation Act 1965 by the Health and Safety Executive (HSE), who regulate safety arrangements at AWE Aldermaston.

1.2.1 The AWE Environmental Management System

The AWE operates an Environmental Management System (EMS) in line with the requirements of the international standard ISO 14001 [1]. The EMS has been specifically designed to integrate with AWEs Safety Management System (SMS) and address all environmental issues for routine, non-routine and emergency scenarios. A policy statement was issued by the Chief Executive in January 1998 and updated and re-issued in April 2000 [36]. To ensure a consistent approach each facility on site was assessed and an Environmental Addenda [5] prepared which formed an appendix to existing Safety Case Documentation. The operation of all hazardous plant and equipment at AWE has to be justified in a Safety Case, which is a requirement of the Nuclear Site Licence conditions, and subject to scrutiny by the regulator the Nuclear Installation Inspectorate (NII). The Environmental Addenda covers the following issues:

- General environmental management;
- Risk identification and the identification of significant environmental issues;
- Risk management and the identification of engineering and managerial controls. For significant contributions the facility is required to meet a minimum standard defined for that particular aspect.
- Performance measurement and the methods that are used to measure contributions.
- Recommendations for meeting Corporate Technical Standards and improving environmental performance.

AWEs EMS requires preparation of an Environmental Statement for lower hazard category plant and facilities (office blocks) to provide a more streamlined assessment. Both the Environmental Addenda and Statement include a Facility Register of Environmental Aspects (FREA), where all available environmental information is summarised [5]. The FREAs are used to populate a database known as the Corporate Register of Environmental Aspects (CREA), which, is used to manage the organisation's aspect information and record legislative requirements.

The method by which environmental management is implemented at AWE is by allocating individual facility contribution (how much and how often) to a corporate environmental aspect. At AWE there are 33 separate sub-aspects, which are grouped into the five main aspects: releases; resource use; land quality; ecology and nuisance. These corporate aspects have been carefully selected and reflect issues that are of greatest importance to AWEs activities. A corporate ranking system [13] has further divided these aspects into one of the following:

- High corporate significance:
- Medium corporate significance;
- Low corporate significance.

Issues that are highly regulated, vital to AWEs business and of major public concern, fall into the high category (i.e. all radioactive discharges). Whilst those issues that are common to all industry sectors and are not an immediate problem are given a lower corporate significance (i.e. nuisance and domestic waste generation).

Individual facilities are then assessed against these corporate sub-aspects to test for significance. The methodology used is as follows:

- If a building or facility contributes >10% of the site total to a **low** significance corporate aspect, this is considered to be a significant contribution;
- If a building or facility contributes >5% of the site total to a **medium** significance corporate aspect this contribution is considered to be a significant contribution;
- If a building or a facility contributes to any **high** significant corporate aspects, this is automatically considered to be a significant contribution.

The results of this significance testing are recorded in the FREA. Any significant contributions are required to meet the Corporate Technical Standard for that aspect, which defines criteria for:

- Risk identification (inventory management);
- Risk management (engineering and managerial controls);
- Performance measurement (monitoring, recording, analysing and reporting releases and resource consumption).

This information is recorded on a central register, the CREA, which is used as a basis for setting objectives and targets for improvement.

This approach to setting up an EMS is known as a top-down approach. A bottom-up approach would require reviewing all procedures and processes and identifying corresponding aspects and impacts. The top-down approach of allocating contributions to defined aspects is quicker to implement, although some experts believe that this method is not as rigorous in identifying all impact scenarios.

The environmental impact of one year's operation at AWE Aldermaston is significant. Raw materials are processed to manufacture nuclear warhead components, which, uses energy and resources. A diagram showing the major flows is given in **Figure 1-1**.

Table 1-1 EMS Terminology

Term	Definition
Corporate Environmental Aspect	Any element of an activity or service that can interact with the environment. Within the AWE EMS there are environmental aspects: Releases; Resources Use; Land Quality; Ecology and Nuisance.
Sub-aspect	Within the AWE EMS there are thirty three sub-aspects which are sub-set of aspects grouped under an environmental aspect (i.e. resource use – electricity is a sub-aspect under the aspect resource use).
Environmental Impact	Any physical changes to the environment, whether adverse or beneficial, wholly or partially resulting from an activity or service
Environmental Effect	The consequence of the impact and its ramifications to human health, erosion, corrosion, ecosystem damage, contaminated potable water supplies etc
Contribution	A physical measurable amount that used to quantify the size of environmental aspect, i.e. kg or m^3 of waste.
Environmental Addenda	A report detailing how EMS issues are addressed in high safety hazard buildings and facilities (i.e. radioactive processing). The report forms an addenda to existing Safety Case documentation.
Environmental Statement	A brief statement detailing how EMS issues are addressed in low safety hazard buildings and facilities (i.e. office blocks). The statement forms and annex to existing building safety information.
Equivalency Factor (EF)	A factor, (usually linear), which when multiplied by the mass of that substance allows aggregation into common units. For example kg of CO_2 equivalents. Equivalency Factors are also known as Impact Potentials or Characterisation factors.
Routine contribution	This is a planned contribution that takes place regularly. The consumption of electricity in a facility is routine contribution, whereas a contribution from plant shutdown or maintenance is an abnormal situation and a fault condition leading an environmental release is an accident situation.
Environmental burdens	The environmental loading on a facility or process. A burden is the contribution that each building, facility or process makes to a defined total.

Figure 1-1 AWE (Aldermaston) Annual Environmental Flows

Inputs:

Raw Materials
Consumables

Resources:

Electricity	8.4E+07	kWh
Steam	364857	Tonnes
Oil	6647	m^3
Gas	2.47E+08	kWh
Water (bore-hole)	863251	m^3
Water (TWU)	118056	m^3

1 year's typical operation at AWE Aldermaston (1999 - 2000)

Discharges:

Trade Effluent	7800	m^3
Sewage Effluent	21283	m^3
R/A Effluent (River Thames)	8739.4	m^3
R/A Effluent (Public Sewer	77941	m^3
R/A waste (ILW)	174.6	m^3
R/A waste (LLW)	738	m^3
Trade Waste	5640	Litres
Domestic Waste	624	Tonnes
R/A to Air (alpha)	1.00E+05	Bq
R/A to Air (tritium)	6.00E+12	Bq
R/A to Air (Kr-85)	5.00E+09	Bq
Carbon Dioxide from fuel (estimate from AWE Energy Manager in 1999)	127190	Tonnes

Outputs:

Trident Warhead Components

1.2.2 Continual Improvement

A fundamental requirement of ISO 14001 is to verify that continual improvement in environmental performance is taking place. A strategy is required to determine where priorities for improvement are to be focussed. This improvement will need to be directed on the processes that are not only making a significant contribution to corporate environmental aspects but those processes that are physically causing the most environmental damage.

Current methods of assessment range from fairly crude and subjective analysis of potential environmental consequences, to the extremely thorough but time-consuming and expensive Life-cycle Analysis (LCA) method, which is not always practicable or efficient for use whilst developing management systems in industry.

1.3 AIM, OBJECTIVES AND SCOPE

This study seeks to investigate the links and relationships between AWEs corporate aspects and resulting environmental impacts.

The overall aim of the study is to develop a generic methodology to establish which processes and activities and associated environmental aspects are causing the most environmental damage, and to use this information to determine where best to target efforts for continual improvement within relevant Industrial Environmental Management Systems. Where aspect contributions do not fit into existing impact assessment methodologies, new quantitative methods will be developed to minimise reliance on value judgements.

The overall aim is achieved through the following objectives:

1. To use the methodology of LCA to identify appropriate impact categories;
2. To consider how the impact from radioactive substances fits into current LCA methodology and develop company specific parameters to cover these aspects;
3. To integrate existing environmental indices and criteria to calculate and measure the severity of the impact;
4. To develop current Risk Assessment methods to evaluate environmental impact from accident scenarios;

5. To integrate and link the LCA impact assessment with the AWE EMS where appropriate;
6. To determine if current methods of significance testing, based on aspect contribution, is fit for purpose.

This study investigates routine contributions and is based on case studies of Facilities at AWE. The scope is to consider approximately 65 separate facilities at AWE Aldermaston selected on their high hazard potential and environmental significance. The scope of the study includes all releases and some resource use aspects but specifically excludes issues of land quality, ecology and nuisance. Land quality is largely a legacy problem caused by practices in the past, and is being addressed as a company-wide issue. Ecology and nuisance are also being addressed as corporate issues not under the direct influence of individual facilities. Aspects associated with the surface water system (engineered and un-engineered) are only applicable to one facility on site and are not included in the routine assessment. The scope of the study excludes the lower hazard category plant, for example office blocks and support buildings, as these facilities represent a very small environmental impact compared with operational process buildings.

Consideration is given also to transport impacts. In this context the current EMS recognises site traffic congestion as a nuisance from staff travelling to and from work and from transport operations on the site and to other AWE sites, however this does not extend to other impacts resulting from vehicle use, such as emissions to air. The site employs approximately 4000 people and most staff use cars to access the site [91].

A new methodology is developed for the identification of Major Accident Hazards and a risk ranking tool is used to evaluate environmental faults. Chapter 4 describes this methodology and its application to an AWE facility.

1.4 METHODOLOGY

The methodology adopted for this study is based on determination of environmental impacts by applying the framework of LCA. Where impact categories are not appropriate new categories and methods of assessment are developed. A new methodology for assessing radiological impacts is presented based on company specific aspects.

The layout of the study is described below and is broken down into parts:

1. **Chapter 1**. This chapter gives an introduction to the study, background information on AWE and its environmental management arrangements.
2. **Chapter 2**. This chapter provides environmental information about the site and its surroundings. This chapter includes information on the hydrogeochemistry of the site, local ecology and the type and location of important receptors and pollution pathways.
3. **Chapter 3**. This chapter gives an assessment of routine conditions where data from separate facility aspect registers is converted into an inventory and analysed to calculate impact potentials and quantify inventory information. Environmental information from Chapter 3 and data from other studies is reviewed and assessed in order to determine criteria and parameters for new impact categories. A new methodology is presented for radiological aspects.
4. **Chapter 4**. This chapter gives a description of the development of a new environmental accident assessment methodology, based on the specific requirements of the COMAH (Control Of Major Accident Hazards) Regulations 1999 [105]. AWE Aldermaston is a lower tier COMAH site and Major Accidents To The Environment (MATTE) need to be identified to fulfil the requirements of the Major Accident Prevention Policy (MAPP) [6]. The development of the methodology is described in Chapter 4 and an example of its application to a specific facility at AWE Aldermaston is summarised and full details are presented given in **Appendices N** and **O**.
5. **Chapter 5**. This chapter gives an interpretation of the results of the assessment of routine conditions in Chapter 3, and provides discussion of the results and techniques for improvement. This chapter also provides a section on sensitivity.
6. **Chapter 6**. This chapter comprises the conclusion to the study.

CHAPTER 2 SUMMARY

In Chapter 2 a description of the Aldermaston site is given which includes details of history, defence and research activities, hydrology, geology, hydrogeology, and geochemistry. The presence of known contaminants is described along with the current environmental monitoring regimes. Information is presented about the local ecology, heritage and agriculture along with data about the human populations that live in the surrounding areas. The importance of the various pollution pathways and sensitive receptor sites are discussed.

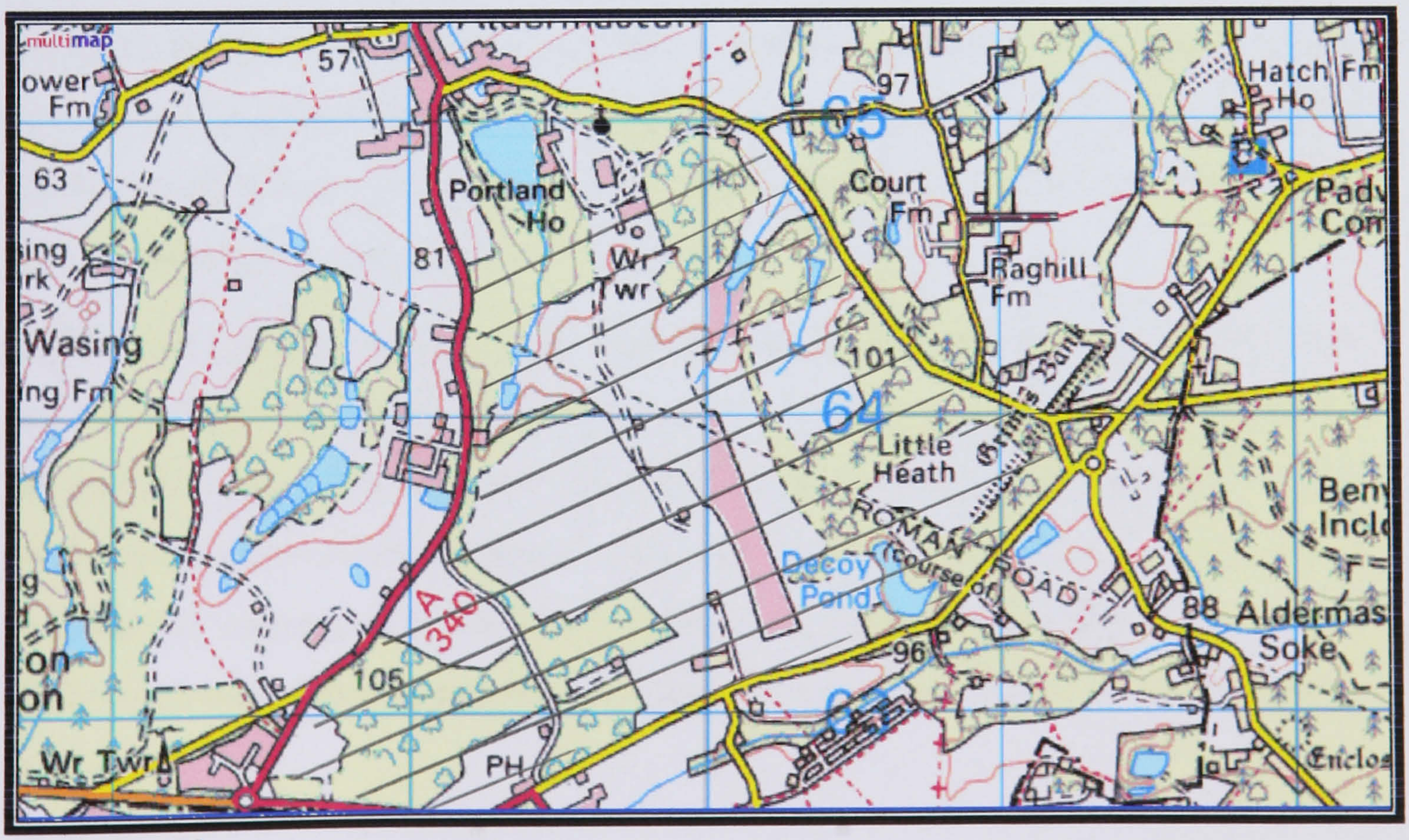
2 ENVIRONMENTAL SITE SETTING

Chapter 1 has introduced the AWE EMS and the requirements for carrying out this research. This chapter gives specific information about the Aldermaston site, in terms of its history, hydrogeochemical and ecological features. The location of sensitive receptors and their significance are given in order to set the site's activities and processes in the context of its local environment to identify important pollution pathways and receptors. Details are given about the type of activities and defence research that is carried out on the site. The site environmental information will help in determining appropriate parameters and criteria for developing methodologies for routine impact assessment and accident condition assessment.

2.1 DESCRIPTION OF THE SITE

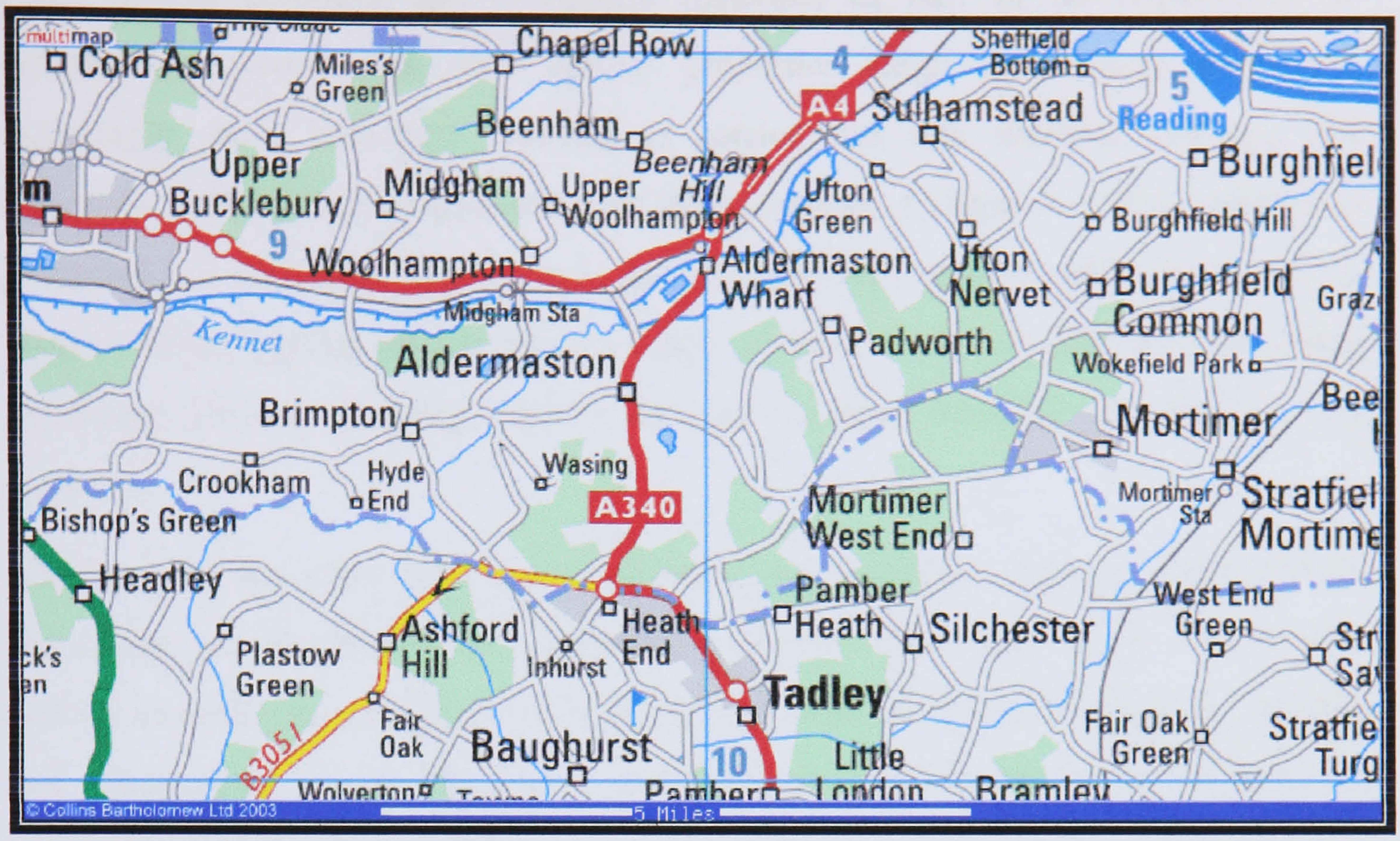
AWE Aldermaston is situated on the border of Berkshire and Hampshire, 15 km south west of Reading and 13 km south east of Newbury. The site is roughly triangular in shape and covers an area of 3.5 km^2. The centre of site is located at National Grid Reference SU 600 637.

Figure 2-1 1:25000 Scale Map



1:25000 scale map

Figure 2-2 1:100000 Scale Map



1:100000 scale map

The site sits on a plateau at an average elevation of 100m Above Ordnance Datum, it is generally level with a slight decline in a south-easterly direction. At the north end of site the ground drops away to give an area of damp low-lying ground extending to some ponds, which were used to collect rainwater run-off from the central site area. Owing to the risk of low radioactive contamination in this area, all rainwater is now directed to purpose-built water collection and settlement tanks prior to being discharged off the site. At the south end of site, the ground is considerably lower than the surrounding area creating a hollow.

A dense network of roads and buildings make up the central and western part of the site. The majority of this area is paved, with the exception of the western corner of the site, which contains land used for recreational purposes. The eastern half of the site is more open, with wooded and grassy areas. There are two long straight roads forming the principal routes on the site, one extending east-west and the other north-south. These roads were formerly runways when the site was a Royal Air Force airfield, prior to 1947.

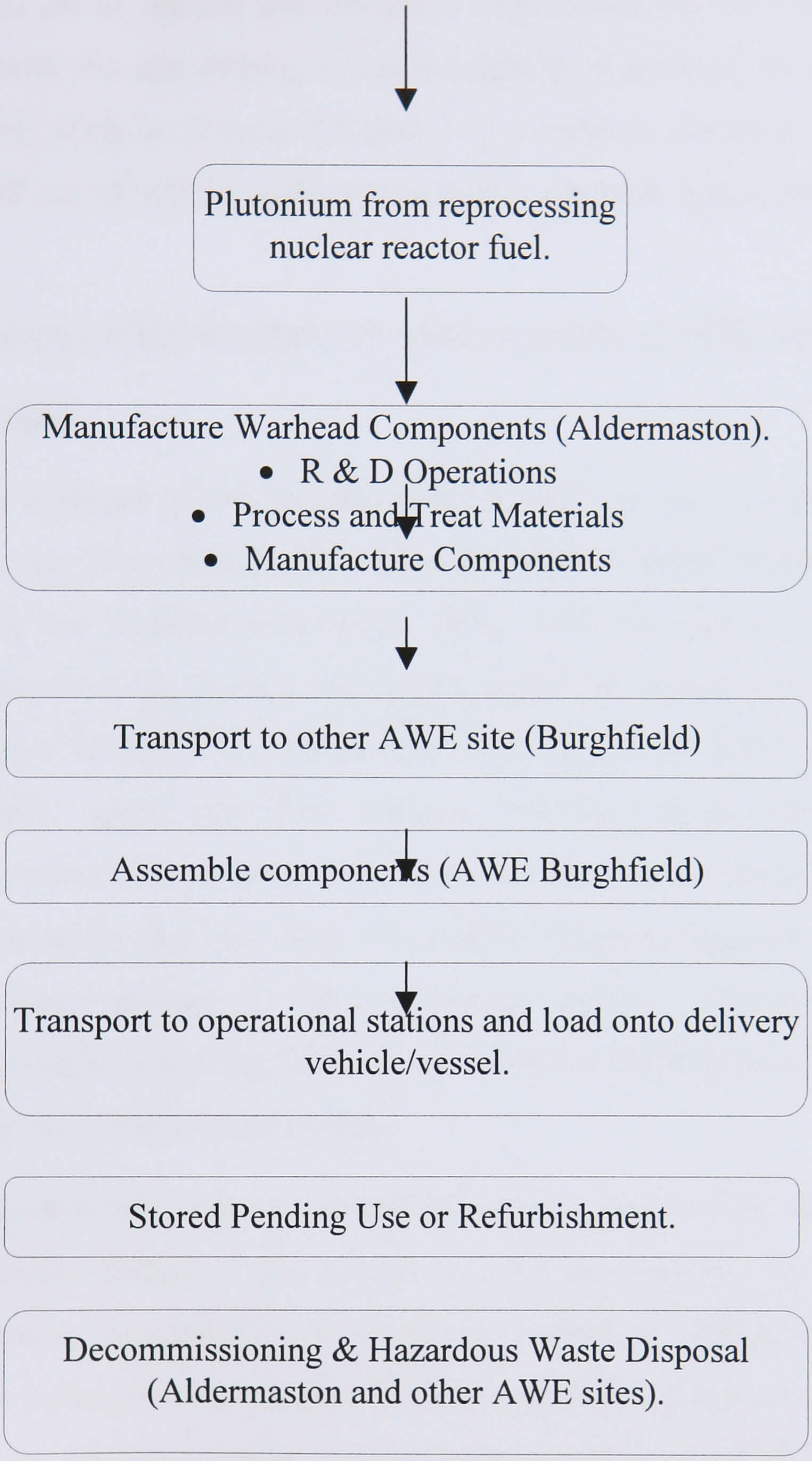
the site. AWE has advanced technological capabilities in engineering rubber, foams. glass, special ceramics and composite materials as part of its requirement to manufacture components with special properties (high temperature resistance, lightweight etc.). Extensive research is carried out into material coatings and corrosion, joining technologies and accelerated ageing. A range of plating operations is carried out including zinc; copper; nickel; cadmium; chrome; silver and gold. In support of the plating operations is a range of other treatment processes including anodising; alkaline cleaning; vapour degreasing; aqua blasting; grit blasting and painting.

AWE carries out trials and theoretical analysis of explosion systems supported by state-of-the-art diagnostics to research the physics of mixing gases. Capabilities include evaluations in environmental chambers to test for shock, climate, acceleration and vibration for a wide range of equipment and materials, (including explosives), supported by advanced modal analysis and finite element modelling techniques. A wide range of research is carried out in the fields of design and testing of electronic and communication equipment. AWE also provides advice on all aspects of radiation safety, which includes provision of personal and facility dosimetry including thermoluminscent dosimeters, personal air samplers, bioassay analysis and whole body monitoring. AWE operates experimental nuclear reactors for research at the Aldermaston site.

In order to meet modern standards redundant and aged facilities have to be safely decommissioned and for this purpose AWE has developed its own capability for post-operative clean-out, dismantling, demolition, size-reduction, nuclear decommissioning, radioactive waste management and contaminated land remediation. AWEs neutron irradiation simulator is used to investigate radiation effects, perform chemical analysis via neutron activation analysis and neutron radiography.

All of the activities described above support AWE's core mission, which is to provide the nation's nuclear deterrent. A diagrammatic presentation of the work at Aldermaston is given in the form of a flow-chart below, which shows the relationship between the Aldermaston and Burghfield sites and the scope of operations being assessed in this thesis.

Figure 2-3 AWE Operational Flow-chart



There are 33 separate environmental sub-aspects, which, are grouped into five main aspects: resources; releases; land quality; ecology and nuisance. These corporate aspects were chosen by the company to reflect the range of activities and processes that are carried out on the site and that are of most importance to AWE. This chapter deals solely with the site setting, a full description of each of the aspects that are assessed in this study is given in Chapter 3. A schematic summary of the principle flows into and out of AWE Aldermaston, over a one-year period has been given in **Figure 1-1**.

2.2 HYDROGEOCHEMISTRY OF THE ALDERMASTON SITE

2.2.1 Hydrology

Surface water drainage on site can take place through one of four routes [8]. Firstly, surface water can flow through the engineered surface water drainage systems, the bulk of which was installed in the early 1950s, with the exception of some earlier drainage dating from the Second World War period. In this system 32 sub-drainage areas have been identified and referenced according to the outfall into which they drain. Secondly, water may flow through semi-engineered systems where, for example, rain runs off from paved areas then into land drains or adjacent permeable areas. Surface water may also flow into natural drainage systems such as grassed areas, permeating through to join a natural surface watercourse or shallow groundwater. Finally, there may be direct surface water infiltration into the trade waste or radioactive (R/A) wastewater systems.

The route which rainfall takes upon reaching the ground will be determined by the infiltration characteristics of the surface i.e., the permeability of the ground, the natural infiltration capacity of the area and any impacts on that capacity arising from installation of paving or storm drains. There is a finite limit, however, to which water can infiltrate any surface and if this limit is exceeded by heavy rainfall, surface run-off will take place. The surface drainage volume for the site is, therefore, influenced by all of these factors [8].

Water entering the surface water drainage system is discharged at outfalls around the perimeter of the site. Drainage takes place mainly towards the northern and southern boundaries and then off-site to the east.

2.2.1.1 External Drainage

Many small brooks and ponds, as well as the larger water courses of the Rivers Kennet and Enborne drain the area around the site. The significant surface watercourses in the area of interest are given in **Appendix A** [8].

2.2.1.2 Surface Water Abstractions

Licensed surface water abstractions within 3 km of AWE Aldermaston are listed in **Appendix B** [8].

2.2.2 Geology

The site lies at the western end of the London Basin syncline, a major geological and hydrogeological structure stretching from the Savernake Forest in Wiltshire to beyond the Thames estuary [8]. The thickness of the tertiary beds deposits (Bagshot beds, London clay, Reading beds) in the core of this syncline is greater than 100m and these are underlain by more than 200m of chalk. Plateau gravels, overlying the tertiary beds and cretaceous chalk underlie the site itself. Valley gravels impinge on the site at SU 603647 [8].

2.2.2.1 Made Ground

Made ground is present in some areas. This made ground is comprised of disturbed in-situ material (soil). The thickness is usually less than 3m, with the exception of the North Ponds area, where depths are greater [8].

2.2.2.2 Valley Grounds

Valley Grounds are found along the valleys of the Rivers Enborne and Kennet, which flow to the north of the site boundary. The gravel fraction is often in excess of 50% and generally defined as highly permeable [8].

2.2.2.3 Plateau Gravels

The Plateau Gravels are present on higher ground throughout the area. They cover most of the site and vary in depth from 1 to 6m [8].

2.2.2.4 Tertiary Deposits

The tertiary deposits lie in a shallow basin within the chalk, thinning to the south and north to expose chalk approximately 10 km from site. The Bagshot beds underlie the

Plateau Gravels and consist of silty sands to silty clays, varying in their depth below ground level from 2m at the north western boundary of the site to 5m in the centre. The depth of this stratum is approximately 10m [8].

London clay has been recorded at a thickness of 64m, to the south of Reading town, thinning gradually towards the western edge of the London Basin. In this area the London Clay underlies the Bagshot beds, outcropping at the eastern slopes of the River Enborne Valley. In the north, the upper boundary of the London clay rises towards ground surface, outcropping to the north of North Ponds. Investigations have shown that the London Clay is nearer to the ground surface at the northern corner of the site, where it has been recorded at 4.2m below ground level. Towards the south western corner of the site it deepens to 11.6m. Although previous investigations have given no indication of the permeability of this stratum, it is considered [8] to have a low permeability. Beneath this grey/green silty clays represent the Reading beds, with a thickness of between 10 and 12m [8].

2.2.2.5 Chalk

At the base of this sequence is the Upper Chalk. This material is pure white limestone, which is fine grained and consolidated, though relatively soft, containing vertical fissures and horizontal bedding planes as well as nodules and tabular layers of flint [8].

2.2.3 Hydrogeology

Chalk is micro-porous and contains water that is locally abstracted by Thames Water Utilities (TWU) for domestic supply. In the London Basin syncline, the chalk sequence is a major aquifer of national importance. Within the Berkshire/Wiltshire area and eastwards towards London, water utilities, water supply companies, industry and private individuals abstract water from this aquifer. The chalk also provides spring sources and baseflow to streams from many areas, which, feed the Thames and allow for surface water abstraction in the west London area [8].

The silts, sands and gravels of the tertiary strata form many locally extensive shallow aquifers. Abstractions from these aquifers are limited and are principally for agricultural purposes. There are no public supplies from these aquifers within the Berkshire/Wiltshire area [8].

2.2.3.1 Local Aquifers

Beneath AWE Aldermaston, two minor aquifers (Plateau Gravels and Bagshot Beds) and one major aquifer (Upper Chalk) are present. The groundwater table in the Plateau Gravels beneath the site is between 0.7 and 3.6m below ground level (mbgl). Below this, the water table in the Bagshot Beds is present at a depth of between 7.5 and 9.6mbgl. Flow in both aquifers radiates out from beneath the highest point in the south west of site and discharges off-site either at springs or as baseflow into surface waters and streams [8].

Tests carried out [8] to determine permeability in the underlying strata suggest that the Plateau Gravels are between ten and one hundred times more permeable than the Bagshot Beds. Therefore, as shown by the Groundwater Vulnerability Map [9] of the area, the Plateau Gravels are highly vulnerable to pollution where they outcrop at the surface of the site, whereas the Bagshot Beds are classed as having intermediate vulnerability. The chalk sequence, which contains the major aquifer beneath the site, is the most permeable of the deposits and is used as a major water supply source. The significance of the London clay, whose permeability is one thousand times that of the Bagshot Beds, and the Reading Beds is, therefore, to protect this aquifer [8].

Consequently, the majority of water, which infiltrates the site from rainfall, accidental spillages or leakages etc., will remain in the Plateau Gravels, with recharge to the Bagshot Beds occurring primarily through vertical leakage in the Plateau Gravels and practically none percolating through the London clay [8].

2.2.3.2 Boreholes

A considerable number of boreholes have been drilled on the site as part of previous site investigations. The objectives of these investigations varied from general screening surveys to efforts to quantify pollution incidents and identify sources of pollution, as well as surveys of the hydrogeological regime of the site. There are also boreholes on the site and in the surrounding area that are used to abstract water for drinking supplies and for other uses. Whilst boreholes are useful for assessing groundwater quality, they can also act as pathways for pollution into the underlying aquifers [8].

2.2.3.3 Ground Water Abstractions

Approximately 85% of the potable water supply to AWE Aldermaston is supplied by on-site boreholes, with the other 15% supplied by TWU. The two on-site boreholes are located adjacent to buildings F30.8 and F30.7 in the centre of the site and are drilled to a depth of 175mbgl, intercepting the chalk at 85 and 86mbgl respectively.

A list of ground water abstractions around the site is given in **Appendix C** [8].

2.2.4 Geochemistry

Made ground in the AWE Aldermaston area is generally 2-4m of gravel with some sand in places overlying sandy and sometimes silty clay. The gravel horizon is interpreted as representing the Plateau Gravels, and the lower less permeable horizons are the Lower Bagshot Beds. Groundwater strikes are between 2-3m below ground level.

Contamination concentration in the soil varies over the site. From a survey of the soil carried out in 1997 [10] some R/A contamination has been found. The results of the survey are summarised in the Table below.

Table 2-1 Radioactivity in Soils [10]

Sample Reference	Sample Depth (m)	Specific Activity (Bqg-1)
Borehole 15, 18, 25, 51, and 63	2	1.2 (alpha)
Borehole 8 & 51	1	1.1 (beta)
01063S	Surface sample	15 (alpha)
01051S	Surface sample	2 (alpha)
01051S	Surface sample	14 (beta)
01008	Surface sample	9.1 (beta)
01051	Surface sample	1.6 (alpha)
01036	Surface sample	15×10^{-3} (tritium)

Alpha refers to alpha emitting isotopes (some Pu and U). Beta refers to beta/gamma emitting isotopes (^{137}Cs, ^{60}Co). Tritium refers to the ^{3}H radioisotope.

A few isolated heavy metal concentrations comprising mainly copper and nickel were recorded. Some surface samples were contaminated with copper, boron, nickel and lead. Copper and lead contamination appeared to have penetrated to a depth of 1 metre.

For a limited number of samples trichloroethene (TCE) and 1,1,1 trichloroethane (TCA) was present. The land in the centre of site was heavily contaminated with TCA, which was released as a result of poor management practices in the 1960's and 1970's.

The south-east corner of the site was contaminated with approximately 3 tonnes of mercury, which was lost to the soil, again due to working practices typical of the period. The consented surface water discharge point at Red Lane has been closed due to concerns over the possibility of releasing Hg-contaminated water from this part of site.

A number of soil samples [10] had a pH of > 9, no soils had a pH of less than pH 5, the ICRCL (Interdepartmental Committee for the Redevelopment of Contaminated Land) threshold. No soil had a sulphate content exceeding the ICRCL threshold of 2000 $mgkg^{-1}$. Some trace concentrations of asbestos fibres were found as this material was disposed of in the backfill of the soil that surrounds many of the mounded buildings on the site.

Groundwater samples from the site did not show any radioactivity above background levels. Lead, chromium and nickel concentrations exceeded the UK drinking water standards in some areas [10].

A number of volatile organic compounds (VOCs) namely TCE, TCA, chloroform and tetrachloroethene were present in groundwater. The solvent 1,1,1 - trichlorethane was within the range 1.3 - 22 μgl^{-1}. TCE was above the UK Drinking Water Quality Guideline value at 2 sites. Two sampling sites indicated significant concentrations of 1,1,1 - trichlorethane (70 and 170 μgl^{-1}). Some mineral oil was present in groundwater and in some places exceeded 600 μgl^{-1} [10].

Parts of the land on site were contaminated and further releases to this receptor would contribute to the increased risk of groundwater pollution, which could affect communities and ecosystems both on and off the main site area.

2.3 ECOLOGY

AWE Aldermaston is home to a wide variety of locally and nationally important habitats including woodland, heath, grassland and areas of marsh and several areas of ponds. These areas support nearly 400 species of plants, more than 250 species of fungi, 400 species of moths and 33 species of butterfly, 21 species of dragonfly and damselfly as well as rare birds, foxes, adders and grass snakes [8].

The area around the site is predominantly rural, comprised mainly of deciduous and coniferous woodland. There is also a high proportion of agricultural land in the surrounding area. There are 10 Sites of Special Scientific Interest (SSSI) in the area, one National Nature Reserve (NNR), one Local Nature Reserve (LNR) and a BBONT Nature Reserve. Aldermaston Court directly to the north, between the site and Aldermaston village, is registered in the English Heritage Historic Parks and Gardens Records (grade II). The SSSI that surround the Aldermaston site are given in **Appendix D** [8].

2.3.1 Local Heritage

The area around AWE Aldermaston is known to have been populated since pre-Roman times and a large quantity of Neolithic to Bronze Age artefacts have been found in the immediate vicinity of the site. The Aldermaston site itself was formerly medieval parkland known as Aldermaston Park. A Roman road crosses the site at the north and a large linear earthwork, known as Grim's Bank, extends onto the south-east corner of the site and is thought to be part of the outer defences of the Roman town of Silchester [8]. There are a number of Iron Age ancient monuments that surround the area of Aldermaston site [8].

2.4 AGRICULTURE SURROUNDING THE ALDERMASTON SITE

AWE Aldermaston is surrounded predominantly by rural land, which is used to grow crops and support livestock. There is very little in the way of large urban development, which is limited to small villages and light industry only.

2.5 HUMAN POPULATIONS

Human populations are one of the most important of all receptors and the location, type and density of people are of prime importance in setting parameters for impact assessment. Within the Aldermaston site there are several residential areas:

- Tadley, a town situated approximately 2 km from the centre of the site to the south;
- The village of Aldermaston, situated approximately 1 km from the centre of site towards the north west boundary;
- Heath End, a village lying adjacent to the south western boundary of the site approximately 1.5 km from the centre;
- Pamber Heath, approximately 2 km from the centre of the site to the south east;

- Woolhampton and Silchester are approximately 4 km north west and 3 km south east respectively.

Other residential areas are made up of individual farms and hamlets. The following mobile home sites are within the immediate vicinity of the site:

- Ravenswing Caravan Site, Aldermaston (150 caravans) approximately 1 km south east of the centre of site;
- Paices Hill Caravan Site, Aldermaston (23 caravans), approximately 1 km west of the centre of site.

There are 10 schools all within 3 km of the site and numerous industrial and commercial developments including the Silchester Sewage Treatment Works (STW) which lies 3.25 km to the south east of site and receives both treated trade and foul effluent from AWE Aldermaston. The site is a significant contributor to the total sewage load treated at Silchester STW.

There are also a number of recreational areas that surround the site including pools and rivers used for coarse and trout fishing.

2.6 ENVIRONMENTAL MONITORING

AWE carries out an extensive programme of environmental monitoring, the results of which are reported to regulatory bodies. A number of internal and external sites, for sampling are used and samples are taken from air, surface waters, rainwater, groundwater, sewage works, soil, vegetation and milk. Results from this monitoring programme in 2000, are recorded in Tables E-1 to E-8 in **Appendix E**. These tables demonstrate AWEs commitment to a thorough monitoring programme for R/A contamination. The results can be compared to Generalised Derived Limits (GDL) which have been developed by the NRPB [11] to provide a guide to the levels which would result in an annual effective dose limit of $1mSvhr^{-1}$ to critical groups of human populations. The GDL values are intended for use as convenient reference levels against which the results of environmental monitoring can be compared [11]. GDLs are directly measurable quantities of concentrations in environmental materials (e.g. milk, food, grass and soil) and are calculated for single radionuclides. The relevant GDLs are given in **Table 2-2**.

Table 2-2 Generalised Derived Limits [11]

	ISOTOPE (Bq kg^{-1})				
Material	**^{90}Sr**	**^{239}Pu**	**^{240}Pu**	**^{241}Pu**	**^{241}Am**
Air (Bqm^{-3})	-	3×10^{-3}	3×10^{-3}	0.2	3×10^{-3}
Fresh Water (Bql^{-1})	20	10	10	400	10
Drinking Water (Bql^{-1})	50	7	7	300	8
Sewage Sludge	6×10^2	3×10^3	3×10^3	1×10^5	4×10^3
Soil (well mixed)	4×10^2	5×10^3	5×10^3	2×10^5	5×10^3
Vegetation (grass)	2×10^3	-	-	-	-
Milk (Bql^{-1})	10	0.7	0.7	5	6

All of the results for air, surface water, rainwater and ground waters, given in **Appendix E,** are below the GDLs given in **Table 2-2**. The dry sewage sample for beta radioisotopes is 140 Bqkg^{-1}, which is less than a third of the GDL for Strontium-90. Interestingly the soil samples show a number of results between 230 and 680 Bqkg^{-1} with the GDL for Strontium-90 being 400 Bqkg^{-1}. Strontium is not an isotope that is used at AWE and no concern should be raised over these levels of beta contamination, which are attributable to tritium. The same comment applies to the relatively high vegetation sample at Thatcham, which is 1840 Bqkg^{-1} and over 90% of the GDL for Strontium-90 (2000 Bqkg^{-1}). Again the beta component for AWE is almost entirely made up of tritium.

2.7 CONCLUSIONS

The AWE Aldermaston site is surrounded by a number of sensitive environmental receptors, and is also home to a number of important habitats and species. The site is extensively developed with a dense network of roads and buildings. The roads, gullies, drains, and steam ducts are all effective pathways for the transfer of pollutants and spilt chemicals to the off-site environment.

A wide range of research activities is conducted on the site using chemicals, metals and radioactive materials. Processes include plating, degreasing, metal surface finishing and the storage and machining of radioactive components. All of these processes and activities generate potentially damaging impacts on the environment. Resources are consumed and various wastes are generated including radioactive, trade and sewage effluent, solid domestic waste, trade waste and radioactive waste gases and solids. Drainage from the site is via consented outfalls that lead to brooks, streams and graded watercourses including the Rivers Thames, Kennet and Enbourne. The protection of these outfalls is of paramount importance and extensive environmental monitoring is carried out in and around the site to provide a level of assurance on the adequacy of containment systems. Radioactive and trade effluent is transferred around site in an ageing network of drains which are subject to infiltration by surface and groundwaters. Authorisations are given under the Radioactive Substances Act (RSA) 1993 [12] for discharges of radioactive substances, and under the Environmental Protection Act (EPA) 1990 [45] for discharges of chemicals covered by Integrated Pollution Control and Integrated Pollution Prevention and Control (IPC/IPPC) regimes. The major aquifer for the area lies beneath the site, which is protected by a layer of London clay.

The area surrounding the site is partly developed for housing and small businesses and partly used for agriculture. Many licences have been granted for the extraction of water for private use. AWE itself obtains most of its own water needs from on-site boreholes and the site is surrounded by a number of graded watercourses. From practices in the past a number of areas on the site have been contaminated with metals, solvents and radioactive materials. Any further contamination will pose a significant risk to local ground and surface waters.

Owing to the nature of the work carried out at Aldermaston, the extensive use of radioactive materials and the interest of the local community, it is clear that the release of radioactive materials, in particular, into the local environment is a major concern. A number of sensitive receptors surround the site and there are any number of effective pathways that could transfer material to the off-site environment. In addition there are a great number of processes that use chemicals, and robust management systems are required to ensure that these are contained and releases minimised during routine and accident conditions.

CHAPTER 3 SUMMARY

The work described in this chapter uses AWE environmental aspect data to perform an impact assessment, using a life-cycle approach, of routine releases and resource consumption. LCA methodology is described in terms of historical development and the components that comprise the process. Normalisation factors are presented for all impact categories based on AWE data and new factors are derived for radioactive discharge categories. A new valuation method is presented which links to the current AWE EMS. The construction of a new LCA inventory is described and presented along with the impact assessment. A new methodology is described, presented and justified to provide equivalency factors for radioactive discharges and hence include them in the LCA framework. A section is also presented which describes the assessment of vehicle transport activities at AWE.

3 ASSESSMENT OF ROUTINE ASPECT CONTRIBUTIONS

3.1 INTRODUCTION

From a knowledge of the site and its surroundings, detailed information about environmental receptors and pathways given in Chapter 2 has been used to draw conclusions about the key issues of importance for environmental management of the site. The work described in this chapter uses aspect register data [5] to perform an impact assessment, using a life-cycle approach, of routine releases and resource consumption.

3.2 REVIEW OF EXISTING DATA

Data, used in this work have been judged by AWE in evaluating the significance of facility contributions to corporate environmental aspects, are recorded on FREAs. These registers provide information on the processes and activities that make contributions to the overall site. In addition the registers also record the engineering and procedural controls in place to manage the activity. An example of a blank FREA is given in **Appendix F**. The example given shows the type of information that is recorded for each of the column headings:

- Corporate aspect, which refers to one of the 33 environmental sub-aspects
- Corporate significance, which refers to the corporate ranking either, high, medium or low;
- Significant facility contribution, which refers to whether or not the contribution is considered to be significant or not;
- Description (quantity), which refers to a descriptive justification for the facility contribution;
- Controls (Engineered and Managerial), which refers to the controls in place to manage the aspect.

A comparison between the site's overall contribution and individual facility's contributions to environmental aspects is made [5] to determine if an individual facility contribution is considered to be significant.

The routine contributions made at AWE over the period of one year are assessed as part of the work described here. Existing data, (originally gathered during 1999 - 2000), for approximately 65 separate buildings and facilities are transferred to spreadsheet format, (see **Appendix H**), to enable a comprehensive inventory of releases and resources to be formulated. A full description of AWE corporate environmental aspects is given along with the current impact categories employed to assess environmental impact.

Data from the FREAs of all high hazard facilities have been collated and entered into Excel spreadsheets to build up an inventory and facilitate mathematical manipulation and analysis. Measured or estimated data on annual facility contributions are recorded on separate Excel sheets (see **Appendix H**).

The purpose of the work described in this chapter is to determine the actual impact of AWE site operations. Contributions are segregated into impact categories, characterised, plotted, normalised and weighted to determine which processes are causing the most environmental damage. Standard environmental indices [38, 43, & 110], (partly reproduced in **Appendix G**), are used to evaluate potential and LCA methodology is used to evaluate the impact. Radioactive substances that do not fit into existing LCA impact categories are assessed using a new methodology. A new methodology is developed to determine the environmental impact of radioactive releases to air, water and of waste.

The complete list of aspects that are assessed in the register is given in **Table 1-1**. The corporate significance of each is given in the adjacent column.

A ranking system [13] based on the outcome of stakeholder concerns, business issues and environmental damage was used to categorise the importance of individual environmental aspects as high, medium or low corporate significance. Those aspects that are assessed in this study are described below in which is given a brief statement about the significance of the aspect and a fuller description of the associated activities and processes which cause them, and the resulting environmental impacts.

Table 3-1 Corporate AWE Aspects

CORPORATE ASPECT	CORPORATE SIGNIFICANCE
RELEASES	
Releases to Air – R/A *	High
Releases to Air – Acids *	Low
Releases to Air – VOCs *	Low
Releases to Air – ODSs *	Medium
Releases to Air – Be *	Low
Releases to Air – Pb *	Low
Releases to Air – Combustion by Products *	Medium
Releases to Water – R/A Effluent *	High
Releases to Water – Trade Effluent *	Medium
Releases to Water – Domestic Effluent *	Low
Releases to Water – Engineered Surface Water	High
Releases to Water – Un-engineered surface Systems	High
Releases of Waste – R/A *	High
Releases of Waste –Trade Waste *	Low
Releases of Waste – Domestic *	Low
RESOURCES	
Resource Use – Electricity *	Low
Resource Use – Gas *	Low
Resource Use – Water On – site *	Medium
Resource Use – Water Off – site *	Low
Resource Use – Chemical/Oil Storage and Use [$]	Medium
Resource Use – R/A Use and Storage [$]	High
Resource Use – Other [$]	Low
LAND QUALITY	
Land Quality – R/A	High
Land Quality – Solvents	High
Land Quality – Metals	Medium
NUISANCE	
Nuisance – Odour	Low
Nuisance – Noise	Low
Nuisance – Visual	Low
Nuisance – Light	Low
Nuisance – Congestion	Low
ECOLOGY	
Ecology – Species	Medium
Ecology – Habitats	Medium
Ecology – Heritage	Medium

NB those aspects marked * are assessed in this study, those marked $ are not measured and cannot be assessed.

3.2.1 Releases to Air

3.2.1.1 Releases to Air - R/A

This aspect is concerned with the release of radioactive material to air. Handling and processing of radioactive material results in the generation of airborne material. This R/A material is retained within containment systems on-site, in glove boxes or fume cupboards, and extracted from work areas using ventilation systems prior to filtration and then final discharge to atmosphere via dedicated stacks. The release of radioactive material to atmosphere is controlled by discharge authorisations or consents, which define annual limits on the amount of material that can be released. The Environment Agency, which grants authorisation under the provisions of the Radioactive Substance Act (RSA) 1993 [12], enforces the consent. AWE is required by the RSA to demonstrate the application of Best Practicable Means (BPM) to minimise radioactive discharges to atmosphere. This aspect has been assigned a high corporate significance. Any contributions, from individual buildings and facilities, to this aspect are automatically considered to be significant.

Radioactive materials are processed at AWE as part of the manufacturing of warhead components. These materials are handled in special protective enclosures known as gloveboxes. These are high integrity sealed boxes made from steel with perspex windows and gloved ports to allow operator access. The boxes are completely sealed to prevent the release of radioactive material and are ventilated to maintain a depression between the laboratory and the inside of the box. The glovebox can contain equipment for cutting or treating radioactive materials including machine tools and furnaces. To maintain the quality of some radioactive components the box is held under a depression using an inert gas of argon or nitrogen to prevent material oxidation. This protective gas is filtered and discharged through a local extract system to atmosphere via a stack. Despite several stages of high efficiency particulate air (HEPA) filtration, some radioactive material is routinely discharged to air.

The impacts from releases of radioactive material into the air include a dose to humans and ecosystems through inhalation pathways. Much of the particulate material released will settle on land through wet and dry depositions and result in contaminated land and water bodies. If the land is used for crops or for grazing animals it may well find its way into the food chain through ingestion pathways. Contaminated water bodies can disrupt ecosystems by causing cell mutations and reducing fertility. If the release is high enough the deposition can cause a dose from direct radiation.

3.2.1.2 Releases to Air - Acids

This aspect is concerned with releases of acids to the atmosphere. AWE uses acids in a number of processes and these are discharged either directly to atmosphere or treated by the use of scrubbers prior to discharge. Releases from processes that are prescribed under the IPC/IPPC regulations require AWE to demonstrate the application of Best Available Technique (BAT). This aspect has been assigned a medium corporate significance.

Acids are used at AWE in some of the manufacturing processes and to dissolve metals and test components for quality purposes. Acids are usually handled in fume cupboards and in some cases, scrubbed prior to discharge. Despite the controls in place some small amounts of acid are routinely discharged to the atmosphere.

Acids released to air cause acidification, which can lead to building damage and disrupt the pH of receiving water bodies and soil. Some acids are ecotoxic and also pose a threat to human health. For example hydrofluoric acid (HF) is particularly damaging to pine trees.

3.2.1.3 Releases to Air - VOCs (Volatile Organic Compounds)

This aspect is concerned with the release of VOCs to the atmosphere. A wide variety of VOCs are used in processes at AWE. The company has prepared a document [14] which gives information on restricted and prohibited substances and the procedures for their control, including VOCs that are likely to be used on site. This aspect has been assigned a low corporate significance.

VOCs are widely used at AWE in a number of processes including degreasing and surface treatment activities. VOCs are handled in fume cupboards with local extract ventilation (LEV). The LEV is designed to protect the operator from harmful vapours, which are then discharged to atmosphere. In most cases these vapours are discharged without any form of abatement.

All solvents and VOCs are classed as prescribed substances under the IPC regulations and many solvent or VOC-containing wastes are usually classified as Special Waste due to their toxicity or flammability. The EU gives the following definition of a VOC:

"Any organic compound having at 293.15 K a vapour pressure of 0.01 kPa or more, or having a corresponding volatility under the particular conditions of use". Another source [15] gives the following definition: "All organic compounds of anthropogenic nature, other than methane, that are capable of producing photochemical oxidants by reactions with nitrogen oxides in the presence of sunlight". Owing to these reactions VOCs are involved with the formation of ground level ozone. VOCs also indirectly contribute to global warming in that methane and photochemical oxidants produced from the use of VOCs are both greenhouse gases. The environmental management system makes no distinction between the individual types of organic compound released.

The release of VOCs can contribute to the generation of ground level ozone (O_3), which has a direct impact on human health. It is a very powerful oxidising agent and is irritating to eyes, respiratory tissues and harmful to plants. Some solvents are toxic and a few, (methyl chloroform), can contribute to global warming. Some solvents give rise to an odour problem and some are known to be ecotoxic. A limited number of solvents can contribute to stratospheric ozone depletion.

3.2.1.4 Releases to Air - ODSs (Ozone Depleting Substances)

This aspect is concerned with the release of substances that have the potential to deplete the protective layer of the ozone in the stratosphere. AWE uses ODS material in refrigeration and air conditioning systems. A few solvents used at AWE for cleaning applications cause stratospheric ozone depletion. This aspect has been assigned a medium corporate significance.

The Montreal Protocol (UN 1987) [41] established a regime for the gradual phasing out of chlorine-based chemicals including:

- Chlorofluorocarbons (CFCs);
- Halons;
- Carbon tetrachloride;
- 1,1,1 – trichloroethane (TCA)
- Methylbromide;
- Hydrobromofluorocarbons (HBFCs);

- Hydrochlorofluorocarbons (HCFCs);

The European Environmental Protection Regulations 1996 place requirements on the UK industry for phasing out ODS use. A review has been carried out on all facilities at AWE [16] giving details of volumes of ODS held and a programme for their replacement, as the release into the atmosphere of certain substances will contribute to the depletion of the stratospheric ozone layer. This impact was one of the first global impacts to be recognised internationally and agreement is now in place through the Montreal Protocol [41] to phase out especially destructive substances. Some ODS also contribute to global warming, human toxicity and ecotoxicity.

3.2.1.5 Releases to Air - Be (Beryllium)

This aspect is concerned with the release of beryllium to the atmosphere. AWE has discharge authorisations for two facilities under existing IPC/IPPC regulations, which require demonstration of the application of Best Available Techniques (BAT) in the management and control of beryllium releases. This aspect has been assigned a low corporate significance.

Beryllium is used in part of the manufacturing process for warhead components. There are two facilities that carry out all beryllium processing operations. As with radioactive and other hazardous materials, beryllium is handled in fume cupboards with its own dedicated filtered extraction system. Despite these controls, some small amounts of beryllium material are routinely released to the atmosphere.

The releases of beryllium to the atmosphere will contribute to direct health effects giving rise to a lung condition known as berylliosis, a severe respiratory disease that may lead to malignant growths in the lungs. Exposure to beryllium dust can cause dermatitis. The release of beryllium will also give rise to ecotoxic impacts.

3.2.1.6 Releases to Air - Pb (Lead)

This aspect is concerned with release of lead compounds to the atmosphere. The production of any compound containing lead is a prescribed process under the IPC/IPPC regulations requiring AWE to demonstrate the application of Best Available Technique (BAT). This aspect has been assigned a low corporate significance.

AWE uses lead compounds in its research and development activities, with some components being manufactured from a composite of materials that include lead. Lead is a hazardous metal that is handled inside fume cupboards with dedicated filtered extraction systems. Most of these extraction systems are fitted with HEPA filters which are 99.95% - 99.99% efficient. Despite these controls, some small amounts of lead material are released to atmosphere.

The releases of lead compounds into the atmosphere will contribute to human health effects and ecotoxic effects. Owing to its high density lead will quickly deposit on nearby soils and water bodies threatening ecosystems and drinking water supplies.

3.2.1.7 Releases to Air - Combustion By Products

This aspect is concerned with the atmospheric release of material during the combustion of fossil fuels. This aspect has been assigned a medium corporate significance.

AWE operates a large boiler house facility that burns oil and gas to generate steam for heating. This aspect is solely associated with the operation of the boiler house at Aldermaston used to generate steam, and should not be confused with the impacts from Resource Use - Electricity that, is a separate system supplied to the site from an external power utility.

The burning of oil and gas in boilers will release by-products into the atmosphere. These by-products will contribute to local acidification through the oxidation of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2). The carbon dioxide released will contribute to global warming and other products will contribute to human toxicity and ecotoxicity. This aspect will also contribute to the depletion of fossil reserves in the form of oil and gas, which are finite resources. These reserves are not expected to last beyond 2400 [17].

3.2.2 Releases to Water

3.2.2.1 Releases to Water - R/A Effluent

This aspect is concerned with the release of radioactively contaminated water into the environment. The R/A drainage system has its own discharge consent prescribing the type, quantity, chemical and physical properties of the effluent. The water is temporarily stored in delay tanks and bunded enclosures prior to being pumped to a central facility where it is treated to separate the radioactivity by ferric flocculation and settling prior to discharge to the River Thames. This flocculation process enables

AWE to remove 95% of the radioactive material. Around 7000m^3 of effluent is treated each year prior to discharge via the Pangbourne pipeline. About 6000m^3 of this is, in fact, rainwater and groundwater that collects in the bunds that form part of the collection system [18]. The treated effluent is monitored and then discharged several times a week via a pipeline entering the Thames at Saltney Mead near Pangbourne, Berkshire. The end section of the pipeline is perforated and lies beneath the bed of the river. The flow-rate of the effluent is such that it is likely to diffuse along the length of the perforated section [19]. The discharge is subject to consent granted by the Environment Agency (EA) and contains trace amounts of radioactivity. The resulting sludge, from the treatment process, is temporarily stored on site, prior to its solidification and disposal as solid R/A waste. This aspect has been assigned a high corporate significance. Contributions, from individual buildings and facilities, to this aspect are automatically considered to be significant.

AWE is currently implementing a scheme to prevent further discharges of R/A effluent. The current discharge pipeline is being decommissioned and a new treatment plant will use evaporator technology and an advanced form of filtration to remove radioactivity from the effluent. The radioactive material removed by this process will be solidified and disposed of to the BNFL Drigg site in Cumbria or stored on site. The new process will enable AWE to remove 99.9% of the radioactive material [18] with the remaining trace levels being discharged to the atmospheric environment during the final evaporation process. Tritium cannot be separated out by the filtration or chemical process because it combines with oxygen to form tritiated water. A separate strategy for dealing with tritium across AWE Aldermaston is being developed [18].

AWE has many buildings and facilities with controlled radioactive areas that are used for processing and storing radioactive materials. Within these areas are processes that generate R/A effluent. In addition hand and floor washings from controlled areas may contain trace amounts of R/A contamination, which are discharged via delay tanks and the active drainage network to the central treatment facility. All fume cupboards and gloveboxes in controlled R/A areas are fitted with drainage points so that washings generated during routine decontamination is directed to the R/A drainage system. There are major initiatives to minimise the generation of R/A effluent.

Water contaminated with R/A material will result in dose to humans via direct radiation and through ingestion from human consumption of contaminated water. If the water is subsequently used as drinking water supply, downstream of the release, dose uptake will also be via the ingestion pathway. The same mechanisms exist for dose to animals, birds and organisms. The overall impact on the environment has not been fully characterised in existing impact assessment methods.

3.2.2.2 Releases to Water - Trade Effluent

This aspect is concerned with the discharge of trade effluent. AWEs operations in support of warhead manufacture leads to the generation of trade effluent. The source of this effluent includes:

- laboratory floor washings;
- boiler house blow-down effluent. This is effluent that contains calcium deposits that have started to line the inside of pipes;
- process cooling water;
- steam condensate;
- hand washings from workshop areas;
- effluent from metal finishing workshop (cadmium and chromium plating operations).

The trade effluent drainage system has its own discharge consents, agreed with Silchester Sewage Treatment Works, prescribing the type, pH, quantity, chemical and physical properties of the effluent. The aspect has been assigned a medium corporate significance.

Trade effluent is pumped via delay tanks, or collected by tanker for delivery to a central treatment facility for processing, prior to being directed off site to the local sewage treatment works. In addition bulk liquid chemical waste is consigned to the Trade Effluent Treatment Plant. The metal finishing workshop next to the plating workshop has its own dedicated treatment plant.

Trade effluent is treated on site to remove industrial contaminants and the pH adjusted to meet the consent agreed with Thames Water Utilities (TWU). Treatments include heavy metal settling and clarification to remove suspended solids. Despite these treatments there are still associated impacts. The treated trade effluent is consigned to the local sewage treatment works contributing to human toxicity and ecotoxic impacts in the receiving water and odour. The treatment process itself generates sludge, referred to as trade waste solids, which, have to be collected and transferred off-site for disposal as special waste and incinerated or sent to a hazardous waste landfill.

3.2.2.3 Releases to Water - Domestic Effluent

This aspect is concerned with discharges of water, via the foul water system, to the local sewage treatment works. An important part of managing this aspect is to protect it from accidental infiltration of trade or R/A effluent. Contributions to this aspect from individual facilities are based on metered water consumption and estimated daily use from the number of building occupants. This aspect has been assigned a low corporate significance.

The majority of buildings at AWE are fitted with toilet facilities and hand basins. Domestic effluent from hand washing, showers and toilet flushing are pumped off-site to the local sewage treatment works. The effluent is treated at Silchester Sewage Treatment Works. The impact from releasing domestic (foul) effluent is associated with disruption to the ecosystems in the receiving water. There may be some impact on human health although this would be associated with leaks and problems with the treatment process rather than normal operation. The transfer and treatment of raw effluent can give rise to nuisance from odour. High concentrations of phosphate, which is common in raw effluent, especially laundry washings, can contribute to nutrification in rivers. The settled sludge from primary sewage treatment ends up as solid waste that has to be disposed of either by incineration or to a landfill site. The sludge can be used to generate methane gas on the treatment site and used to power parts of the plant. Many modern sewage plants run energy-positive, generating enough energy to power the plant and still sell excess energy back to the national grid. The price paid for this excess is high because, it is not generated using fossil fuels (the UK non-fossil fuel levy). The effluent that is discharged back into the rivers after sewage treatment is often of a better quality than that which is in the river already, thus acting to purify the water and promote the health of aquatic ecosystems.

3.2.2.4 Releases to Water - Surface Water Systems (Engineered and Un-Engineered)

The engineered surface water systems include guttering, downpipes, drainage network and the bulk storage tanks. These systems are used to transfer and store storm water prior to discharge from consented outfalls to surrounding brooks, streams and ponds. AWE has its own surface water management facility that takes storm water from the processing buildings to a dedicated buffer storage facility that allows for monitoring and storage of storm water prior to discharge over a weir into a nearby un-engineered surface water system. The operation, maintenance and protection of this system is of the utmost importance to AWE. The management of this aspect has been given a high corporate significance.

The un-engineered surface water systems include streams, brooks, ditches, ponds and areas of surface water run-off. Any pollution of these systems has the potential to disrupt plants, species, wildlife and ecosystems that use these areas. The maintenance and protection of this system is also very important to AWE. The management of this aspect has been given a high corporate significance.

Under routine conditions facilities do not contribute to these aspects. However, during accident and emergency situations these systems are vulnerable, acting as effective pathways for the transfer of pollutants off-site to sensitive receptors including streams, rivers, lakes and groundwaters. These aspects are not included in the assessment of routine conditions, however the significance of the surface water systems is considered in the accident assessment methodology in Chapter 4.

3.2.3 Releases of Waste

3.2.3.1 Releases of Waste - R/A

This aspect is concerned with the generation and release of solid radioactive waste. At AWE solid waste falls into one of two categories:

- **Low Level Waste (LLW)** - material containing between 0.004 and 4 GBq/tonne alpha and 0.004 and 12 GBq/tonne beta-gamma.
- **Intermediate Level Waste (ILW)** - material with > 4 GBq/tonne alpha or 12 GBq/tonne beta-gamma but which is not heat generating.

Low level waste is packaged into 200 litre drums or a large container called an ISO container, which is either 36m^3 capacity (full ISO) or 18m^3 (half-height ISO). The waste is transferred to the British Nuclear Fuels Limited (BNFL)-operated Drigg site in Cumbria for shallow land burial. Intermediate level waste is packaged into 200 litre drums for storage on-site, pending transfer to the Nirex deep geological land based repository. The generation of radioactive waste has a significant impact on the environment in that it uses up valuable land and has to be contained to a high degree of protection to prevent the leakage of radioactive material into the surrounding soils, rock and groundwater systems. This aspect has been assigned a high corporate significance. Any radioactive waste contributions are automatically considered to be significant.

Radioactive materials are used routinely for many operations at AWE, which give rise to radioactive waste. A physical barrier is sited at the entrance to all controlled areas where staff change into special protective clothing. Upon exit from a controlled area some gloves, overshoes and other protective equipment are discarded into bins for disposal as R/A waste. Routine monitoring operations and decontamination operations generate R/A waste in the forms of contaminated swabs, rags and filter papers. HEPA filters from R/A ventilation systems become R/A waste once they become blocked. Redundant equipment from controlled areas that cannot be fully dismantled to expose all surfaces for monitoring has to be consigned as R/A waste. A trade-off is made between the time/cost involved in stripping equipment for monitoring and the cost of discarding it as R/A waste. Redundant R/A plant generates a significant volume of waste during decommissioning. There are major programmes of decommissioning at AWE as plant reaches the end of its life. Most R/A facilities are 40 years old and are being gradually replaced.

The impacts from the disposal of solid radioactive waste include human dose, dose to plants, animals and organisms, and the loss of materials which could be re-used had they not been contaminated or activated. At present in the UK there is only one site for disposal of R/A waste and this is at the shallow land burial site at Drigg in Cumbria. Shallow burial of waste under normal conditions results in a loss of land, which will have only a restricted end-use, disruption to ecosystems, (during construction of the site), and dose impact on nearby organisms. The waste will pose a threat to humans and the environment for many years, depending upon the decay half-life of the nuclides involved, and the integrity of the containment systems used to protect the surrounding soil and groundwater. The overall impact on the environment has not been fully characterised in existing impact assessment methods.

3.2.3.2 Releases of Waste -Trade Waste

This aspect is concerned with the generation and release of industrial waste. At AWE solid trade waste is transferred to a central facility where licensed contractors for landfill or incineration consign it all off-site. All trade waste generated at AWE is treated as 'Special Waste' in accordance with the Special Waste regulations 1996 [20]. This aspect has been assigned a low corporate significance.

Trade waste is generated on a routine basis and includes, unwanted paint, oils, batteries, light fittings, waste chemicals and equipment contaminated with chemicals. On-going maintenance of plant and equipment and decommissioning of redundant laboratories are the main contributors to waste in this category.

The impact from the disposal of trade waste will include a contribution to human toxicity and ecotoxicity from placing hazardous waste material in the ground. Natural resources will be lost and be unavailable for re-use. Ecosystems will be disrupted during the construction of the site and land will be lost, again during construction and filling, with a restricted end-use once closed. The waste poses a threat to humans, plants, animals and organisms and measures are required to prevent pollution of the surrounding soils and groundwaters. This is especially important for hazardous (trade or special) waste where persistent organic compounds can take many years to degrade. One important environmental benefit associated with landfill is the generation of methane (CH_4) gas during waste decay, which, can be used to power gas engines to generate electricity. This electricity can then be sold to the national grid. The price paid for this electricity is high because, it is not generated using fossil fuels (the UK non-fossil fuel levy). Where the methane gas generated by degradation is not used to power engines it must be burnt off resulting in a contribution to global warming. The alternative to landfill is incineration, which is a common practice for certain hazardous organic wastes. This has the benefit of dramatically reducing waste volumes but with the dis-benefit of hazardous airborne emissions. These emissions can include acids, particulate matter and toxic gases, including CO_2 and CO, as a result of incomplete combustion. Special incinerators are now being built which can operate at the very high temperatures (1200 °C) [21] required to destroy persistent organic compounds (PCBs and dioxins). These new incinerators can also use the heat released to produce steam and assist in the generation of electricity, although the calorific value is much lower than that of coal.

3.2.3.3 Releases of Waste - Domestic Waste

This aspect is concerned with the generation of domestic refuse from offices and laboratories on the site. A sub-contractor collects all of this waste for off-site disposal, to a licensed landfill site or for incineration. Waste is segregated at source into recyclable paper and other domestic waste. This aspect has been assigned a low corporate aspect.

Domestic waste is generated on a routine basis from offices, laboratories and workshops. Domestic waste includes paper, waste food and drink wrappings, metal, old furniture and waste food products from the restaurant. The refurbishment of buildings and the dismantling of redundant facilities also leads to the generation of domestic waste.

The impacts from the disposal of domestic waste are the same as those that are generated from the disposal of trade waste, except that the toxicity risks to humans and ecosystems are much reduced from the less hazardous and in most cases inert (wood, building materials and rubble etc.) waste. The major impact is the loss of land-use from the landfill construction its limited use post-closure and the loss of natural resources that are unavailable for re-use or recycling.

3.2.4 Resource Use

3.2.4.1 Resource Use - Electricity

This aspect is concerned with the use of electricity as a resource. AWE uses a significant amount of electricity that is supplied to the site. Essential services are supported by an on-site facility that uses gas turbines to generate electricity for use in an emergency. In addition to this the site generates and supplies its own steam heating by burning oil and gas. The consumption of electricity has been assigned a medium significance.

Electricity is supplied to most buildings to provide lighting, heating and power to laboratory plant and equipment. Buildings that contain hazardous plant and equipment are fitted with back-up battery plant that provides uninterruptible power to essential plant including ventilation equipment, fire detection and monitoring systems.

The supply of electricity to the site comes from local utility suppliers and is assumed to be entirely from coal and gas-fired sources. The use of electricity results in similar impacts associated with those for combustion by-products, including global warming, principally from CO_2 emissions and acidification from SO_2 and NO_2. Other by-products, including carbon monoxide (CO) will contribute to human and ecotoxic impacts. This aspect will also contribute to the depletion of fossil reserves in the form of coal and gas, which are both finite resources.

3.2.4.2 Resource Use - Gas

This aspect is concerned with the consumption of gas that is piped to laboratories and furnace burners. It covers the indirect use of steam in buildings, which is generated by burning natural gas in the main boiler house. It does not cover the use of bottled gases used for research and development purposes.

The consumption of natural gas has been assigned a low corporate significance.

AWE uses natural gas for some process operations. It is fitted to most fume cupboard systems although its use is not widespread. Gas is used as fuel in the Main Boiler House (MBH) and in the back-up gas turbine generators of Essential Services Supply Pump House (ESSPH).

Gas for use in boilers will result in a contribution to global warming and the gas itself, depending upon concentration, is toxic to both humans and ecosystems. Furthermore the use of gas will contribute to the depletion of fossil reserves.

3.2.4.3 Resource Use - Water On-Site

This aspect is concerned with the consumption of water that is extracted from the chalk aquifer using the two on-site boreholes. Approximately 85% of the site is supplied with potable water from these boreholes, which extract from the chalk aquifer beneath the site. Water is purified in a dedicated on- site facility using standard treatment methods. The use of on-site water has been assigned a medium corporate significance.

Water is used all the time at AWE for washing, cleaning, drinking, cooling and steam production. The use of water as a resource eventually results in the same impacts as those for releases of waste - domestic effluent. In order to avoid double accounting in the EMS however, the impacts associated with this aspect are restricted to upstream impacts, i.e. those impacts associated with the extraction of water from rivers or groundwater aquifers. Over-extraction can lead to a depletion of a vital resource especially in periods of low rainfall; in the UK 30% of all drinking water is supplied from groundwaters [21]. Ecosystems can be disrupted and plants will be lost due to moisture deficiency in soil. As human populations grow extraction from groundwater supplies can outstrip the recharge from precipitation. Chemical spills and pollution from fertilisers and pesticides can pollute groundwaters making the protection of this resource even more important.

3.2.4.4 Resource Use - Water Off-Site

This aspect is concerned with the consumption of water that is supplied to the site by Thames Water Utilities (TWU). Approximately 15% of the site is supplied with potable water from TWU. The use of off-site water has been assigned a low corporate significance.

Water is also supplied to a small number of buildings that fall into the TWU catchment. This resource accounts for approximately 15% of the site's need. The impacts associated with this aspect are the same as for on-site water use.

3.2.4.5 Resource Use - Chemical/Oil Storage and Use

This aspect is concerned with the storage and use of chemicals and oils, which do not pose a threat to the environment under normal conditions. It is only under accident conditions including spills and loss of containment that this aspect will result in an impact.

The use and storage of chemicals and oils has been assigned a medium corporate significance.

A wide range of chemicals and oils are used at AWE. Oil is used in a number of machines for cooling and lubrication purposes and chemicals are used for cleaning, degreasing and in the manufacture of specialised compounds. In excess of 500,000 litres of oil is used for insulating the electrical generators used to test materials for resistance to radiation. Hydrocarbon fuels are used to power vehicles used on the site and oil is burnt in the main boiler house and the essential supply pump house. There is a large legacy of redundant chemicals stored on site from past operations. Various pesticides and herbicides are used for ground maintenance. Heavy metals are used in research and metal finishing operations.

The impacts from this aspect are limited to those associated with the manufacture of the chemical and oils (energy use, associated emissions and depletion of natural resources). If, chemicals and oils are properly stored there will be no further impacts except for when chemicals are used in a process and the other release-aspects cover this event. Other aspects cover the impacts from disposal of chemicals and oils.

At present there is no recorded measurement of chemical and oil consumption, therefore this aspect cannot be assessed under routine conditions.

Consideration is given in Chapter 4 to accident conditions which will result in a variety of downstream impacts.

3.2.4.6 Resource Use - R/A Use and Storage

This aspect is concerned with the storage and use of radioactive materials. Storing and using radioactive materials pose a direct impact to humans in the form of ionising radiation dose. In addition to this, accident conditions from spillages and loss of containment will result in a threat to the environment.

The storage and use of radioactive materials has been assigned a high corporate significance. Any contributions to this aspect are automatically considered to be significant.

Radioactive materials are used and stored on site to support key activities associated with warhead component manufacture. R/A materials are stored in safes and gloveboxes and accountable material is subject to very strict inventory controls. Accountable material is R/A material that is fissile.

As with chemical and oil storage and use, the impacts from this aspect are associated with the handling and processing of different radioisotopes (human dose, reactor operations, fuel fabrication and radioactive material transport). Other aspects cover the disposal of radioactive waste. Under proper storage arrangements there will be no further impacts except for human dose.

The measurement of R/A material consumption is classified and has not been assessed further in this work.

3.2.4.7 Resource Use - Other

This aspect is concerned with the consumption of resources that do not fall into any of the other specific resource use aspects. Resource use in this aspect includes steam, office consumables, batteries, light fittings and components used in routine plant maintenance.

The consumption of resources for this aspect has been assigned a low corporate significance.

AWE use many resources to support its activities and this aspect is for contributions of material use that do not fall into any of the other resource categories previously defined.

The impacts from this aspect are associated with the manufacture of materials and consumables that are used each year at AWE. This is energy use, associated emissions and the depletion of natural resource. Other aspects cover the disposal of these resources, once used.

At present there is no recorded measurement of other resources apart from the indirect measurement of domestic and trade waste. This aspect cannot be assessed under routine conditions.

3.2.5 Aspect Description Summary

The various corporate environmental aspects and sub-aspects have been described in terms of AWE operations and corporate significance. All aspects that are under the direct control of individual facilities and included in the scope of the study are described. Issues associated with the aspects of land quality, ecology and nuisance have not been described. Land quality is largely a legacy problem caused by practices in the past, and is being addressed as a company-wide issue. Ecology and nuisance are also being addressed as corporate issues not under the direct influence of individual facilities. Aspects associated with the surface water system (engineered and un-engineered) are only applicable to one facility on site and are not included in the routine assessment.

3.3 LIFE-CYCLE ANALYSIS METHODOLOGY

3.3.1 Historical Development

The first examples of environmental assessment of products were carried out on packaging and published at the end of the 1960s and the beginning of the 1970s in the US. They were called "Resource and Environmental Profile Analyses" (REPAs) and focussed primarily on energy consumption, resource consumption and generation of waste, in accordance with the environmental debate at the time [43]. At that time there was still too little knowledge on process emission of hazardous substances and their possible impacts on the environment [43].

At the beginning of the 1980s, interest in the environmental assessment of products grew in connection with discussions on environmental impacts from various forms of packaging, and LCAs were used in several European countries to compare different beverage packaging [43]. Obtaining unambiguous results and conclusions proved to be difficult in some cases, because the database and the methods varied in the different studies. This was unsatisfactory, and it was one of the reasons why a more systematic development of the methodological basis for the life-cycle assessment of products began.

From the end of the 1980s to today, interest in LCA has grown strongly, with a number of differing and increasingly complex products and systems being assessed.

The international scientific society of environmental chemists, SETAC (Society of Environmental Toxicology and Chemistry) started work on LCA in 1990, and within a few years it became the international forum for discussion of the methodological development of LCA.

3.3.2 Current Status of LCA

Life-cycle analysis is a technique, which has gained acceptance as a means of quantifying environmental effects. The process is broken down into the following steps, each of which is then described briefly:

1. Goal definition and Scope;
2. Inventory Analysis;
3. Impact Assessment;
4. Improvement Analysis.

Goal Definition and Scope - It is essential to clearly define the specific project aims and set the scope for the LCA study. Without a clear definition of the scope the LCA can grow rapidly beyond what was originally planned.

To carry out an LCA it is also necessary to define the System Boundary, which is contained within a System Environment, which represents the source of all raw materials, energy and other inputs and the disposals for all products, wastes and all other outputs.

The LCA process is based on the Law of Conservation of Mass and Energy. The System Boundary is therefore the boundary across which all mass and energy calculations are carried out. The system must be balanced, accounting for all inputs and outputs.

The specification for the goal definition is a description of system boundaries, the functional unit and data requirements. The goal definition for this study is based around the operation of the AWE Aldermaston site for one year. The choice of a functional unit for this study is not simple to define because many components are manufactured and a great deal of Research and Development (R & D) also takes place, all contributing to a common aim of warhead component manufacture. Raw materials are brought onto the site and processed to make up weapon parts. Actual assembly takes place at Burghfield and the delivery system is developed and manufactured in the US. A ideal functional unit would be a complete warhead, however as the unit is manufactured and assembled on different sites and different countries this is outside the scope of the study. The aim of this study is to assess operations on the Aldermaston site and identify processes that are causing the most environmental damage, whilst making the assessment relevant to the Company EMS. Based on this overall aim the functional unit has been chosen as:

" Nuclear Deterrent Component Manufacture at AWE Aldermaston in One Year".

Inventory Analysis - In this step data on raw materials and energy (inputs) and waste heat, effluents, solids and gaseous emissions (outputs) are quantified. It is essential that these inputs and outputs be expressed in the same units and relate to the functional unit of the system. The quality of data should be as accurate as possible and any assumptions need to be clearly stated. The need for good quality information often makes data gathering a laborious and time-consuming task. This part of the LCA study can be used for decision making in its own right because the information is quantitative and objective. It is possible to evaluate scientifically where the largest impacts are taking place e.g. high-energy usage.

The inventory consists of a quantitative analysis of all transfers of masses and energies across the interface between the system boundary and system environment. The inventory includes issues of transport and packaging and all inputs and outputs have to be identified, quantified and balanced.

The net balances of energy and of mass have to be zero for the overall system [22]. and the law of conservation of mass (see Footnote 1) [23] & [24] underpins the LCA inventory process.

The issues, which are not normally quantified in LCA, include [25]:

- capital equipment, infrastructures;
- accidental spills;
- human resources.

For this study the inventory data come from the FREAs that have been prepared for the operational control phase of the EMS. The FREAs contain quantitative data on energy and resource use, along with the volumes of waste and quantities of materials released to the environment. The inventory is reproduced in full in **Appendix H**.

Impact Assessment - In this step the inventory is grouped and interpreted in terms of environmental impacts. The inventory provides the data of environmental exchanges for the system being assessed. Some exchanges are environmentally important. Others are of no significance. For the LCA to be able to support decisions, the data in the inventory must be interpreted [43]. This is where the quantified burdens are categorised by attempting to interpret inventory data by linking it to identifiable environmental problems. These problems typically include depletion of fossil fuels, contribution to the greenhouse effect, stratospheric ozone depletion, photochemical smog generation, acidification, nutrification and landfill use. The impact assessment stage is often contentious and open to interpretation.

Impact assessment is divided into four sub-sections:

1. Classification
2. Characterisation
3. Normalisation

---

1. There is no detectable change in mass in an ordinary chemical reaction - The law of the conservation of mass which was first stated in 1798 by the Frenchman Antoine Lavoisier and reproduced in Page 82 of Fundamental of Environmental Chemistry by Stanley Manahan [23]. Since no atoms are lost, gained, or changed in chemical reactions, mass is conserved. Similarly energy can neither be created or destroyed in any process. It is just changed from one form to another. The work of Einstein has shown that mass and energy can be interconverted [24].

4. Valuation

Classification - In this step the different inputs and outputs of the system are aggregated in terms of scale (local, regional or global) and/or medium (air, water and land) and assigned to different impact categories.

Characterisation - This is a quantitative step in which the relative contributions of each input and output to the assigned categories are assessed through the application of impact potentials or equivalency factors (EF) (see **Appendix G**). The contributions are then aggregated within the impact categories to produce an environmental profile of the system. For each impact category, endpoints are defined (e.g. kg CO_2 equivalents for Global Warming Potential) together with a method for calculating or transforming single substances into these. Usually a linear characterisation factor is found which expresses the potential contribution to a category per mass of an input or output in the inventory [32] thus:

$$Sji = MiQji$$

Where:

Sji potential contribution to impact category j from input or output i

Mi Environmental quantity (mass of input or output i)

Qji characterisation factor (impact potential or equivalency factor) for substance i to impact category j

The total potential contribution to the impact category j from all inputs and outputs can then be calculated [32] as:

$$Sj = \Sigma iSji$$

An impact can be defined at any point in the cause-effect chain but a distinction is normally made between early effects and late effects along the route [25]. In the ISO standards on LCA, associating each category with a place in the cause-effect chain, (beginning, middle and end), where the impact indicator is defined makes this distinction. The effect of Global Warming, is defined as a change in "radiative forcing" and this occurs at the beginning of the cause-effect chain [25]. Global warming will lead to other effects including sea level change, climate disruption and loss of biodiversity, but the impact can only be defined once to avoid double accounting.

A standard list of impact categories and spatial parameters currently used by LCA practitioners are given in **Table 3-2**.

Table 3-2 LCA Impact Categories

Impact Category	**Spatial Parameter**
Global Warming / Climate Change	Global (the World)
Stratospheric Ozone Depletion	Global (the World)
Fossil Reserve Depletion	Global (the World)
Photochemical Smog Formation	National (Great Britain)
Acidification	National (Great Britain)
Nutrification	National (Great Britain)
Ecotoxicity	Local (site / community specific)
Human Toxicity	Local (site / community specific)
Landfill volume / Waste Generation	Regional or National

Normalisation – This is an optional step within the impact assessment phase that employs baseline or reference information from outside the Life-cycle Impact Assessment (LCIA) framework [37]. The purpose of normalisation is to take the results of the characterisation exercise and better understand the relative magnitude of the impact categories. The characterisation results are compared to reference information for each impact category and normalised so that the categories can be meaningfully compared with each other. The impacts are compared against normalised reference levels based on activities from the whole of society (local, regional or global), over the period of time corresponding to the functional unit (1 year in this thesis). In other words normalisation relates the data to the total magnitude of the given impact category to some area and time [25]. The reference information used to determine normalisation values is given in **Appendix I** and summarised in **Table 3-3**.

The choice of spatial parameter for the impact categories are in agreement with those used by LCA practitioners [43]. The normalisation factors for global warming, ozone depletion and fossil reserve depletion are based on global releases and resources reference data [43]. The release of CO_2 or an ozone depleting substance to the atmosphere is soon dispersed globally, so that point of the release is not important, as local and regional emissions contribute to *global* problems. Fossil reserve depletion of non- renewable resources of iron, coal and oil are extracted and widely distributed and consumed on a global scale, hence the impact from diminished sources is felt globally. AWE uses oil, gas and fuel for operations on the Aldermaston site and these materials are used to calculate this impact's normalisation factor. Photochemical smog episodes, nutrification in rivers and acidification of the atmosphere are all national impacts, restricted to the nation, which generated the release. Ecotoxicity and human toxicity are issues that cause impacts on a very local scale (usually not outside 10-15km radius of a site). It is only under catastrophic accident conditions that toxicity and ecotoxicty cause national or international problems. Modern landfill sites only cause problems of land use and groundwater quality on a region-by-region basis (i.e. at a county level).

The author has selected England and Wales as spatial parameters for the new impact categories of radioactive waste landfill and environmental irradiation (to air and water). The radioactive category's spatial parameters are based on releases from nuclear sites in England and Wales (population of approx. 50 Million). The disposal of radioactive waste in a land-based repository is an issue of national importance only, and assuming waste is disposed of in a land-based repository, it will not affect neighbouring countries, likewise, environmental irradiation, under routine conditions will not have an impact outside national boundaries. A major catastrophe is required, similar in magnitude to the accident at Chernobyl in 1986, to cause impacts outside national boundaries and this is not considered to be a credible basis upon which to determine normalisation factors.

The use of global reference values for global impacts and national, regional and local reference values for national, regional and local impacts will cause an imbalance in the normalisation calculation. This imbalance will result in global impacts appearing to be much less than other impacts because they are compared with the activity of the population of the entire world, while others are compared only with the activity of a much smaller population. To correct this bias the normalisation factors are adjusted to *person-equivalents (PE)* giving the normalisation factor the unit "impact potential per person per year". This is achieved by multiplying the normalisation factor by the relevant population as follows [43].

$$NF_{(PE)} = NF.P$$

Where:

$NF_{(PE)}$ Normalisation factor per person per year

NF Normalisation factor (AWE fraction of the reference total)

P Population (either global, national, regional or local)

For example the global warming normalisation factor is calculated thus:

- Total global emission of greenhouse gases (kg CO_2 –eq/year) ~ 4.59 E13
- Annual total from AWE ~ 1.27 E5
- NF = 1.27 E5/4.59 E13 = 2.77 E-9
- P = 6 E9
- $NF_{(PE)}$ = 2.77 E-9 x 6 E9 = 1.66 E1

The person equivalent normalisation factors are applied to the characterisation results and included in the presentation of results given in **Appendix J**.

Table 3-3 Normalisation Values [Source - See Appendix I]

Impact Categories	**Spatial Parameter**[2]	**Normalisation Factor**	**Population**[4, 5, 6 & 7]	**Normalisation Factor (PE)**[9]
Global Warming / Climate Change	Global	2.77E-09	6.00E+09	1.66 E+01
Stratospheric Ozone Depletion	Global	1.04E-08	6.00E+09	6.23 E+01
Fossil Reserve Depletion	Global	2.05E-06	6.00E+09	1.23 E+04
Photochemical Smog Formation	National	2.07E-04	5.80E+07	1.2 E+04
Acidification	National	6.53E-03	5.80E+07	3.79 E+05
Nutrification	National	N/A	5.80E+07	1.00 E+00
Ecotoxicity	Local	N/A	4.06E+05	1.00 E+00
Human Toxicity	Local	N/A	4.06E+05	1.00 E+00
Landfill volume / Waste Generation (Domestic)	Regional	2.26E-05	7.25E+05	1.64 E+01
Landfill volume / Waste Generation (Trade)	Regional	2.72E-06	7.25E+05	1.97 E+00
Special Landfill / Radioactive Waste Generation[1 & 8]	England and Wales[3]	2.76E-03	5.00E+07	1.38 E+05

Impact Categories	**Spatial Parameter**[2]	**Normalisation Factor**	**Population**[4, 5, 6 & 7]	**Normalisation Factor (PE)**[9]
Environmental Irradiation[1] Radioactive Release to Water	England and Wales[3]	3.87E-08	5.00E+07	1.93 E+00
Environmental Irradiation[1] Radioactive Release to Air	England and Wales[3]	4.19E-05	5.00E+07	2.10 E+03
Radiation Dose	England and Wales[3]	1.94E-03	5.00E+07	9.68 E+04

1. Denotes a new impact category developed by the author.
2. The spatial parameter is used in this context to set the geographical boundary for the reference area upon which the normalisation factor is calculated - See Appendix I for more details.
3. These spatial parameters are defined by the author.
4. Global population is the current accepted population of the world (6 Billion) [26].
5. National populations are considered to be that of the Great Britain total (58 million) 1991 Census - National Statistics Official UK Site www.statistics.gov.uk/statbase)
6. Regional populations are considered to be those in AWEs host county of Berkshire (724661) (1991 Census - National Statistics Official UK Site www.statistics.gov.uk/statbase).
7. Local populations are considered to be those residents from the major population centres in a 15km radius of the site including Basingstoke and Deane, Newbury and Reading (405639) (1991 Census -National Statistics Official UK Site www.statistics.gov.uk/statbase).
8. The normalisation factor for Radioactive Waste Generation is based on the Bq released into the environment rather than the volume of waste generated - See Appendix I for more details.
9. PE (Person Equivalents), see discussion below.

Valuation – This is another optional step within the LCIA framework and is the process whereby different impact categories are weighted using numerical factors based on value choices. Different weighting factors can be applied to each impact category to highlight the relative importance of categories. This is the most subjective and contentious part of the LCIA methodology. There are no internationally agreed rules on how valuation should be tackled and importance varies between studies. Three methods are generally favoured:

Distance to target - where the scale of the impact relative to some legislative, political or scientific target is compared. Impacts that are closer to a pre-determined detrimental level are given higher weighting. Conversely impacts that are close to targets set for an observed "no detrimental environmental effect", for example trigger values for contaminants in soil to determine land quality, are given lower weighting. Political or legislative targets established at protocols can also be used, for example the UK target reduction in global warming emissions.

Monetary based - where actual costs are assigned to dealing with or accounting for the relative impacts. Those that attract more cost are given higher weighting.

Societal preference - where decision-making panels, stakeholders and experts are canvassed for their opinion. Also weighting by company environmental targets can be used [43], thus linking LCIA valuation to a Company Environmental Management System. Obviously there will be a wide variation in the relative importance placed on different impact categories, and this will depend on many factors. The danger is people are often driven by their own local personal preferences, (i.e. noise, waste or congestion), rather than more global issues including climate change, loss of resources and stratospheric ozone destruction. As the general public has such a major influence on the success of an organisation and their views are of increasing importance, this method of weighting societal preference is considered to have merit. This is especially true of nuclear waste problems (see Footnote 2)[27]. The views of experts from the regulatory bodies, (EA and the HSE in the UK), are widely respected and are another reason in support of this approach.

As part of this research, it is proposed to make use of a combination of the monetary based and societal preference methods, based on the values used in the corporate significance assessment process [13], in order to derive a robust and acceptable process of valuation.

Improvement Analysis – During this stage the results are evaluated and decisions are made. Due to some of the subjective elements within impact assessment the results of the LCA need to be analysed and interpreted with care. The improvement analysis phase of LCA in this thesis is presented in Chapter 5.

3.3.3 LCA in Industry

Although standardisation through ISO [28] has helped the technique of LCA gain international acceptance the methodology is still very much in its embryonic stage. To date, most of the studies have concentrated on products from the packaging industry and parts used in the automotive industry. More recently complex analysis has been carried out on products used in the telecommunications electronics industry [29]. The work of Francis [30] in developing a complex methodology has taken LCA forward

---

2. The need for public acceptability has been recognised in professional journals on nuclear waste and environmental management. An article, prepared to reflect on the UK Governments response to the House of Lords Select Committee report on the Management of Nuclear Waste, noted that " the management of nuclear wastes had become primarily a problem of political commitment and of fashioning administrative procedures that command public support, rather than one of technology" [27].

into a very important industry sector. A key requirement in developing this complex methodology was the early recognition that present burden databases are not comprehensive. There are thousands of chemicals and materials, which can be categorised, in the impact assessment stage of LCA, but are not currently included in the inventory stage. Without the inclusion of industry-specific burdens it is likely that the impacts assigned to those products or processes will not be representative. Without these inclusions LCA will not be able to truly reflect the environmental impacts that are associated with the electronic industry. Similarly the nuclear industry processes and discharges nuclear material, which has unique impacts that do not fall readily into current impact categories.

The most recent research work of importance that is relevant to this thesis is LCA development carried out by Francis [31] and its application to the electronics industry, and that of Solberg-Johansen [32], who carried out LCA on the nuclear fuel cycle. Until quite recently LCA was restricted in its application to simple products and systems before being attempted on more complex systems including the motor car. Francis recognised that if the full value of LCA was to be realised the methodology would have to be developed to include a wider range of environmental burdens. Francis successfully developed LCA for application to complex systems within the telecommunications industry.

Research at the Centre for Environmental Strategy at Surrey University has included a lot of work on the application and development of LCA. In 1998 Solberg-Johansen completed a study [32] into the Life-cycle Assessment of the Nuclear Fuel Cycle based on a functional unit of 1TJ of electricity and using data from case studies of actual nuclear sites. As with the work of Francis this study was forced to develop the existing LCA framework and subsequently identified new impact categories for human and environmental irradiation. A thorough review of available scientific literature relevant to this thesis is assessed. The fate of radioactivity in the environment and its assessment within the context of environmental management is considered to be very important and this formed the bulk of the literature reviewed.

The work of Solberg-Johansen assessed the LCA of the nuclear fuel cycle [32], and proposed categories for radiological impacts on human health and radiological impacts on the environment. In this research the work of Solberg-Johansen is reviewed, and a new methodology developed to include industry-specific burdens from contributions made at AWE Aldermaston is proposed. This thesis addresses specific aspects and burdens to give a comprehensive analysis of all impacts at AWE.

3.3.4 LCA in this Study

Life-cycle Analysis is primarily a quantitative tool that can be used to determine environmental impacts associated with all stages in the life-cycle of a product from extraction of raw materials through to manufacturing, packaging, transport, use and final disposal. With increasing need for good quality data on which to make decisions the methodology has been refined and applied to complex systems in the electronics industry. Francis [31] has developed a methodology that includes industry-specific burdens for the telecommunications industry and in the process has realised major cost savings for Nortel (Northern Telecom, UK).

Based on the recognition that LCA methodology needs to be developed to consider industry-specific burdens and aspects related to the radiological discharges, this study is being undertaken. At present there are no provisions for the determination of radioactive (R/A) impacts within the current LCA framework. Recent research by Solberg-Johansen [32] has investigated the environmental life-cycle assessment of the nuclear fuel cycle. This study has been reviewed as part of the current research and used as check to add credence to the site-specific methodology developed and presented for R/A releases from AWE in this study.

The methodology of LCA has been chosen to help achieve this thesis aim because the method is quantitative and objective, as opposed to qualitative and subjective, and will allow information, that has already been gathered, to be converted, into an inventory for impact assessment. Other methods that have been considered include Environmental Impact Assessment (EIA) and Environmental Risk Assessment (ERA). Environmental Impact Assessment was developed as a way of assessing planning applications for new developments and has become widely accepted in environmental management. Environmental Impact Assessment is broken down into the following stages:

1. assessment of the environment in which the project will be placed;

2. assessment of the project to establish impact factors and their level of danger for the environment;
3. valuation of impacts, their importance (positive and negative), probability, frequency, duration etc.;
4. assessment of alternative strategies.

The main drawback with this technique is that it is geared towards an option study exercise as a means of justifying a proposed strategy. There is no life-cycle or cradle to grave analysis and the shift of burdens to other sites or stages can be overlooked.

Environmental Risk Assessment is a tool that seeks to estimate the frequency of an undesirable outcome, along with an estimate of the magnitude of the consequence. It is most often used to assess the tolerability of fault conditions but can also be applied to routine releases. Whilst carrying out a risk assessment some form of judgement must be made as to what degree of harm is tolerable. Tolerability refers to a willingness to live with a risk so as to secure certain benefits, in the confidence that these risks are being properly controlled and managed. The concept of a tolerable risk is central to the regulation of the UK nuclear industry by the Nuclear Industry Inspectorate (NII) and departs from the Environment Agency's current philosophy [33], which does not accept risk-based arguments and assesses the actual amounts released (radiological) by discharges.

The judgement on what is tolerable or not, requires some knowledge of risk perception and the trade-offs between perceived risks and perceived benefits. This judgement is often difficult as people and groups have different perceptions of risk, which may be influenced by a range of issues. These issues include [34]:

- **Familiarity** - people under estimate risks that they are familiar with and over estimate those with which they are not familiar.
- **Control** - people underestimate risks that they control themselves and overestimate those risks that are in other people hands.
- **Proximity in space** - people overestimate risks, which may occur near to them and underestimate those that will occur at a remote location.

- **Proximity in time** - people tend to ignore risks that are going to arise much later in time.
- **Fear** - people tend to exaggerate the risks associated with the phenomena they do not understand. This is especially true of radiological risks and risks associated with nuclear power.
- **Scale** - large-scale consequences usually get more media attention.

Bearing in mind the difficulties and contentious nature of some aspects of risk assessment, this method was discarded in favour of LCA for the assessment of routine contributions. Risk Assessment is a valuable tool and has been chosen by the author as the basis for developing a methodology for assessing accident conditions described in Chapter 4.

Specific parts of LCA methodology are used to determine the environmental impact of AWE operations. The goal and scope of this study is to determine the environmental impact of a year of operation at AWE. The study specifically includes the high hazard process facilities but excludes offices and support buildings. The objective is to identify which processes and facilities are causing the most environmental damage as a method of setting targets for subsequent improvement. Existing information generated to populate the FREAs is used as a basis for building up the Life-cycle Inventory for one year's operation. This information is analysed to calculate the environmental impact against the various categories in LCA. A new methodology and impact category is developed for releases of radioactive material.

The complete life-cycle system for AWE operations is given in **Figure 3-1**. This diagram illustrates the specific boundaries of the systems, (the system boundaries), that are being modelled in this study, and are shown in the bold highlighted boxes.

Figure 3-1 System Flow-chart

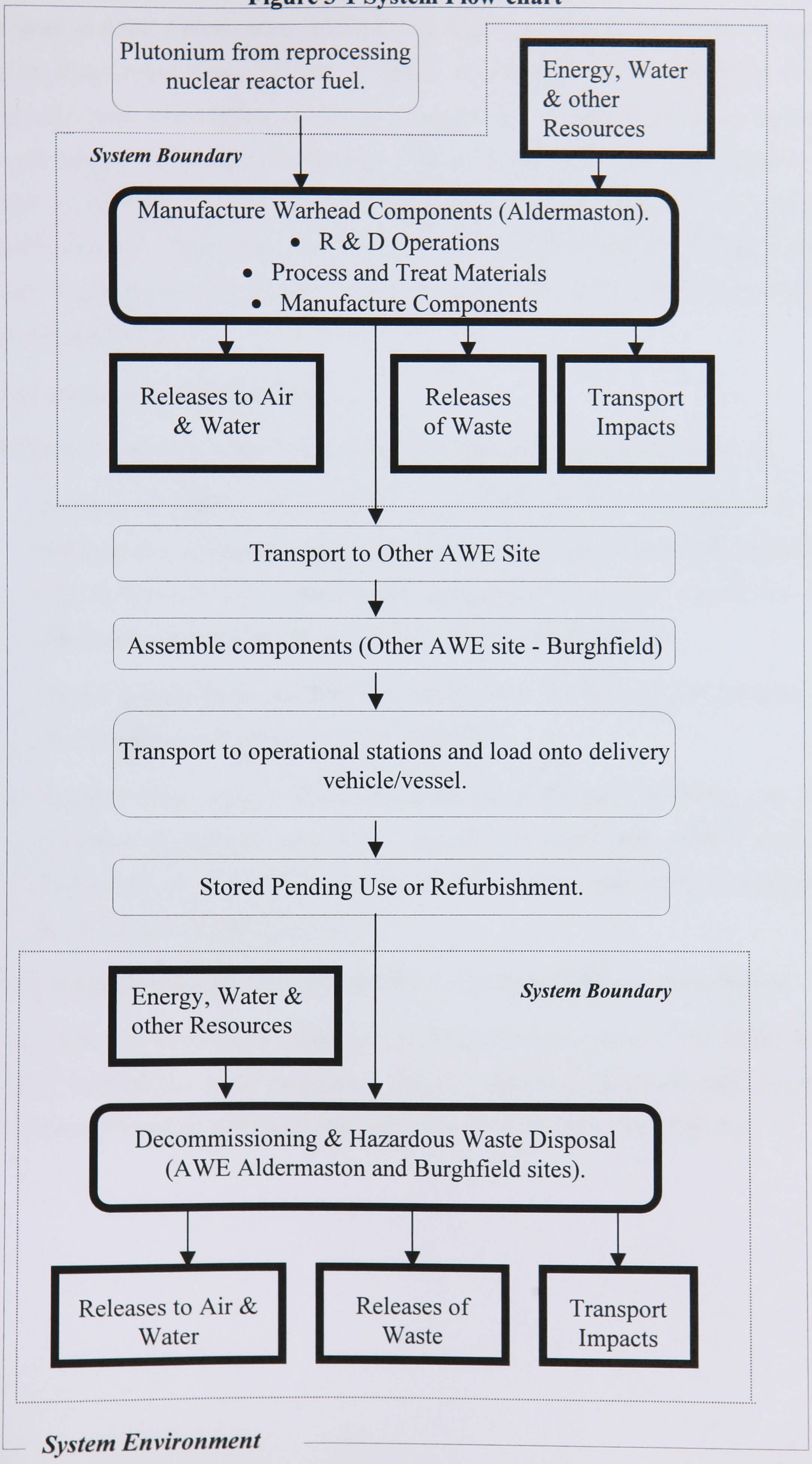


Figure 3-1 shows the system boundary, which represents an analysis of one year's operation at AWE Aldermaston. Although the diagram is simplistic it should be noted that the scope covers many different processes across many system boundaries where losses and open loop outputs cannot be accounted for. It is not possible to calculate the net balances of energy and mass to zero for the overall system and reliance is placed on the data supplied by AWE environmental staff (Facility Environmental Representatives). These data, originally used to populate Facility Environmental Aspect Registers, are used in this thesis to form the basis of the Life-cycle Inventory (see **Appendix H**).

3.3.4.1 Assumptions for this Study

The research presented in this thesis is based on the following key assumptions:

- Background impacts are bounded by individual facility contributions to the corporate environmental aspects. For example, all impacts associated with fossil reserve depletion are included in the assessment of electricity use, oil use and other resource use recorded in the FREA for individual facilities.
- The LCA specifically excludes the supply chain and all activities upstream of the Aldermaston site operation (see **Figure 3-1**).
- Transport impacts are assessed for Releases to Air only. Resource use, fuel extraction manufacture and other impacts associated with vehicle use and disposal are not assessed as they are cannot wholly be attributed to, or required for, AWE Aldermaston operations.

3.3.4.2 Links Between LCA and the AWE Environmental Management System

At this stage it is worthwhile stating the similarities between various LCA stages, their meaning with respect to the assessment methods applied in this thesis and how they match elements within AWEs current EMS. This is summarised in **Table 3-4**.

Table 3-4 Similarity between LCA and the AWE EMS

LCA Step	Definition in this thesis	Equivalent component within AWE EMS
Goal definition and Scope	Nuclear Deterrent Component Manufacture at AWE Aldermaston in One Year	Establish EMS to meet ISO 14001
Inventory Analysis	Established from data in FREA, (see Appendix H)	Facility and Corporate Register of Environmental Aspects.
Impact Assessment	Based on categories defined and new categories for company specific issues including R/A aspects (see Chapter 3)	Impact is assumed to be proportional to magnitude of the contribution made to the aspect.
Improvement Analysis	Identification of facilities and processes causing the most environmental impact (see Chapter 5).	Recommendations for improvement.

The main finding is that the EMS assumes that environmental impact is proportional to the contribution that a facility makes to a corporate aspect. This thesis explores the links between the aspect contribution and environmental impact to test the adequacy of this assumption and identify those processes, activities and facilities that are causing the most environmental damage.

3.3.4.3 Development of A Valuation Method

As part of this research, it is proposed to make use of a combination of the monetary based and societal preference methods, based on the values used in the corporate significance assessment process [13], in order to derive a robust and acceptable process of valuation. An initial assessment of the relative merits of these valuation methods is therefore performed using a SWOR (Strength, Weakness, Opportunity and Risk) analysis, and the findings are summarised in **Table 3-5**.

Table 3-5 Application of SWOR Analysis to a Valuation Method [35]

	Valuation Method		
SWOR Criteria	**Distance to Target**	**Monetary based**	**Societal Preference**
Strength	This method does have some scientific basis. Legislative targets are based on preventing the deleterious effects of pollution.	Linking the LCA valuation stage with monetary costs is consistent with company policy. All major company decisions are driven by cost.	Wide body of opinion can be canvassed. Public stakeholders have an opportunity to contribute to the process, which is a commitment in the environmental policy [36].
Weakness	Some targets are based on social, economic and political issues, which are not necessarily based on environmental damage.	Not scientifically proven that the most environmentally damaging activities cost the most to rectify. This is particularly true of some R/A risks as the money spent by the nuclear industry on minimising releases is not proportional to the health risk they pose.	Unless credible experts are consulted, the method can lack scientific validity.
Opportunity	The results of the LCA can be compared to reference levels based on the activities for the whole of society. This puts activities at AWE in context with the rest of society based on local, regional or global impacts.	Opportunity to harmonise the results of the study with other cost driven issues in the company. Business issues (costs) were used as criteria in setting the priority for weighting corporate environmental aspects [13].	Opportunity to link the LCA with the EMS and get stakeholder acceptance of the study.
Risk	There is a risk that political issues are favoured over scientific issues.	Placing the emphasis on money rather than environmental damage could undermine results of the LCA.	Lack of scientific basis could undermine the results of the LCA.

The conclusion that can be drawn from this SWOR analysis is that there are both advantages and disadvantages to each of the methods. The distance to target method has some scientific basis and can relate issues at AWE to those in society as a whole. The normalisation phase however, effectively places each of the impact categories relative to the whole of society and there seems to be little merit in attempting to weight them again against targets. For the new impact categories defined for radioactive releases there are no actual targets established owing to the lack of scientific knowledge about the effects of low dose radiation on humans and other species. There is considered to be very little merit using the distance to target method for valuation in this thesis.

The opinions of the local community are considered to play a vital role in winning support for the EMS as a whole and in accordance with commitments made in the Environmental Policy, consultation with the local community is a necessity [36]. The valuation method proposed in this thesis is based on monetary and societal preference components.

The monetary and societal preference elements are derived from the business and stakeholder scores used to determine corporate significance as part of the AWE EMS [13]. These scores for monetary issues are reproduced in **Table 3-6** along with the corresponding impact categories and ratings for each as either High (>6), Medium (3 – 6) or Low (<3). Business issues were used in the original assessment, which were based on costs to the company and civil liability.

Table 3-6 Valuation - Monetary Based Analysis

Corporate Aspect	Impact Categories	Original [13] Monetary Based Score[2]	Monetary Preference (H/M/L)
Releases to Air - R/A	• Radiation dose • Environmental Irradiation[1]	7	H
Releases to Air – Acids	• Acidification • Human toxicity • Ecotoxicity	3	M
Releases to Air – VOCs	• Ozone creation • Global warming • Human toxicity • Ecotoxicity	3	M
Releases to Air – ODSs	• Stratospheric ozone depletion • Global warming • Human toxicity • Ecotoxicity	4	M
Releases to Air – Be	• Human toxicity • Ecotoxicity	3	M
Releases to Air – Pb	• Human toxicity • Ecotoxicity	1	L
Releases to Air - Combustion by Products	• Global warming • Acidification • Human toxicity • Ecotoxicity	1	L
Releases to Water - R/A Effluent	• Radiation dose • Environmental Irradiation[1]	9	H

Corporate Aspect	Impact Categories	Original [13] Monetary Based Score[2]	Monetary Preference (H/M/L)
Releases to Water - Trade Effluent	• Human toxicity • Ecotoxicity • Nutrification	5	M
Releases to Water - Domestic Effluent	• Human toxicity • Ecotoxicity • Nutrification	3	M
Releases of Waste - R/A	• Radiation dose • Environmental Irradiation[1] • Special Landfill volume[1]	8	H
Releases of Waste - Trade Waste	• Human toxicity • Ecotoxicity • Landfill volume	3	M
Releases of Waste – Domestic	• Human toxicity • Ecotoxicity • Landfill volume	4	M
Resource Use – Electricity	• Global warming • Acidification • Human toxicity • Ecotoxicity	2	L
Resource Use – Gas	• Global warming • Acidification • Human toxicity • Ecotoxicity	2	L
Resource Use - Water On - site	• Resource depletion • Disruption to ecosystems	5	M
Resource Use - Water Off – site	• Resource depletion • Disruption to ecosystems	2	L
Resource Use - Chemical/Oil Storage and Use	• Human toxicity • Ecotoxicity	7	H
Resource Use - R/A Use and Storage	• Radiation dose • Environmental Irradiation[1]	9	H
Resource Use – Other	• Human toxicity • Ecotoxicity	2	L

1. Denotes new impact categories developed for this thesis
2. Out of a maximum score of 9

This table shows that some aspects contribute to more than one impact category and that impact categories are common to several different aspects.

Table 3-7 shows how the impact categories are weighted and scored. A high rank is weighted by a factor of 3, a medium rank by 2 and a low rank by 1. Where the impact category was common to more than one aspect a midway ranking has been given. For example global warming potential is ranked low (1) and medium (2) and has thus been assigned a score of 1.5. Human Toxicity and Ecotoxicity categories are mostly ranked as medium but is also ranked as low and on one occasion as high (Resource Use- Chemical/Oil Storage and Use). The Human Toxicity and Ecotoxicity impacts have been assigned a medium rank factor, as this is the most common score.

Table 3-7 Valuation - Monetary Based Weight Factors

IMPACT CATEGORY	MONETARY PREFERENCE	WEIGHT FACTOR
Radiation Dose	High	3
Environmental Irradiation	High	3
Acidification	Low to Medium	1.5
Human Toxicity	Low, Medium and High	2
Ecotoxicity	Low, Medium and High	2
Photochemical Ozone	Medium	2
Global Warming Potential	Low to Medium	1.5
Ozone Depletion	Medium	2
Special Landfill for R/A waste	High	3
Landfill	Medium	2
Resource Depletion	Low to Medium	1.5
Nutrification	Medium	2

The scores for societal preference are reproduced in **Table 3-8**, which also gives the corresponding impact categories, and rating for these categories as either High (>10), Medium (6 – 10) or Low (5 or less). Societal preference scores were based on the stated concerns of the following stakeholders:

- The regulatory bodies (the Environment Agency and the Nuclear Installations Inspectorate);
- The general public especially the local community;
- The Ministry of Defence (the customer);
- AWE Senior Management.

Table 3-8 Valuation - Societal Preference Analysis

Corporate Aspect	**Impact Categories**	**Original [13] Societal Based Score[2]**	**Societal Preference (H/M/L)**
Releases to Air - R/A	• Radiation dose • Environmental Irradiation[1]	15	H
Releases to Air – Acids	• Acidification • Human toxicity • Ecotoxicity	5	L
Releases to Air – VOCs	• Ozone creation • Global warming • Human toxicity • Ecotoxicity	5	L
Releases to Air – ODSs	• Stratospheric ozone depletion • Global warming • Human toxicity • Ecotoxicity	10	M
Releases to Air – Be	• Human toxicity • Ecotoxicity	6	M
Releases to Air – Pb	• Human toxicity • Ecotoxicty	3	L
Releases to Air - Combustion by Products	• Global warming • Acidification • Human toxicity • Ecotoxicity	6	M
Releases to Water - R/A Effluent	• Radiation dose • Environmental Irradiation[1]	14	H
Releases to Water - Trade Effluent	• Human toxicity • Ecotoxicity • Nutrification	5	L
Releases to Water - Domestic Effluent	• Human toxicity • Ecotoxicity • Nutrification	3	L
Releases of Waste - R/A	• Radiation dose • Environmental Irradiation[1] • Special Landfill volume[1]	14	H
Releases of Waste - Trade Waste	• Human toxicity • Ecotoxicity • Landfill volume	5	L
Releases of Waste – Domestic	• Human toxicity • Ecotoxicity • Landfill volume	7	M
Resource Use – Electricity	• Global warming • Acidification • Human toxicity • Ecotoxicity	5	L

Corporate Aspect	**Impact Categories**	**Original [13] Societal Based Score[2]**	**Societal Preference (H/M/L)**
Resource Use – Gas	• Global warming • Acidification • Human toxicity • Ecotoxicity	5	L
Resource Use - Water On - site	• Resource depletion • Disruption to ecosystems	6	M
Resource Use - Water Off – site	• Resource depletion • Disruption to ecosystems	6	M
Resource Use - Chemical/Oil Storage and Use	• Human toxicity • Ecotoxicity	8	M
Resource Use - R/A Use and Storage	• Radiation dose • Environmental Irradiation[1]	14	H
Resource Use – Other	• Human toxicity • Ecotoxicity	6	M

1. Denotes new impact categories developed for this thesis
2. Out of a maximum score of 15

It is clear from the table that some aspects contribute to more than one impact category and that impact categories are also common to several different aspects.

In **Table 3-9** each impact category is weighted and scored. A high rank is weighted by a factor of 3, a medium rank by 2 and a low rank by 1. Where the impact category was common to more than one aspect a midway ranking has been given.

Table 3-9 Valuation - Societal Preference Weight Factors

IMPACT CATEGORY	SOCIETAL PREFERENCE	WEIGHT FACTOR
Radiation Dose	High	3
Environmental Irradiation	High	3
Acidification	Low to Medium	1.5
Human Toxicity	Low to Medium	1.5
Ecotoxicity	Low to Medium	1.5
Photochemical Ozone	Low	1
Global Warming Potential	Low to Medium	1.5
Ozone Depletion	Medium	2
Special Landfill for R/A waste	High	3
Landfill	Low to Medium	1.5
Resource Depletion	Medium	2
Nutrification	Low	1

These two sets of weight factors can be combined to give an overall valuation factor for each impact category. The valuation method developed is considered to be consistent with the requirements of the AWE EMS Policy which states a commitment to focus environmental attention based on societal preference and monetary/business issues. Normalisation and valuation steps are both optional within the framework of LCIA [37], but are considered to be important because they put the overall analysis in context of potential environmental damage both nationally and globally, and provide a link with the existing AWE EMS.

The combined weighting factors are given in **Table 3-10**.

Table 3-10 Valuation - Combined Weight Factors

IMPACT CATEGORY	Monetary Based Factor	Societal Based Factor	Combined Factor
Radiation Dose	3	3	6
Environmental Irradiation	3	3	6
Acidification	1.5	1.5	3
Human Toxicity	2	1.5	3.5
Ecotoxicity	2	1.5	3.5
Photochemical Ozone	2	1	3
Global Warming Potential	1.5	1.5	3
Ozone Depletion	2	2	4
Special Landfill for R/A waste	3	3	6
Landfill	2	1.5	3.5
Resource Depletion	1.5	2	3.5
Nutrification	2	1	3

3.4 ENVIRONMENTAL INDICES AND IMPACT CATEGORIES

Before giving details of the various indices used and the established impact categories it is important to make clear the distinction between environmental aspects, impacts and effects.

In the context of this study an **environmental aspect** is defined as:

- *Any element of an activity or service that can interact with the environment.*

An **environmental impact** is defined as:

- *Any physical changes to the environment, whether adverse or beneficial, wholly or partially resulting from an activity or service.*

An **environmental effect** is defined as:

- *The consequence of the impact and its ramifications to human health, erosion, corrosion, ecosystem damage, contaminated potable water supplies etc.*

An example of these terms is given in the following analysis.

Burning coal to generate energy is an example of an environmental aspect. The release of CO_2 as a result of the combustion process will result in a contribution to global warming. The global warming is the physical change and is an environmental impact. The disruption to weather systems, flooding, coastal erosion and loss of habitat as a result of global warming are the environmental effects.

In order to determine the impact of a release an evaluation of its damage potential against a known standard needs to be made. Several published sources give impact potentials for different chemical releases for various impact categories. A review of these sources has been made. The environmental indices used in this study are reproduced from published sources [43 & 110] in **Appendix G** where various equivalency factors (EF) and potentials are listed. In addition a comprehensive database of characterisation factors from Leiden University in the Netherlands is also used [38]. The Leiden University source has factors for most chemical substances currently known to man for each of the impact categories currently used by LCA practitioners, and has been subjected to internal and external peer review. The spreadsheets used in **Appendix J** for the impact assessment reference the precise source for each of the equivalency factors used. Potentials are reproduced from published sources [43 and 110] in **Appendix G** for the following impact potentials:

Global Warming Potential

Potentials are given for a wide variety of substances, for example CH_4 which has a potential value of 21, which, when released into the atmosphere can contribute to global warming. Carbon dioxide (CO_2) is the reference substance and has been assigned a value of 1. Values for other substances are relative to CO_2.

Photochemical Ozone Creation Potential (POCP)

POCP values are given for a wide variety of hydrocarbon and VOC compounds, which under the action of UV light generate ozone. Ethylene is the reference substance and has been assigned a value of 100. Values for other substances are relative to Ethylene (C_2H_4). It is interesting to note that nitrogen monoxide (NO) has a negative potential (-42.7). In urban air there is an abundant supply of nitrogen dioxide (NO_2) whose photolysis leads to ozone formation, however fresh emissions of NO lead to ozone removal. The full cycle of ozone formation from NO_2 and removal from emissions of NO is as follows:

$NO_2 + UV \Rightarrow NO + O^{\cdot}$

$O^{\cdot} + O_2 \Rightarrow O_3$

$NO + O_3 \Rightarrow NO_2 + O_2$

The reactions to generate and remove O_3 by NO_2 and NO are very rapid and equilibrium is eventually reached thus:

$$\text{Generation of } O_3 = \frac{\text{rate constant } F_l \text{ for } NO_2}{\text{rate constant } K_3 \text{ for } NO}$$

F_l and K_3 are the rate constants for NO_2 photolysis and the O_3 removal reaction respectively. This is termed the photostationary state. The concentration of O_3 is determined by the value of F_l and NO_2/NO and is highest at peak sunlight intensity [39].

Stratospheric Ozone Depletion Potentials

Values are given for a range of common organic compounds containing chlorine or bromine, which are efficient destroyers of stratospheric ozone once released into the atmosphere. Chloroflurocarbon 11 ($CFCl_3$) is the reference substance and has been assigned a value of 1. Values for other substances are relative to CFC11 ($CFCl_3$).

Equivalency Factors (EF) for Acidification

Values are given for a range of substances, which, can lead to acidification once released into the atmosphere. Sulphur dioxide (SO_2) is the reference substance, which is assigned a value of 1. Values for other substances are relative to SO_2.

Equivalency Factors (EF) for Nutrification

Various values are given for nitrogen and phosphate substances, which can cause eutrophication of water bodies.

3.4.1 Impact Categories

The current impact categories that are used in LCA are given in **Table 3-2**. A brief discussion of each of these categories is given in the following sections.

3.4.1.1 Global Warming

Some human activities have had such a dramatic effect on nature that the impact is influencing all parts of the earth and may thus be regarded as global. Global warming is a widely known phenomenon for which there is now a consensus of scientific opinion that believes the temperature of the planet is being artificially increased.

The climate may show large natural variations, and it can therefore be difficult to identify the extent of man-made contributions. Nevertheless, it is estimated that since the Industrial Revolution (circa. 1850), global warming has caused measurable changes in the climate. The global average temperature has increased by over 0.5°C since 1850 [40].

Global warming is caused by the release of certain gases to the atmosphere that retain heat radiation, which would otherwise be lost from the earth into space. High frequency solar radiation, including infrared and visible light, that reaches the earth's surface is absorbed and re-radiated at lower infrared frequencies. It is this energy that is absorbed in the atmosphere and mostly re-radiated back to earth. This process regulates the temperature of the earth's surface, without which the temperature would be much lower and the diurnal fluctuations huge. Climate scientists now believe that the additional release of "greenhouse gases", predominantly CO_2, by man is artificially increasing global temperatures. These gases increase the efficiency of the insulating blanket of atmospheric gas that regulates the earth's temperature, causing an enhanced greenhouse effect, whereby reflected radiating heat from the earth is trapped and prevented from escaping to outer space.

The atmospheric content of these insulating gases has increased significantly over the last 100 years, especially since the Second World War. Most of the increase is attributable to the combustion of fossil fuels, oil, coal and natural gas. Burning fossil fuel for electricity generation releases tonnes of greenhouse gases principally carbon dioxide (CO_2), which has a high residency time (approx. 100 years) and is used as the reference gas for comparing warming potentials of all other potential greenhouse gases.

The effects and consequences of global warming have already started to manifest themselves. As sea temperatures rise sensitive coral reefs suffer from an effect known as bleaching where the coral dies, sometimes permanently. Major ocean currents melt and dislodge icebergs diverting warm currents and causing local climate changes. Melting glaciers, polar ice caps and rising sea levels lead to alterations in the conditions of life for man and ecosystems at a speed, which will render gradual adaptation impossible. Industrialisation of the Third World could increase future emissions of CO_2 and other greenhouse gases dramatically.

3.4.1.2 Stratospheric Ozone Depletion

The gas ozone (O_3) in the stratosphere provides a thin protective layer preventing excessive ultraviolet (UV) radiation from reaching the earth's surface. The gas is constantly being formed and broken down by the action of radiation from the sun and was formally in balance at an altitude of 15-40 km above the earth's surface. The breakdown however has been accelerated by man-made emissions of halocarbons, i.e. organic compounds containing chlorine or bromine, and which are sufficiently long-lived to break through the upper atmosphere and into the stratosphere. Oxygen molecules in the stratosphere split apart, to produce atomic oxygen (O). These free atoms combine with the available molecular oxygen to create triatomic oxygen (ozone). This reaction is reversible, and the ozone molecule may break down again into its original components as a result of further absorption of UV radiation. Ozone molecules are also broken down in chemical reactions with various compounds containing nitrogen, hydrogen and chlorine, all of which occur naturally in the atmosphere. Although present in only small quantities, they become efficient ozone destroyers as a result of their ability to initiate catalytic chain reactions.

The Montreal Protocol 1987 [41] set up the framework for phasing out the use of chemicals that are known to cause destruction of the stratospheric ozone layer. Chlorofluorocarbons (CFCs) and related hydrobromofluorocarbons (HBFCs) and halons have made a major contribution to ozone depletion. These chemicals have been used as propellants and as refrigerant media and are inert and chemically very stable. This stability ultimately allowed them to accumulate in the atmosphere gradually diffusing into the stratosphere where the photochemical action of UV radiation breaks them down to release free chlorine (Cl) into the ozone layer. Catalytic chain reactions initiated by the free chlorine then begin the process of depleting the ozone layer.

The reduced ozone level in the stratosphere means a higher intensity of UV in the sunlight reaching the surface of the earth leading to a higher frequency of skin cancers and cataracts as well as contributing to reduced immune defence efficiency in animals and humans.

3.4.1.3 Fossil Reserve Depletion

Many of the resources upon which the material world is based are regenerated so slowly that they can be considered as finite. They can be regarded as capital that does not earn interest. By burning fossil fuels including oil, coal and gas the reserves of these materials for use by future generations are being reduced. Based on current projections, if these non-renewable reserves continue to be exploited at the current rate, they will be completely depleted in a few decades [43]. The continued industrialisation of the Third World and rising material standards places greater demand on these finite resources which will lead, in turn, to international tensions with the possibility of armed conflict fighting for the remaining reserves. The western world is dependent upon large quantities of oil for its economy and this has been at the root of several instances of conflict most recently the Gulf War in 1991.

To counter the concerns over the loss of this valuable resource large parts of the western world are adopting initiatives to prevent over-reliance on fossil fuels. These initiatives include:

- use of renewable energy sources, solar, wind and hydro-electric;
- more recycling of materials that would otherwise have been lost to landfill or incineration;
- increased use of nuclear power;
- improved insulation of buildings to prevent unnecessary heat loss.

3.4.1.4 Photochemical Smog Formation

When solvents and other volatile organic compounds are released into the atmosphere, they are often degraded within a few days. The reaction involved is oxidation, which occurs under the action of UV light from the sun. In the presence of oxides of nitrogen (NO_2 and N_2O), ozone (O_3) can be formed. The oxides of nitrogen are not consumed during ozone formation, but have a catalyst-like function.

This process is termed photochemical ozone formation and leads to the generation of smog that pollutes air within the troposphere. The ozone generated has a half-life of a few days and thus cannot rise to the stratosphere to counteract ozone depletion.

Ozone attacks organic compounds in plants and animals or materials exposed to air. Ozone acts as an irritant to humans and leads to an increased frequency of problems in the respiratory tract in humans during periods of photochemical smog in cities.

Photochemical smog is an impact, which affects the environment on both a local and regional scale.

3.4.1.5 Acidification

When acids, or compounds which can be converted to acids, are released to the atmosphere and deposited in soil or water bodies, the addition of hydrogen ions may eventually result in a decrease in pH, increasing acidity.

The consequences from increased acidity can have a detrimental effect on forests leading to a loss of habitat, result in increased mortality of fish species and accelerate corrosion of metals and building materials.

Acidification can be caused by emissions released into air, water and onto land.

3.4.1.6 Nutrification

Nutrient enrichment is an impact on ecosystems from substances containing nitrogen or phosphorus. The availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if added, growth of algae or plants will be increased. One definition is that nutrient enrichment of waters results in the stimulation of an array of symptomatic changes, among which an increased production of algae and deterioration of water quality causing an interference with water use. The effects of nutrification include unpleasant tastes and smells which are difficult to treat, decreased fish diversity, lowering catch rates (fish unable to see the bait in turbid algae rich water), damage to fish spawning areas and making fish taste unpleasant. Contact water sports put the users at risk if they get into blue-green scums, aesthetic value is lost and farmers may lose livestock if animals drink blue-green scums. In warm climates water hyacinth may cover the entire surface of a lake and impede navigation of rivers.

On land ecosystems naturally poor in nutrients including raised bogs, commons and heathlands are gradually disappearing as a result of the excessive addition of nitrogen.

The use of fertilisers in agriculture is usually blamed for emission of nitrogen into the aquatic environment but oxides of nitrogen from combustion processes are also a significant source for both aquatic and terrestrial ecosystems. Leaching of phosphorus from agricultural land and phosphorus in urban and industrial effluents are the most significant sources of phosphorus emissions [43].

For a compound to be regarded as contributing to nutrification it must contain nitrogen or phosphorus in a form, which is biologically available. Free nitrogen is not regarded as contributing to nutrient enrichment, because it does not have any additional fertilising effect. The greater part of the atmosphere is made up from nitrogen (approximately 70%).

3.4.1.7 Ecotoxicity

Chemicals released to the environment as a result of human activity contribute to ecotoxicity if they affect the function and structure of ecosystems by exerting toxic effects on the organisms, which live within soil, habitation or aquatic environments. If the concentrations are high enough, the toxic effects can occur as soon as the substance is released. This is known as acute toxicity, often resulting in death of the organism exposed. Toxic effects that manifest themselves after repeated long-term exposure, are known as chronic ecotoxicity. Substances often cause chronic ecotoxicity which have a low degradability in the environment and which therefore remain for a long time after being released. Some substances also tend to accumulate in the living tissue of organisms, so those organs can be exposed to substances at concentrations far greater than the surrounding environment. Toxicity, biodegradability and bioaccumulation in living organisms therefore determine chronic ecotoxicity. The consequences of ecotoxicity include reduced reproductive capacity and eventual loss of species. This impact is typified by the problems of widespread use of pesticides from the 1940s, which led to the loss of bird life.

Ecotoxic impacts can involve many different mechanisms, with the common feature that they all result in direct toxic impacts on ecosystems.

3.4.1.8 Human Toxicity

As with ecotoxicity chemicals released to the environment can contribute to human toxicity via exposure pathways in nature. The most important exposure pathways are via inhalation or ingestion. The types of toxicity can be either acute or chronic. As with ecotoxicity, a substance's bio-degradability and bioaccumulation in human tissue, contribute to chronic human toxicity.

3.4.1.9 Landfill Volume / Waste Generation

The creation of waste is one of the most important environmental impacts, which has been steadily increasing with population growth, affluence and consumerism. Most domestic waste in the UK is consigned to landfill sites for shallow burial. This is a major impact itself resulting in the loss of land for many years during the filling of the site and restricted use after reinstatement. The waste is left to biodegrade over many years posing a threat to local groundwaters. The degradation of the waste also generates landfill gas (methane), which has to be burnt off or collected to power gas turbines for power generation. Landfill operations also generate lechate, a cocktail of chemical effluents that must be carefully managed to prevent pollution to surrounding aquatic environments. The number of sites available for landfilling are diminishing and there is a greater focus on recycling or incineration using combined heat and power (CHP) plants to generate power.

Waste from industrial processes falls into several categories:

- Domestic office waste suitable for landfill or incineration;
- Trade waste requiring pre-treatment prior to landfill or incineration;
- Sludge from sewage treatment works requiring landfill or incineration;
- Incineration ash requiring landfill;
- Special waste requiring characterisation, segregation and disposal to a specially designated and licensed landfill site;
- Inert construction waste from building and demolition works;

- Radioactive waste requiring special treatment, packaging and storage prior to burial in a specially designed geological repository.

The consequences of waste generation are varied but ultimately pose a threat to air quality, river and ground water quality, human and animal health and the loss of materials that could otherwise be recycled or reused.

Contributions to the environmental aspects used in the AWE EMS generate a variety of environmental impacts, the following section identifies appropriate impact categories.

3.4.2 Aspects and Environmental Impact Categories

Contributions to the environmental aspects will result in a contribution to one or more environmental impact categories. **Table 3-11** shows the links between various aspects and impact categories, which, will subsequently be used to represent the magnitude of the impact.

Table 3-11 Environmental Impact Categories for AWE Aspects

AWE ASPECTS	ENVIRONMENTAL IMPACT CATEGORIES
Releases to Air – R/A	R/A dose to humans, ***undefined impacts to the environment***
Releases to Air – Acids	Acidification, human toxicity and eco-toxicity
Releases to Air – VOCs	Ozone creation, global warming, human toxicity and eco-toxicity
Releases to Air – ODSs	Stratospheric ozone depletion, global warming, human and eco toxicity
Releases to Air – Be	Human and eco-toxicity
Releases to Air – Pb	Human and eco-toxicity
Releases to Air – Combustion by products	Global warming, acidification, human and eco-toxicity
Releases to Water – R/A Effluent	R/A dose to humans, ***undefined impacts to the environment***
Releases to Water – Trade Effluent	Human and eco-toxicity and nutrification
Releases to Water – Domestic Effluent	Potential human and eco-toxicity, odour and nutrification from treatment works
Releases of Waste – R/A	R/A dose to humans, ***undefined impacts to the environment***, landfill volume.
Releases of Waste – Trade Waste	Human and eco-toxicity, landfill volume
Releases of Waste – Domestic	Human and eco-toxicity, landfill volume
Resource Use - Electricity	Global warming, acidification, human and eco-toxicity
Resource Use – Gas	Global warming, acidification, human and eco-toxicity
Resource Use –Water on Site	Valuable resource depletion, disruption to ecosystems
Resource Use – Water off Site	Valuable resource depletion, disruption to ecosystems
Resource Use – Chemical/Oil Storage and Use	Human and eco-toxicity from exposure
Resource Use – R/A Use and Storage	R/A dose to humans, ***undefined impacts to the environment***
Resource Use – Other	Human and eco-toxicity from material manufacturing processes

NB The undefined impacts on the environment category are developed as part of the work described in this thesis.

3.5 IDENTIFICATION OF EXISTING ENVIRONMENTAL BURDENS

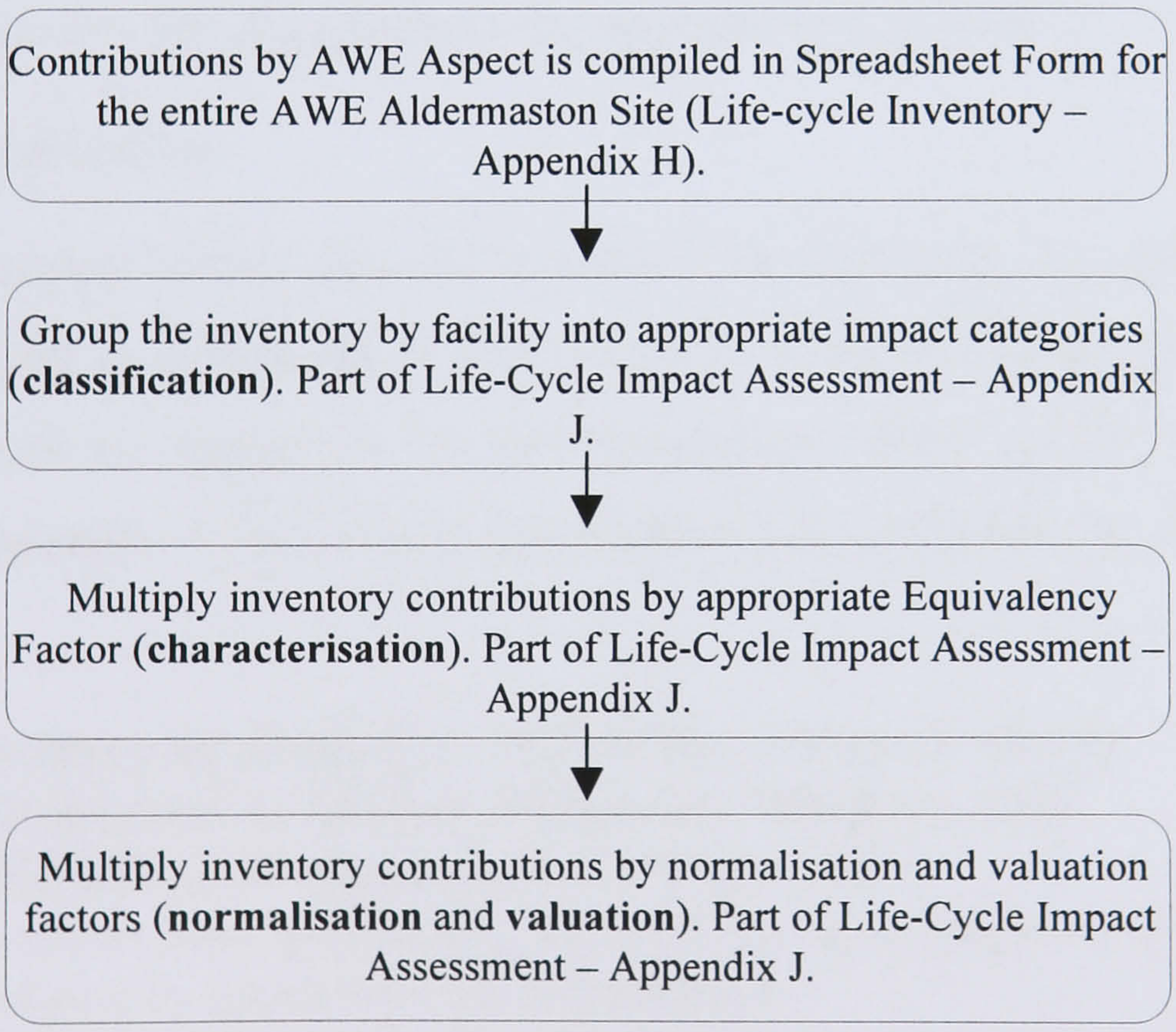
The contributions from each facility at AWE made to individual environmental aspects have been compiled as an inventory of burdens in **Appendix H.** The inventory is a key stage in LCA and forms the base data from which the impact is calculated.

The data have been taken from FREAs for each of the facilities considered in this study. Quantitative data have been extracted from the FREA and transferred into spreadsheet format to facilitate mathematical manipulation (**Appendix H**). The source of the data is given in the spreadsheet, which indicates whether the data are measured, calculated using proven assessments or an estimate. It should be noted that the inventory represents the use phase in LCA for one year's operation at AWE Aldermaston. A separate section has been devoted to transport activities at Aldermaston (see Section 3.8).

3.6 DETERMINATION OF ENVIRONMENTAL IMPACTS

In this section the data, compiled and recorded in **Appendix H**, on environmental contributions are used to calculate environmental impacts compatible with the LCA framework. This process involves four key steps (Section 3.3.2) and each of these is discussed in more detail in terms of the processes involved and outputs derived from each step. A flow chart is presented in Figure 3-2, illustrating the process.

Figure 3-2 LCIA Flow-chart



Contributions by AWE Aspect is compiled in Spreadsheet Form for the entire AWE Aldermaston Site (Life-cycle Inventory – Appendix H).

Group the inventory by facility into appropriate impact categories (**classification**). Part of Life-Cycle Impact Assessment – Appendix J.

Multiply inventory contributions by appropriate Equivalency Factor (**characterisation**). Part of Life-Cycle Impact Assessment – Appendix J.

Multiply inventory contributions by normalisation and valuation factors (**normalisation** and **valuation**). Part of Life-Cycle Impact Assessment – Appendix J.

3.6.1 Inventory Compilation

All contributions are compiled as an entire inventory of data in **Appendix H**. Data is presented for each of the environmental aspects in the AWE EMS, and is built up from a series of linked spreadsheets.

3.6.2 Classification and Characterisation

Table 3-11 has already grouped AWE aspects into possible impact categories. The inventory is now broken down and grouped according to appropriate impact categories (classification) so that subsequent multiplication by various factors, (characterisation, normalisation and valuation), can be performed. Characterisation is the process after classification where releases are scored according to their damage potential. The method for calculating an impact is based on the multiplication of the mass released by an equivalency factor or impact potential. For this study some relevant factors are recorded in the indices in **Appendix G**. Data from the inventory is grouped onto spreadsheets as a matrix of aspect contributions by environmental impact categories for each individual AWE facility. Multiplication of the contribution (mass) by the equivalency factor (EF) is performed and recorded in **Appendix J**.

3.6.3 Normalisation

The normalisation factors that are calculated for this study are presented for each impact category in **Appendix I**. The results of the calculations are summarised in **Table 3-3**, and are applied to the characterisation values and shown in the results given in **Appendix J**. Individual spreadsheets are given for the following impact categories:

- ***Environmental Irradiation (radioactive releases to water);***
- ***Environmental Irradiation (radioactive releases to air)***;
- ***Special Landfill/Radioactive Waste Generation***;
- Radioactive Dose to Humans (not used for impact assessment in this thesis but reproduced in Appendix I for information);
- Global Warming/Climate Change;
- Stratospheric Ozone Depletion;
- Photochemical Smog Formation;
- Acidification;
- Nutrification (it is not possible to calculate with any reliability AWE Aldermaston's contribution to Phosphate and Nitrate discharge and therefore a default factor of 1 is used);

- Ecotoxicity (it is not possible to calculate with any reliability AWE Aldermaston's contribution to ecotoxicity and therefore a default factor of 1 is used);
- Human Toxicity (it is not possible to calculate with any reliability AWE Aldermaston's contribution to human toxicity and therefore a default factor of 1 is used);
- Domestic Waste;
- Toxic/Special Waste;
- Fossil Reserve Depletion.

The normalisation factors for impact categories shown in italics above are new categories and the author has selected England and Wales as the spatial parameter to calculate the factor. The methodology applied to calculate the normalisation factor is described in Section 3.3.2.

3.6.4 Valuation

Valuation is the final step in the LCIA framework and the numerical values that are developed for application in this study, and described and presented in Section 3.3.4.3, are applied to the characterisation results after normalisation. The results of the valuation process are given in **Appendix J**.

By way of illustration an example of the life-cycle impact assessment process for the A1 facility for the impact of global warming is presented in **Table 3-12**.

Table 3-12 Example of LCIA Process for Global Warming for A1

	Releases to Air – ODS (kg)	**Other Releases and Resource Use etc.**	**Total Impact By Category**	**Normalisation Factor (person equivalents)**	**Normalised Impact for Facility**	**Valuation Factor**	**Total Weighted Impact for Facility**
Annual Contribution	0.01	…					
Chemical Species	CF_2Cl_2	…					
Chemical Name	Dichloro-difluoromethane	….					
Global Warming Potential (EF) (relative to CO_2)	8.5E+4	…					
GWP Impact (kg of CO_2 equivalent)	**6.97E+2**	**…**	**1.1 E+6**	**1.66 E+1**	**1.83 E+7**	**3**	**5.5 E+7**

3.7 IDENTIFICATION OF CONTRIBUTIONS THAT REQUIRE NEW IMPACT CATEGORIES

3.7.1 Development of Methodology for Company Specific Aspects

In this section the development of a methodology to allow company-specific aspects to be included in the Life-cycle Impact Assessment, is discussed. For the radioactive aspects there is at present no recognised impact category (**Table 3-11**) apart from radiation dose to humans. In this thesis the following new impact categories are proposed:

- Environmental Irradiation from R/A Releases to Water
- Environmental Irradiation from R/A Releases to Air
- Special Landfill for R/A Waste

Radiation dose to humans is a recognised method for assessing the health effects from radioactive discharges, although protection of humans will not always ensure protection of the environment as a whole [42]. Man has traditionally been used as the indicator species to measure environmental damage from radioactive releases. The choice of man as a representative species is based on the fact that humans are among the most radiosensitive mammalian species [42] and, are central to the concept of sustainable development.

In terms of global environmental impacts, releases of substances concerned share the following characteristics [43]:

- Long life in the environment, leading to wide dispersal before the substances are degraded or immobilised.
- High mobility in the environment, leading to transport to all parts of the global environment, including those parts, which are sensitive to the substance's impacts.

The substances are often emitted in such large quantities that the effects can be felt globally, even if the substances are greatly diluted on dispersal.

Until quite recently the approach to many disposal problems was to allow material to dilute and disperse into the environment. This approach is only acceptable when the receiving media can cope with pollution loading without any deleterious effects.

Different media however, have varying levels of tolerance and surprising effects can be the result:

- Limited loading before soil reaches its maximum toxic chemical adsorption capacity;
- Tidal effects on the dumping of raw sewage at sea;
- Ability of sea water to concentrate some pollutants;
- Persistency of some very damaging materials in leachate from dilute and disperse landfill sites that can eventually pollute groundwaters;
- Unpredictable behaviour of radionuclides dumped in the sea and in freshwater environments.

Owing to these problems and greater awareness and understanding of environmental issues these practices of dumping of chemicals and waste are in decline. The emphasis has shifted therefore towards replacement of chemical substances with environmentally friendly alternatives, immobilisation and containment of hazardous materials until degradation has taken place.

The characteristics that make substances a problem in the environment are however, also very good indicators of actual environmental impact. For example poly-chlorinated Biphenyl (PCB) is an electrical insulator, which displays both persistency and mobility characteristics. It is not just the toxicity of PCBs, which causes environmental harm, but its persistence in the environment resulting from a very slow degradation process. It is clear that similar characteristics need to be defined as criteria in helping to determine a radioactive substance's environmental impact.

Determining the predicted environmental concentration and comparing it to values for Environmental Quality Standards (EQS) or Environmental Assessment Levels (EAL) provides an indication of damage to the environment. The EQS is derived from a broad consideration of 'harm to the environment' rather than simply human health [44]. In this context harm is defined as [45]:

"Harm to the health of living organisms or interference with the ecological systems of which they form a part and, in the case of man, includes offence to any of his senses or harm to his property".

There are at present no agreed standards for individual radionuclides in the environment. Although the UK Environment Agency recognises that an EQS for radionuclides would be very useful it has not yet defined any values. This is due to the fact that the behaviour and interaction of radioactive material in the environment is a complex process. At present discharges are monitored and controlled on the basis of how radionuclides could result in exposure to members of the public [11]. The National Radiological Protection Board (NRPB) has defined Generalised Defined Limits (GDL) for some key radioisotopes [11]. These limits provide a guide to the levels, which would result in an annual effective dose limit of 1mSv, to critical human groups, from anthropogenic sources. The World Health Organisation (WHO) has set guideline values for potable water of 0.1Bql^{-1} for gross alpha and 1.0Bql^{-1} for gross beta from all sources, natural and anthropogenic. These values however, are conservative estimates for concentrations in drinking water to avoid any health detriment to humans and are not ideally suited as an indicator of environmental impact.

As part of this work, it is proposed suitable Equivalency Factors be developed to allow for the inclusion of the R/A aspects within the LCIA framework. Literature on the behaviour of radionuclides in the environment has been reviewed and a discussion on specific radionuclides discharged on a routine basis from AWE is given. From this review a more specific assessment of appropriate case studies is carried out in order to identify the important criteria that influence environmental impact. The approach is designed to determine Equivalency Factors for specific AWE radionuclides released into water and air. These Equivalency Factors do not define standards for environmental quality but can be used to determine environmental impact that is compatible with the LCIA framework. Establishing equivalency between various radioactive environmental interventions will allow for aggregation into common units for a meaningful comparison.

3.7.2 Literature Review on the Impact of Radionuclides in the Environment

A description is given in this section of the findings of a literature review into the impacts of radioactivity in the environment under the following headings:

- General discussion of radionuclides and the environment;

- Radioecology of Isotopes Released from AWE;
- Radiation chemistry of water;
- Radiation chemistry of air.

The purpose of the literature review is to determine the behaviour of radionuclides in the environment and to identify factors and criteria that determine environmental damage.

3.7.2.1 Radionuclides in the Environment

Radiation is a natural feature of man's environment, from high-energy charged particles, which make up cosmic radiation to the radioactive decay of radionuclides in the earth's crust and in the biosphere. The transfer and physical impact of radioactivity on the environment are also discussed.

The penetration of different types of radiation is summarised in the table below:

Table 3-13 Different Types of Radiation

Type	Symbol	Particle	Stopped by
Alpha	α	Helium – 4 nucleus (heavy, positive charge).	A few cm of air, or 40 μm tissue.
Beta	β	Electron (light negative charge).	A few mm of plastic.
Gamma	γ	Photon (electromagnetic radiation).	Progressive attenuation by heavy nuclei - 40-mm lead reduces to 1/10.
X – rays	X	High-energy short-wave electromagnetic radiation.	Progressive attenuation by heavy nuclei - 40-mm lead reduces to 1/10.
Neutrons	n	Neutron (Heavy, uncharged).	Progressive attenuation by light nuclei - 250 mm of water reduces to 1/10.

Radioactivity can decay to stable non-radioactive isotopes in one of four different ways:

- **Alpha decay.** The excess energy is lost by emission of an alpha particle which consists of 2 neutrons and 2 protons and is the nucleus of a helium atom;
- **Beta decay.** This is a weak interaction in which an unstable atomic nucleus changes involving the conversion of a neutron into a proton with the emission of an electron and an electron antineutrino, or of a proton into a neutron with the

emission of a positron and an electron neutrino [46]. These emissions are called beta particles.

- **Gamma decay.** Gamma radiation is electromagnetic waves emitted by excited atomic nuclei during the process of passing to lower excitation state. Gamma radiation ranges in energy from about 10 keV to 10 MeV corresponding to a wavelength range of about 10^{-10} to 10^{-14} metre [46].
- **X-rays.** These are electromagnetic radiation similar to gamma rays with a shorter wavelength than ultraviolet radiation. They are produced naturally when high-energy particles such as electrons collide with other particles or atoms.

Radionuclides in the environment have been extensively studied since the detonations at Nagasaki and Hiroshima in 1945, and from the atmospheric tests and nuclear accidents that have occurred since then. From research [70] it is known that only a few Curies ($1 \text{ Ci} = 3.7 \times 10^{10}$ Bq) of radioisotopes per km^2 are required to render land unsuitable for cultivation under current radiation safety standards [70].

The entire ecosystem on earth is irradiated by natural and artificial radionuclides. Thus radioactivity is distributed heterogeneously all over earth and moves from one component to another, from a plant or animal species to another and is transported by fluids. Understanding environmental damage and environmental transfer is the objective of radioecology - the study of the impact of radiation on the environment. In particular, radioecology contributes to the study of the movements of air, surface water and underground water, as well as the transfer of radioactive and stable elements in soil, plants and animals, and the food chain.

Research into contamination of components in the aquatic ecosystem (sediments, plants, water, fish, etc.) have concentrated on the study of fixing mechanisms of radionuclides in bryophytes, such as mosses which are good bio-indicators of radioactive contamination [47]. Studies of sediments and particles suspended in water are based on observations of their contamination. Radionuclides are accumulated by sedimentation and by absorption on suspended matter and a balance is generally established between water and sediment. When radioactivity in water decreases, sediment releases a part of the fixed radioactivity.

Radio-sensitivity of Plant and Animal Species

The lethal dose, (LD_{50}, the dose resulting in 50% mortality), of plant species varies from 10 to 1000 Gy. The most radio-resistant plants are mosses, lichens and unicellular species. The most radiosensitive are woody species and forests, whose LD_{50} varies between 10 and 200 Gy. The resinous woody species (pine trees) are especially radiosensitive. The radio-sensitivity of crops is expressed as reduction of yields (YD_{50} is the dose causing a 50% reduction in expected yield). The radio-sensitivity values of various important crops are given in the tabulation below [47]:

Table 3-14 Radio-sensitivity of Crops

Crop	YD_{50} (Gy)
Cereals	5 - 50
Rice	140
Leafy vegetables	2 - 60
Root vegetables	5 - 100
Herbs and pastures	150 - 200

Unfavourable growing conditions, such as moisture deficiency, can increase radio-sensitivity by a factor of 4. The radio-sensitivity of a plant increases with age. Irradiation of tissue and moisture deficiency increases the stress on a plant, which can induce desiccation and possibly death. Stress can be detected early by studying the enzyme systems.

Trees are very radiosensitive. This radio-sensitivity is stronger in autumn than in spring - the period of growth. Below the LD_{50} (50 - 200 Gy), trees have difficulties in reproduction and there is a reduction in photosynthesis. Morphological anomalies are observed in chronic irradiations (1 $mGyh^{-1}$) over several years.

Metabolic modifications in herbs (diminution of growth, disappearance of the more sensitive species) for dose rates between 1 and 10 $mGyh^{-1}$ are observed. The same kind of metabolic modifications are observed in lichen at 1 Gyh^{-1} dose rate.

The LD_{50} for a variety of mammals, birds, reptiles, fish and other species is given below [47].

Table 3-15 Lethal (LD_{50}) Radiation Doses

Animal	**LD_{50} (Gy)**
Small mammal	6 – 16
Large mammal	1.5 - 2.5
Birds	10
Reptiles and amphibians	2 – 22
Invertebrate	600
Young invertebrate	100
Invertebrate larvae	20
Fishes	10 – 100
Fish larvae and embryos	0.1

Lethal doses of radiation required to give other species a lethal dose within 30 days are given below [48].

Table 3-16 Lethal (LD_{50}) Radiation Doses Within 30 days of Exposure

Species	**LD_{50} (Sv)**
Pig	2
Man	2.5
Mouse	6.5
Gerbil	10
Snail	100
Fruit fly	600

Table 3-16 shows that man compared with other species has an LD_{50} close to that of a pig. These doses also add credence to the view that protection of man automatically assumes protection of other species. This view is being challenged however and it is envisaged that protection of the environment as a whole, (and therefore man), will be the focus of future assessments [83].

Experiences from Major Nuclear Accidents

Extensive research has been carried out into radioecology following nuclear accidents. The main damage resulting from release at Kyshtym in 1957 and Chernobyl in 1986 was to forests. The extent of the dose and the observed effects ar Kyshtym is given in **Table 3-17**. The dose delivered to forests during the summer and autumn following the accident was estimated at about 40 Gy.

Table 3-17 Effects of Radiation on Forests [47]

Dose (Gy)	Observed Effects
200	50 % death of Birch trees.
> 50	Delayed budding amongst Birch trees.
> 20	Death of pine trees.
> 5	• Desiccation; • Loss of needles; • Absence of new shoots; • Reduction in the size of cones; • Reduction in the quantity of seeds.

Recovery of the forest was normal in areas that were contaminated at levels below 100 $MBqm^{-2}$. Most cattle exposed to doses in excess of 50 Gy were killed within 10 days of the accident. Fish stocks did not show any deleterious effect from being exposed at $mGyh^{-1}$ doses. Flora and fauna have been shown to generally exhibit strong radio-resistance.

3.7.2.2 Radioecology of Isotopes Released from AWE

This section discusses the specific behaviour of radioisotopes that are released from AWE into the environment, and how they interact with soil, plants, animals and aquatic environments. The various pathways to humans are discussed and an evaluation of general environmental significance is made. The objective is to identify what parameters should be considered to determine environmental significance and impact.

Processes that Generate and Lead to the Release of Radioactive Isotopes from AWE

Processes at AWE routinely encounter and use all types of radiation. Alpha and beta contamination mainly comprise of ^{239}Pu, and ^{3}H respectively, gamma radiations arise from the decay of induced radiation from reactor operations (^{60}Co) and neutrons are encountered during the running of AWEs experimental reactor's when the nuclear fuel releases enough neutrons to sustain a chain reaction to generate energy (criticality). Neutrons are emitted from the nucleus of a heavy atom when it splits apart due to the impact from another neutron. When a neutron strikes the U^{235} or ^{239}Pu nucleus, it produces fission fragments, free neutrons and heat energy. The released neutrons may then strike another heavy atom, releasing more neutrons, fission fragments and heat energy. The process continues and a chain reaction develops (criticality), ^{235}U spontaneously emits neutrons (fissile) as does ^{239}Pu. The speed of these neutrons has to be slowed down using a moderator, (water or graphite), to ensure that a chain reaction develops and the process continues. Thermal energy is used to heat up the water to produce steam to make electricity. Experimental nuclear reactor operations at AWE also result in the discharge of ^{85}Kr. ^{137}Cs is a fission product arising from experimental nuclear reactor operations. X-rays are used in experimental equipment to test the radiation tolerance of materials and components and during radiography to reveal defects in materials. X-rays also accompany some radioactive emissions (i.e. the alpha decay from ^{239}Pu).

Plutonium – 239. Plutonium is a member of the actinide series of elements. The actinide elements have similar chemical properties to the rare earth (lanthanide) elements. The actinides are considered a second rare earth series. Elements beyond uranium (atomic number 92) in the periodic tables are called transuranic elements. Plutonium has an atomic number of 94 and occurs naturally only in very small quantities. It is formed continuously in uranium ores by neutron capture, the neutrons being produced by the spontaneous fission of uranium. The uppermost layers of the earth's crust contain only a few kilograms of ^{239}Pu. Plutonium naturally occurring can only be detected in the richest uranium ore. The most important of the 15 plutonium isotopes is ^{239}Pu, which has a half-life of 24065 years and is produced from uranium in nuclear reactors.

Plutonium can exist in four valence states in aqueous solutions: III, IV, V and VI [49]. The IV State is the most common under physiological conditions where it will exist in solution only as a strongly complexed ion. Weak complexes of Pu (IV) in neutral solutions will form polymeric hydroxides. Plutonium oxides rapidly and, thus, the very insoluble PuO_2 is the most common form in the environment, although Pu (VI) has been reported in oceans [50] and drinking water [51]. Some plutonium will be complexed with biological ligands and incorporated in micro-organisms or in plant or animal tissues.

Plutonium-239 (the form of plutonium most commonly used at AWE) emits alpha radiation. Since the X-rays accompanying the alpha emissions are low energy, concentration of these isotopes that might occur in the environment would not cause biological effects unless they are incorporated into biological material. Deposition in the lungs and absorption from the gastro-intestinal tract following ingestion are the most important routes of entry into the bodies of animals and human beings.

Table 3-18 summarises the properties of ^{239}Pu.

Table 3-18 Properties of Plutonium - 239

Parameter	**Value**
Half-life (years)	24065
Energy (MeV)	5.24
Principal decay mode	Alpha
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	300
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	4 E4
Specific activity (Bqg^{-1})	2.3 E9

When plutonium enters soil it is usually insoluble, regardless of soil type [52]. Diffusion coefficients for surface soils [53] are universally low (10^{-7} cm^{2}s^{-1}). Therefore the majority of it remains in the top layer of soil even with water percolation [54]. Less than 0.1% of plutonium in soil is soluble accounting for limited plant uptake and chemical mobility. Very strong acids are required to dissolve plutonium metal [55].

Physical processes account for some vertical movement in soil. Cultivation results in redistribution within the plow layer (30 cm) and long-term field studies have traced plutonium migration to 30 cm in undisturbed arid soil [56]. In the latter case, the increased mobility over that predicted by diffusion alone has been attributed to biological transport and particle movement.

Since plutonium is strongly absorbed on surface soils, wind and water erosion become primary environmental transport mechanisms [52]. Dispersion will be a function of particle size of the substrate with which plutonium is associated. Particles in the fine silt-clay size range are the most likely to contain the highest concentrations of plutonium, to be transported the greatest distance by wind and water, and to remain attached to biological surfaces.

Transport to vegetation is by foliar interception and root uptake. Foliar uptake is dependent upon chemical form and size of the particle intercepted, residence time and weathering reactions of the leaf. Soil-to-plant concentration ratio varies from 10^{-3} to 10^{-8}. Solubility in soil (< 0.1%), rather than discrimination at the plant root level, is the limiting factor in plant uptake [57]. Plutonium is not uniformly distributed in the plant.

The primary sources of plutonium to animals are through inhalation and consumption of plant tissues containing plutonium in surface absorbed particles or tissues. In grazing herbivores, plutonium is primarily associated with the gastro-intestinal tract and pelt, and to a lesser degree, with the lungs [52]. The fraction of ingested amount absorbed and deposited in the bone and liver is approximately 10^{-4}.

The transfer of plutonium to diet from fallout has been studied. The highest concentrations were found in shellfish, with progressively lower levels found in grain products, fresh fruits and vegetables. The lowest concentrations were in meat, milk, eggs, fresh fish and processed foods. The values indicate that external contamination is a factor in the occurrence of plutonium in foods. The cumulative transfer of plutonium to diet depends very much on residence times in soil. Based on the mean residence time of 50 years transfer factors from deposition density to diet give between 0.2 and 0.6 Bqm^{-2} for ^{239}Pu.

Plutonium is mobilised off watersheds to rivers and coastal waters and has a residence time of 10^3 to 10^4 years [52]. Environmental studies indicate that 96% of plutonium released to water is rapidly transferred to sediments [58]. Higher concentrations of plutonium are observed in lakes with a low pH, high sulphate content. A relationship exists between the concentration of plutonium in water and the concentration in sediments or particulate matter. The concentration of plutonium in many freshwater lakes and rivers is controlled by the equilibrium between water and sediment. The distribution constant, (K_D), varies between 10^4 and 10^5.

Plutonium concentration factors for organisms relative to water generally decrease at higher trophic levels. Typical values are [59]:

- 10 for fish;
- 100 for crustacea;
- 1000 for molluscs and algae.

Extensive research on the pathways of transfer to man indicate that intake by inhalation is the dominant route. Ingestion was shown to be insignificant relative to inhalation. Once inside the body plutonium is tenaciously retained. This is borne out by studies on excretion from humans. Based on research the biological half-life of plutonium in the skeleton is 100 years and 40 years for the liver.

Americium – 241. ^{241}Am is a man made radioactive metal. It is a silver white, crystalline metal that is solid under normal conditions. ^{241}Am primarily emits alpha particles, as well as gamma rays. ^{241}Am is daughter product from the decay of Plutonium 241. ^{241}Am is not used at AWE but occurs as a result of ^{241}Pu decay and leads to gamma in-growth whereby the dose from gamma radiation increases with time. **Table 3-19** summarises the properties of ^{241}Am.

Table 3-19 Properties of Americium - 241

Parameter	**Value**
Half-life (years)	432.2
Energy (MeV)	5.637
Principal decay mode	Alpha plus Gamma
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	300
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	3 E4
Specific activity (Bqg^{-1})	1.27 E11

Once inside the body, ^{241}Am tends to concentrate in the bone, liver and muscle. It can stay in the body for decades and continue to expose the surrounding tissues. Any ^{241}Am that is swallowed may dissolve and pass into the bloodstream.

Plutonium – 241. ^{241}Pu is a beta emitter and is used in experiments at AWE. ^{241}Pu although fissile is impractical both as a nuclear fuel and a material for nuclear warheads. Some of the reasons are high cost, short half-life and higher radioactivity compared with ^{239}Pu. **Table 3-20** summarises the properties of ^{241}Pu.

Table 3-20 Properties of Plutonium - 241

Parameter	**Value**
Half-life (years)	14.4
Energy (MeV)	0.021
Principal decay mode	Beta
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	2 E4
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	2 E6
Specific activity (Bqg^{-1})	3.8 E12

Uranium (HEU & DU). Uranium is a fairly abundant element in the earth's crust. Concentration in the crust is approximately 2 ppm. Uranium ore when extracted is radioactive, but being extremely long-lived is only very slightly so, and the main hazard is its chemical toxicity which is similar to that of lead. Natural Uranium contains 3 isotopes, ^{234}U, ^{235}U and ^{238}U, which have the following properties:

Table 3-21 Properties of Natural Uranium

Isotope	MeV	% in Uranium Ore	Half-life (years)	Principle decay mode
^{234}U	4.76	0.006	247 E3	Alpha
^{235}U	4.52	0.7	710 E6	Alpha
^{238}U	4.21	99.3	4.51 E9	Alpha

Uranium is a very heavy, silver-white metal. It is chemically very reactive and readily forms oxides. In powder form it is highly pyrophoric. Uranium is soluble only in strong acids, including nitric (HNO_3) and hydrochloric (HCl) acids, forming tetravalent salts. Uranium displaces hydrogen from mineral acids. The specific activity of natural uranium is 24790 Bqg^{-1}. The specific activities of the individual isotopes of natural uranium are given in **Table 3-22**.

Table 3-22 Specific Activity - Uranium Isotopes

Uranium Isotope	Specific Activity (Bqg^{-1})
^{234}U	230214
^{235}U	77700
^{238}U	12321

When ^{235}U has been extracted from natural uranium, for use in the manufacture of reactor fuel, the remaining uranium is called depleted uranium (DU) because it has been depleted of ^{235}U. DU is an important material that is used in processes at AWE and is about half as radioactive as natural uranium.

The Annual Limit of Intake (ALI) for Uranium isotopes is as follows:

Table 3-23 Annual Limit of Intake - Uranium Isotopes

Uranium Isotope	ALI Inhalation (Bq) (ICRP 68)	ALI Ingestion (Bq) (ICRP 68)
^{234}U	2.35 E3	4.08 E5
^{235}U	2.6 E3	4.35 E5
^{238}U	2.74 E3	4.55 E5

Tritium. Tritium (^3H) is a radioactive isotope of hydrogen, which decays to the stable nuclide helium (^3He). Tritium is a pure beta emitter with a half-life of 12.26 years, which is produced naturally in the atmosphere, resulting from the interaction of high energy cosmic ray protons and neutrons with nitrogen, oxygen and argon. Man-made tritium, in amounts substantially larger than the natural inventory, has been injected into the stratosphere by thermonuclear explosions. In addition, tritium is produced during the operation of nuclear reactors.

Tritium is used extensively in processes at AWE and it is the most abundant beta emitter that is released from the site into the atmosphere. The following paragraphs give details of the behaviour of tritium in the environment [49].

Most of the natural tritium is found in the environment as tritiated water (HTO) and follows the hydrological cycle and penetrates into all components of the biosphere, including man. In the lithosphere and hydrosphere tritium is produced by interaction of neutrons with ^{6}Li (lithium) nuclides. Almost all the tritium produced by fallout occurs as HTO in the atmosphere and hydrosphere. Tritium occurs in nuclear reactors by ternary fission in the fuel and also by neutron activation reactions with lithium and boron isotopes dissolved in, or in contact with the primary coolant as well as with naturally occurring deuterium in the primary coolant. Tritium is dominant in the walls of reactor bioshields because of neutron activation of the impurities in the concrete [60], accounting for more than 90% of the radioactive inventory.

Tritium gas is very mobile even in fairly dense materials like concrete, penetrating up to a metre over a 25-year period [60]. In gaseous form it can also permeate rubber and steel. Tritiated water is considered to be more hazardous than gas since it diffuses rapidly through the hydrosphere and biosphere. HTO is considered by the International Commission of Radiological Protection (ICRP) to be 25,000 times more hazardous in air than tritium gas because of its mobility and uptake.

Experimental evidence suggests that tritium is four or five times more effective at inducing cancer than would be predicted just on the basis of its energy alone [61]. Owing to its very low energy as a weak beta emitter, radiation dose only occurs from inhalation or ingestion. Tritium vapour can also diffuse through intact skin.

Artificial production of tritium on an industrial scale is necessary to provide an essential component of thermonuclear weapons [49]. A significant inventory of tritium is released from process operations at AWE, direct to the atmosphere. This is because of the difficulties of filtering and containing this very light and mobile isotope.

The following Table summarises the properties of ^{3}H.

Table 3-24 Properties of Tritium

Parameter	**Value**
Half-life (years)	12.26
Energy (MeV)	5.7 E-3 (average)
Principal decay mode	Pure beta
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	1 E9
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	1 E9
Specific activity (Bqg^{-1})	3.55 E14

Tritium released to the atmosphere will eventually reach the stratosphere. Tritiated water vapour is transferred from the stratosphere to the troposphere with a half-life of about 1-year, then from the troposphere to the earth's surface through rainfall and molecular exchange with a half-life of a bout 10 days. Tritiated water then follows the hydrological cycle. Water deposited on the ocean surfaces is diluted, part of it evaporates at a much lower concentration, while a small fraction is transferred to the deep ocean. Tritiated water deposited on land surfaces is partitioned partly to surface run-off and partly to infiltration in the soil, from where it can be absorbed by plants, evaporate or move with groundwater. Tritium dissolves easily in ground water.

Tritiated water deposited on soils finds its way into vegetable and animals and thus contaminates dietary foodstuffs.

The residence time of tritium in the atmosphere is not known with certainty but estimates vary between 5 to 10 years [62]. The main removal processes are bacterial action and photochemical oxidation.

Transfer to man of environmental HTO takes place via inhalation, diffusion through skin and ingestion of beverages and foodstuffs. Inhalation is the most important pathway to man. Exposure to an atmosphere contaminated with tritiated water vapour results in total absorption of the inhaled activity through the lungs and absorption of about 50% of that amount through the intact skin [63].

HTO passes through the human body in approximately 12 days, however, when the radionuclide unites with carbon in the human body, plants or animals it becomes organically bound (OBT) and can remain for 450 - 650 days. As it moves up the food chain it may become more concentrated. Pigs fed with tritiated foods became tritiated as did their off-spring. The blood, heart and kidneys of the piglets were more tritiated than the food initially eaten by the pigs [49].

Owing to tritium becoming organically bound to molecules it becomes part of the bio-system with the beta emission accompanied by an atom changing from hydrogen to helium. After the particle releases its radioactivity into the cell, a helium ion is formed. The helium springs away from the beta particle and severs the bond with the compound to which the tritium had attached itself. The compound acquires a positive charge and becomes chemically active. When this takes place biological molecules are disrupted by polarisation with unpredictable new bond formation. This process takes place throughout the whole body of organic creatures and thus tritium has one of the most pervasive radiobiological actions on living organisms. HTO can spread through the body's biochemical processes and can concentrate in DNA and bone marrow.

Tritium is carcinogenic, mutagenic and teratogenic. Human beings can receive chronic exposures to OBT through the ingestion of plants and animals exposed in an effluent pathway, in addition to direct uptake through inhalation, absorption and drinking contaminated water.

Caesium – 137. Caesium is element number 55 in the periodic table. It is an alkali metal like potassium, and resembles potassium metabolically. The radioactive isotope ^{137}Cs is produced in nuclear fission and is a significant fission product which, in controlled amounts, is released to the environment in gaseous and liquid effluent streams [49]. ^{137}Cs is a beta/gamma emitter with a decay half-life of 30.27 years. Observations of ^{137}Cs released during atmospheric tests revealed that fallout from the stratosphere and seasonal air movement resulted in a half-life in air of 1 year. This can be compared with the ^{137}Cs half-life in air observed in the months following the Chernobyl accident, which was just 8 days. The deposited ^{137}Cs is re-suspended in air. Since 1986 the half-life of ^{137}Cs in air has been 3 years.

^{137}Cs is chemically very similar to potassium, it can be assimilated by aquatic organisms and this can enter the food chain. Studies at Pond B in Savannah US, show that the ecological half-life of ^{137}Cs is 10 years [64].

The following Table summarises the properties of ^{137}Cs.

Table 3-25 Properties of Caesium - 137

Parameter	**Value**
Half-life (years)	30.3
Energy (MeV)	0.661

Decay mode	Beta/gamma
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	2 E6
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	1 E6
Specific activity (Bqg^{-1})	3.2 E12

Plants take up ^{137}Cs deposited in soils or sediments. Plants and animals living in environments with low potassium levels may accumulate more ^{137}Cs in their tissue, because caesium acts like potassium, and will replace it where there are low levels. ^{137}Cs binds tightly to soils, with micaceous clay, being responsible for its tightest retention. ^{137}Cs has been widely studied in plant/soil systems with its fixation by clay soils being positively correlated with the soil concentration of calcium (Ca) and magnesium (Mg). Organic soils act as a temporary sink of plant-available ^{137}Cs. The addition of potassium before planting significantly decreased ^{137}Cs uptake by lettuce, turnips, okra, eggplant, corn and beans. Plants in organic soil accumulate ^{137}Cs in higher quantities than plants in mineral soils. ^{137}Cs also appears to be highly mobile in plant tissue. In mineral soils the movement of ^{137}Cs is appreciably less than that of ^{90}Sr (strontium), another significant fission product. Within 3-4 years after deposition on the soil surface, the depth to which ^{137}Cs had penetrated was less than 20mm [65]. Uptake by plants is by direct deposition onto plant surfaces or by root uptake from accumulated deposits in soil. Direct foliar adsorption is the predominant mode of contamination. Root uptake is low except in cases where the soil conditions promote it (organic soil and where it is wet and peaty). Retention times from deposition are the same as for other particle debris and a removal half-time of 14 days due to weathering is generally assumed [49].

Fixation of ^{137}Cs by sediments in aquatic environments occurs in a similar fashion to fixation in soil. The adsorption of ^{137}Cs to the micaceous components of sediments has been demonstrated under environmental conditions [49]. The amount of ^{137}Cs in the soluble phase decreases with increasing suspended solid concentration. Potassium is also sorbed, but to a much less degree [49]. The low mineral content of fresh water also enhances the absorption of ^{137}Cs by aquatic plants. ^{137}Cs accumulates via the food chain in aquatic species and the excretion rate of potassium is about 3 times higher than that of ^{137}Cs. As a result concentrations per unit of potassium in tissue increases by a factor of 3 at each trophic level [66]. The food web also accumulates ^{137}Cs from suspended and bottom sediments. Concentration factors for ^{137}Cs are related to potassium concentration and turbidity. For fresh water systems the value is 1000 for algae, plants, molluscs and invertebrates. The concentration factor for non-piscivorous fish is 5000/K_W (where K_W is the stable potassium concentration µg/g) and 1500/K_W for piscivorous fish. This concentration factor falls by a factor of 5 in turbid waters (> 50µg/g suspended solids) [49]. The concentration factors for ^{137}Cs in the ocean are 10 for algae and molluscs and 30 for fish [67].

The biological half-life of ^{137}Cs varies from species to species and this has also been widely studied [49]. The following table gives biological half-lives for ^{137}Cs in different species.

Table 3-26 Biological Half-life for ^{137}Cs in Different Species

Species	Half-life (years)
Wood Ducks	2
American Coots	5
Reindeer	3
Fish (Bass)	13
Man	0.3

^{137}Cs can transfer from fish to humans through the ingestion pathway and to other fish and ecosystems. ^{137}Cs can also bioaccumulate in aquatic food chains, with top-level predators like Bass having concentrated more ^{137}Cs than the fish they fed on.

Cobalt – 60. Cobalt is a silvery steel grey hard metal that is naturally present in certain ores of the earth's crust (in the stable form only - ^{59}Co). The abundance in the earth's crust is between 0.001 - 0.002%. The non-radioactive form of cobalt is essential to life in trace amounts and exists in the form of various salts. Non-radioactive cobalt has both beneficial and harmful effects on health.

^{60}Co is the most common form of radioactive cobalt. It is a beta and a gamma emitter and is used in radiation therapy, in level gauges and in medical research. It has a relatively short half-life of 5 years, decaying to stable nickel-60 (^{60}Ni). At AWE it is formed by neutron irradiation of impurities in steel and concrete that are used as shielding materials for research reactors. AWE has two nuclear reactors, one is closed and defuelled on a care and maintenance regime, the other is still operational. Some ^{60}Co material is released to the atmosphere from reactor ventilation systems, and some is bound into shielding structures that will eventually become radioactive waste.

The following Table summarises the properties of ^{60}Co.

Table 3-27 Properties of Cobalt - 60

Parameter	**Value**
Half-life (years)	5.272
Energy (MeV)	1.17 - 1.33 (gamma energy)
Energy (MeV)	0.318 (beta energy)
Principal decay mode	Beta minus with a lot of Gamma energy
Annual Limit of Intake for humans via inhalation (Bq) (ICRP 61)	2 E6
Annual Limit of Intake for humans via oral ingestion (Bq) (ICRP 61)	7 E6
Specific activity (Bqg^{-1})	4.18 E13

The behaviour of ^{60}Co in the environment is the same as for non-radioactive cobalt. The water solubility of cobalt and it salts range from highly soluble to practically insoluble. All of the ^{60}Co at AWE is in metallic form and is considered to be virtually insoluble. Cobalt can move from the soil to underground water and is taken up by plants from the soil. Cobalt and its salts are highly persistent in water, with a half-life of 200 days.

Only a few plant species accumulate cobalt above 100 ppm, which, causes severe phytotoxicity [68]. Hyperaccumulators have been found which contain over 1% in dry leaves. Soil pH is very important in cobalt uptake and phytotoxicity. More acidic soils sorb cobalt less strongly. Cobalt's availability is primarily regulated by pH. At low pH it is oxidised to trivalent cobalt often found associated with iron. Absorption of divalent cobalt on soil colloids is high between pH 6 - 7. Leaching and plant uptake of cobalt is enhanced by a low pH [68].

Krypton – 85. Krypton belongs to the group of inert gases along with helium, neon, argon, xenon and radon. It occurs naturally in the atmosphere to an estimated extent of $1 - 2 \times 10^{-6}$ by volume. ^{85}Kr is produced by nuclear fission in the fuel of nuclear reactors and in very low trace amounts in the moderator or coolant, due to contamination with fissile material. ^{85}Kr is present in the environment as a result of spontaneous fission of natural uranium and interactions of cosmic neutrons with atmospheric ^{84}Kr [49].

^{85}Kr discharged to the environment disperses in the atmosphere and largely remains there until decay (half-life of 10.7 years). It can be washed out by rain and diffuse into surface layers of soil and oceans, but these processes account for very little transfer of ^{85}Kr from the atmosphere. Materials released to the atmosphere are transported downwind and dispersed according to atmospheric mixing processes. The low water solubility of ^{85}Kr limits the accumulation in rainwater. Adsorption of ^{85}Kr on particulate matter in air and subsequent deposition of the particles provides a removal means of very low efficiency [69]. The transfer of ^{85}Kr to soil can occur by diffusion processes; however, estimates of this transfer can account for about 0.05% of the total krypton in the atmosphere [69]. Therefore, soil in general is not an important removal sink for ^{85}Kr. The efficiency of the oceans as a sink for ^{85}Kr can be determined from the natural krypton content of the atmosphere and of the mixed layer of the ocean. Figures show that the oceans serve as a major sink for ^{85}Kr discharged into the atmosphere [69]. Once released to the atmosphere ^{85}Kr becomes widely dispersed. External irradiation, from the cloud or dispersed gas, and inhalation are the principle exposure routes to man.

Table 3-28 Properties of Krypton - 85

Parameter	**Value**
Half-life (years)	10.72
Energy (MeV)	0.25
Principal decay mode	Beta
No committed dose, all external radiation which is given as an effective dose rate per unit air concentration (Sv/day/Bqm^{-3}) (ICRP 61)	2.2 E-11
Specific activity (Bqg^{-1})	1.48 E13

^{85}Kr decays directly to the stable nuclide Rubidium-85 by ejecting a beta-particle (electron). After one period of 10.72 years, 50% of the atoms in a sample of krypton-85 will have transformed themselves into Rubidium-85; after 10 half-lives (approximately 108 years) the sample will contain just 0.1% Krypton-85 and 99.9% Rubidium-85, and the radioactivity of the sample will have decreased in proportion to the amount of krypton remaining.

3.7.2.3 Radiation Chemistry of Water

The radiation chemistry of water has been studied since the discovery of natural radioactivity [71]. Radioactive material releases into water will either dissolve and be dispersed or fall out and mix with the sediment. Any ecosystems that thrive in water will be threatened by the various reactions that take place in water. The behaviour of various isotopes is described in previous sections.

3.7.2.4 Radiation Chemistry of Air

Radiolysis of a gas may generate ions, excited atoms and molecules, and free radicals. The effects of radiation in the atmosphere has been extensively studied from the many nuclear atmospheric test explosions that have been carried out [70]. The first energy to escape from a nuclear explosion is gamma rays produced by the nuclear reactions [70]. These gamma rays have energies in the MeV range, and a significant number of them penetrate through the tampers and bomb casing and escape at the speed of light. The gamma rays strike and ionise the surrounding air molecules, causing chemical reactions that form a dense layer of smog tens of metres thick around the bomb. This smog is composed primarily of ozone and oxides of nitrogen.

Many experimental techniques have been employed to study gas phase reaction mechanisms, including mass spectrometry and the measurements of ion currents [71]. The frequent types of reactions include the direct formation of electronically excited molecules as shown in the reactions below [71]:

M y M*	Where M is a molecule; Y is ionising radiation (radiolysis). M* is an excited molecule.
M y M^+ +e^- v M*	This is known as indirect excitation by neutralisation of an ion pair.
M* + m v M + m*	The resulting energy from an excited molecule can be transferred to another molecule. This is called collision of the second kind.
M* v M+ light	Excitation energy may be emitted as light
M* v $A^{\cdot}$ + $B^{\cdot}$	Alternatively an excited molecule may lose energy by collisions with other molecules. Excited molecules may decompose into radicals.
M* v C + D	Excited molecules may decompose into molecular products.

The radiolysis of molecular oxygen is an important reaction in the atmosphere. Five primary reactions have been identified.

$O_2\ y\ O_2^+ + e^-$	Oxygen has a covalent bond which makes it stable. The radiolysis causes an electron to leave one molecule making it positive.
$O_2\ y\ O^+ + O^\cdot + e^-$	Radiolysis causes splitting of O_2 resulting in O^+ and $O^\cdot$. To fill missing hole electron moves out to another shell and has become excited.
$O_2\ y\ 2O^\cdot$	Radiolysis causes a split to result in two separate excited oxygen atoms.
$O_2\ y\ O_2*$	Radiolysis causes both oxygen atoms in molecule to become excited.
$O_2^+ + e^-\ v\ 2O^\cdot$	Electron - ion recombination generates oxygen atoms. The stray electron has influenced both oxygen atoms. Both the oxygen atoms have become excited and split ($2O^\cdot$).
$O^+ + e^-\ v\ O^\cdot$	The stray electron has caused no change to the oxygen atom but it is excited ($O^\cdot$).
$O_2 + e^-\ v\ O_2^-$	Electron capture generates O_2^- ions. The stray negative electron makes the O_2 negative.
$O^\cdot + O_2 + M\ v\ O_3 + M$	Ozone is formed by the reaction. The first oxygen has no charge but has been excited (hit by electron). The second oxygen molecule is balanced. M are other molecules of oxygen, which acts as third body to remove excess energy and conserve momentum. The transfer will react to form ozone.

Thus, the overall radiolysis reaction converts molecular oxygen to ozone. This is a very important reaction, which demonstrates that ionising radiation when released into the atmosphere can generate the secondary pollutant O_3. In order to quantify this it is necessary to determine how much O_3 is generated by different radioisotopes with different energies and varying concentrations (Bq). This is necessary in order to determine if any of AWEs radioactive releases to air contribute to photochemical smog formation or if the releases contribute only to a local human health episode. A study has already been carried out into the generation of environmental impacts from ionising radiation [72], which concluded that for routine releases within international legislative limits the amount of ozone generated was trivial. Although this reaction is important, for routine authorised discharges that occur at AWE this is of no concern.

3.7.2.5 Summary of Findings

The findings of the review of literature, on the impact of radioactivity in the environment, are described in this section.

^{60}Co is a relatively energetic gamma ray emitter whereas ^{3}H is a weak beta emitter. The radiological significance of these two radionuclides can be expressed in terms of the damage done per unit intake. Although these effects can be measured in many different ways, one common approach, based on dose received by ingestion, indicates that ^{60}Co is 190 times more potent than tritium [73]. This assumes however, that the only impact category is human dose. The full environmental impact depends on mobility and behaviour within the environment.

As discussed in the previous sections on ^{3}H and ^{60}Co the radiation produced by ^{3}H does not give rise to a radiation dose unless ingested or inhaled. The radiation from ^{60}Co is more penetrative and can give rise to a radiation dose following ingestion or by proximity owing to the strong gamma radiation fields. As well as the difference in radiological effect, the two radionuclides behave quite differently in the environment. ^{3}H becomes rapidly dispersed and diluted to near background levels in large volumes of water [73], whereas ^{60}Co tends to be absorbed onto silt particles, and can therefore be found in sediments.

Following this review of all the data on the behaviour of radioactive material in the environment in general, and the specific radioisotopes used at AWE, the following parameters are identified as influencing environmental impact:

- *Parameter 1* *Life-time in the environment based on half-life (years)*
- *Parameter 2* *Total activity (Bq)*
- *Parameter 3* *Concentration per mass/specific activity (Bq/g)*
- *Parameter 4* *Energy (MeV)*
- *Parameter 5* *Linear Energy Transfer (LET)*
- *Parameter 6* *Radiation type alpha, beta or gamma*

- *Parameter 7 Ozone creation potential (releases to air only)*
- *Parameter 8 Bioaccumulation in soil and freshwater systems (non-living organisms)*
- *Parameter 9 Bioaccumulation in biota (living organisms)*
- *Parameter 10 Biological half-life in indicator species*
- *Parameter 11 Residence time in soil/water*
- *Parameter 12 Radio-sensitivity of indicator species*
- *Parameter 13 Chemical behaviour and toxicity of the radionuclide*
- *Parameter 14 Chemical behaviour and toxicity of the stable isotope(s) associated with the decay of the radioisotope*
- *Parameter 15 Chemical form and reactions of the species intercepted*
- *Parameter 16 Behaviour once ingested or inhaled by species*
- *Parameter 17 Chemical properties of receiving media (water/soil)*
- *Parameter 18 Presence of other hazardous substances*
- *Parameter 19 Solubility of radionuclide*

It is clear that the fate and mobility of radioactive material in the environment is complex and dependent upon many interrelated factors in nature. A reliable indication of impact must be made based on these parameters, however, more in-depth analysis of the relative importance of these parameters is required to quantify environmental impact.

3.7.3 Previous Work

Radiation as an LCA impact category is now included in SETAC Europe [74]. Attempts to quantify this impact category have been made by Clift et al. [75] who states that radiation should not be assessed simply in human toxicity terms, since irreversible effects of high-energy radiation and the extremely long lifetime of some isotopes make the precautionary principle [76] of paramount importance. One of the most important applications of the precautionary principle is within the Rio Declaration from the 1992 United Nations Conference on Environment and Development. The declaration states:

'In order to protect the environment, the precautionary principle approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation'.

This greater need to clarify uncertainty and take a more holistic approach to radioactive discharges has been recognised and a separate impact category for environmental irradiation proposed by Solberg-Johansen [32], in the analysis of discharges from the nuclear fuel cycle. Shiels and Garner [77] have also made a case for adopting life-cycle assessment techniques to inform decision-making by considering the impact of various radioactive waste disposal strategies (^{14}C from BNFL THORP discharged to either air, water or as solid waste). They [77] argue that a fully holistic approach should be adopted to include the assessment of non-radioactive environmental impacts (i.e. global warming etc.) alongside radioactive impacts (i.e. dose to humans), otherwise there is a very real danger of focussing on single issue environmental impacts to the exclusion of other environmental impacts. This becomes apparent as the nuclear industry is placed under increasing pressure to strive towards zero emissions, where reduction of radioactive releases inevitably leads to higher energy demands, resource consumption, waste generation and financial cost.

Furthermore, for discharges to be reduced to zero or near to background for radioactive species and hazardous substances; will create environmental impacts in other areas of the ecosystem, which depending upon the approach taken, may go unrecognised [77]. For this reason the use of LCA methodology is considered to be a transparent, holistic and scientifically acceptable method that will capture *all* environmental impacts.

Although the LCIA framework does not at present include provision for R/A impacts, some research has been carried out at Surrey University [32 & 75] into establishing a methodology for R/A releases. This work utilised the concept of an Environmental Increment (EI) originally proposed by Amiro [78] in 1993 as part of the assessment of the geological disposal site for nuclear waste in the Canadian Precambrian Shield. These increments establish tolerance values for radionuclides for different compartments (soil and water) below which there are "no detectable effects" on the environment. The Environmental Increment is determined by calculating the standard deviation from the environmental monitoring data. Amiro proposes that ecosystems can tolerate an increase of one standard deviation without showing detectable effects. Cosmogenic and primordial radionuclides have substantial natural concentrations and it is assumed that measurements of radionuclides in unpolluted areas today reflect past concentrations and can be used as the baseline value. One standard deviation of the mean background estimate is considered to be the EI value [32]. In the case of anthropogenic radionuclides, baseline data are not available so EIs can be based on data from other isotopes with a similar chemical behaviour [31]. For example ^{129}I has low natural concentrations, but nuclear testing has increased this globally, so stable ^{127}I is used as an analogue to ^{129}I, so that the standard deviation of ^{129}I in soil can be scaled with that of ^{127}I using an atom ratio of 1 x E-9 ^{129}I/^{127}I [78]. Solberg-Johansen [32] used these EI values, in effect, as a rough approximation of the 'No Effect Level' as used in the ecotoxicity category of LCIA, in the absence of direct ecotoxicological data.

The University of Leiden in the Netherlands has developed a database of equivalency factors for use in LCIA [38]. This database includes a category for radiation using the 'problem-oriented approach' developed by Frischknecht [79]. The values relate to human health damage due to ionising radiation and are reproduced in the table below:

Table 3-29 Relative Radiation Characterisation Values [79]

Radioisotope	Value given under the 'Radiation' heading (DALYs) KBq
^{241}Am	No data given
^{137}Cs	1.3 E-08
^{60}Co	1.6 E-08
^{85}Kr	1.4 E-14
^{239}Pu	8.3 E-08
^{241}Pu	No data given
^{3}H	1.4 E-11
^{234}U	9.7 E-08
^{235}U	2.1 E-08

Radioisotope	**Value given under the 'Radiation' heading (DALYs) KBq**
^{238}U	8.2 E-09

These values are assumed to be relative to one another and are a measure of damage to human health expressed in Disability Adjusted Life Years (DALYs). These values relate to human health only and are not media specific. Also there is no apparent timescale over which the impact is considered. Based on the relative values however, it would appear that gamma emitters (^{60}Co and ^{137}Cs) are considered to be more harmful than alpha emitters (U and Pu) with beta emitters being the least harmful by a significant margin (^{85}Kr and ^{3}H). This is in general agreement with the conclusion reached by SEPA over environmental discharges of ^{3}H and ^{60}CO [73] – see also Section 3.7.2.5.

Solberg-Johansen [32] applied environmental increment values, as described above, to assess the impact from nuclear fuel cycle releases. Environmental increments are based on the method originally developed by Amiro [78] and are reproduced in the table below for the isotopes relevant to AWE:

Table 3-30 Environmental Incremental Values for Soil, Water and Air [32 & 78]

Radioisotope	**Surface Water (m^3/Bq y) [32]**	**Soil (kg/Bq y) [32]**	**Surface Water (Bq/m^3) [78]**	**Soil (Bq/kg) [78]**	**Air (Bq/m^3) [78]**
^{241}Am	5.04 E+00	4.2 E-03	3 E-04	3.6 E-01	-
^{137}Cs	No data given	No data given	2 E-01	6.6 E+1	-
^{60}Co	No data given	No data given	No data given	No data given	-
^{85}Kr	-	-	-	-	3 E-01
^{239}Pu	7.1 E-03	2.37 E-05	4 E-03	1.2 E+00	-
^{241}Pu	1.09 E+00	1.31 E-1	4.8 E-02	4 E-01	-
^{3}H	1.57 E-06	1.57 E+01	3.6 E+01	3.6 E-03	-

Radioisotope	Surface Water (m^3/Bq y) [32]	Soil (kg/Bq y) [32]	Surface Water (Bq/m^3) [78]	Soil (Bq/kg) [78]	Air (Bq/m^3) [78]
^{234}U	1.4 E-06	1.08 E-07	2 E+00	2.6 E+01	-
^{235}U	1.08 E-08	8.14 E-10	9 E-02	1.2 E+00	-
^{238}U	7.68 E-11	5.91 E-12	2 E+00	2.6 E+01	-

The values given above are mainly for soil and freshwater which are assumed to represent the terrestrial and aquatic biota as a whole [32 & 78]. As this methodology was developed by Amiro [78] to assess solid waste disposal concepts, atmospheric values are only reported for some noble gases (including ^{85}Kr) [32]. The values above are compared with those developed in this research (**Table 3-37** and **Table 3-38**) and discussed later in this section.

In addition to the work by Amiro and Solberg-Johansen, assessment of human health damages related to releases of radioactive material has been made based on the French nuclear fuel cycle [80]. This assessment derived equivalency factors for effect-oriented impact assessment of human health from different electricity supply systems. The assessment considered effect analysis based on carcinogenic and hereditary effects based on a time frame of 100,000 years. The factors derived are calculated to kBq of ^{235}U air-equivalents, however no data is supplied for Pu and Am isotopes in water or ^{241}Pu/Am isotopes in air. Owing to the different timeframes over which the damage is considered there is little correlation with the equivalency factors derived in this thesis. Additionally nuclear generation in Korea has also been assessed in the context of LCA [81]. The classification factors were derived and considered to be less significant when compared with other LCA impact categories. The classification factors included inhalation of air and ingestion of water (both as litres/Bq), however as with the work described for the French nuclear fuel cycle the work did not cover all of the isotopes discharged from AWE for both air and water compartments. The air compartment only assessed ^{3}H and ^{60}Co and the water compartment only additionally covered uranium isotopes. The Korean paper based the factors on risk coefficients prepared by Eckerman [82].

The Environment Agency in conjunction with English Nature published a report on the impact of ionising radiation on wildlife [83]. This report provides up to date information on research and the impact of ionising radiation to wildlife and gives interim guidance on how to perform assessments for nuclear operators in England and Wales. The research detailed forms part of an EC (European Commission) funded project (**F**ramework for **ASS**sessment of **E**nvironmental impac**T** – FASSET) started in November 2000 and expected to deliver a harmonised framework for adoption in the EU for future radiation assessments by October 2003.

The report [83] challenges the ICRPs traditional stance that if man is adequately protected from ionising radiation, then so are other species. The EC believes that the understanding of radiation impacts on the environment is insufficient to permit the introduction of new legislation at a community level. The authors of the UK report conclude however, that after completing impact assessments using scenarios of radioactive contamination and measured values in ecosystem components from around UK nuclear sites, that wildlife are not significantly impacted upon by exposure from ionising radiation from authorised discharges. This would suggest that the ICRP stance is sensible, especially in light of the fact that a great deal of work has been carried out by the ICRP into dose uptake by man culminating in Dose Coefficient Factors (DCF) which, include environmental factors when making dose determinations to humans via inhalation and ingestion pathways [84]. Moreover, there has been no evidence of species destruction from discharges that have been limited to levels designed to protect man. There are cases where individuals have been harmed from routine exposure but there is no evidence that entire populations of a species or an ecosystem has been destroyed.

The EA report [83] concludes that most of the research into radiation effects has focussed on acute impacts to individuals rather than the chronic effects to populations and that the range of acute lethal dose varies considerably for different organisms indicating wide radiosensitivity. The range of organisms is from viruses, mosses and algae (10 E4 Gy) through to fish, birds, higher plants and mammals (< 10 E1 Gy). The general conclusion is that the simpler the organism the greater its radio-tolerance. The impact assessment methods described use an ellipsoid shape proportional to a species body mass to calculate dose, however, no bio-kenetic model is used and the method is not as sophisticated as those used by the ICRP for assessing whole body doses to vital organs in the human body. The report concludes that further research is required to determine concentration factors necessary to estimate internal radionuclide concentrations for reference organisms and greater emphasis should be placed on the interaction of pollutants (radioactive and non-radioactive) at any one site.

In the context of this research it is concluded that at present the methods proposed in the EA report [83] are not ideally suited for use in LCIA methodology. Moreover, the ICRP stance still provides a degree of confidence and man represents a good indicator of how radionuclides behave in living organisms. Whilst it is recognised that protection of man from ionising radiation does not ensure protection of the environment as a whole, it does indicate which radionuclides are relatively more damaging in a representative receptor species and hence can be used within LCA impact assessments. For these reasons it is proposed in this work, to base the new environmental irradiation categories on Dose Coefficient Factors, chemical toxicity and radionuclide behaviour in the environment. Dose Coefficient Factors [84] used in this thesis are reproduced in the table below.

Table 3-31 Dose Coefficient Factors [84]

Radioisotope	DCF for Inhalation (Adult Medium Acting) (Sv Bq^{-1})	DCF for Ingestion (Adult) (Sv Bq^{-1})
^{241}Am	4.2 E-5	2.0 E-7
^{137}Cs	9.7 E-9	1.3 E-8
^{60}Co	1.0 E-8	6.4 E-9
^{85}Kr	2.2 E-11 (Sv/Bqm^{-3})	-
^{239}Pu	5.0 E-5	2.5 E-7
^{241}Pu	9.0 E-7	4.8 E-9
^{3}H	4.5 E-11	4.2 E-11
^{234}U	3.5 E-6	4.9 E-8
^{235}U	3.1 E-6	4.7 E-8
^{238}U	2.9 E-6	4.5 E-8

3.7.4 Methodology for Determination of Equivalency Factors (R/A)

It is proposed here to use the nineteen parameters identified in 3.7.2.5 as a basis for calculating EF values. In addition Dose Coefficient Factors [84] will also be used to help to determine the EF value. Radiation dose to humans is widely accepted as providing a very good indication of the human health effects from ionising radiation released into the environment. Over the last 50 years Health Physicists have developed reliable methods to calculate radiation doses that can be readily compared to natural sources, for risk assessment purposes.

From this research the AWE radioactive aspects, (Section 3.2), can be assessed under the following new categories:

- Environmental Irradiation from R/A Releases to Water
- Environmental Irradiation from R/A Releases to Air
- Special Landfill for R/A Waste

In order to quantify the environmental impact of radioactive releases a methodology is required to enable releases of different radioactive species to be compared once they have been emitted into various environmental compartments. The method also needs to be compatible with the existing LCIA framework. Equivalency Factors (EF) are used therefore to allow different radioactive species with different types of decay, (alpha, beta or gamma), to be compared and the relative environmental impact determined for air and water receiving media and as solid waste. Of the factors that influence environmental impact (identified in Section 3.7.2.5), those that need to be quantified in derivation of EF are:

- Life time and total activity of the radioactive material (Parameters 1 and 2);
- Type of decay (alpha, beta or gamma) (Parameter 6);
- Chemical properties (sorption, solubility, toxicity - based on the stable material's behaviour) (Parameter 14);
- Chemical form (solid, liquid, gas, powder or particulate) (Parameter 16);
- Behaviour in the environment (aquatic, terrestrial and atmospheric behaviour as summarised in Sections 3.7.2.1 and 3.7.2.2) (Various Parameters);
- Factors that influence exposure to ecosystems (pH, organic loading, food chain webs, presence of other hazardous substances, aquatic, atmospheric and soil characteristics) (Various Parameters).

To determine a suitable formula for identifying Equivalency Factors it is proposed to use Dose Coefficient Factors in conjunction with chemical toxicity and environmental fate criteria. Equivalency Factors are derived for the isotopes released from AWE to air and water. High radiation doses will lead to increased problems with reproduction and disease bringing about a loss of species, reduced biodiversity and hence a greater environmental impact. Ecosystems consist of abiotic or non-living components (soil, water and climate) and biotic or living components. The protection of biotic species is considered to be paramount in protecting the abiotic environment in which they dwell.

Radioactive substances behave differently to stable substances in that depending upon their decay rate they will, eventually lose energy by emission of radiation, and become a stable isotope. For example ^{60}Co will eventually decay to the stable isotope ^{60}Ni, so that assuming a long enough period for the LCIA (100 years is used in this thesis), the Equivalency Factor will need to consider 3 factors:

1. radio-toxicity of the isotope (e.g. ^{60}Co);
2. the environmental impact potential from the chemical behaviour of the stable analogue (^{59}Co in this case);
3. the environmental impact potential from the chemical behaviour of the substance to which it decays (stable ^{60}Ni in this case).

It should be noted that ^{60}Co is a fairly straightforward as it decays to a stable daughter product (^{60}Ni). For heavier radionuclides a chain of daughter products may be involved, only the last of which will be stable. The three factors upon which the Equivalency Factor is based, is included in the methodology proposed (**Table 3-36**). This methodology is broken down into 3 stages and summarised in the following diagram:

Figure 3-3

RADIOLOGICAL EQUIVALENCY FACTOR DEVELOPMENT STRATEGY

STAGE 1 LITERATURE REVIEW

Review of Published Case Study(s) to determine what parameters influence the exposure of indicator species from radioactive material released to: Air and Water. See section 3.7.2.5 for list of Parameters.

STAGE 2 DEVELOP EF FORMULA

Include relevant parameters in a formula to derive EF for the respective isotopes used at AWE for releases to air and water.

The Formula will be based on environmental ***effect****, (as defined in part by DCF values [84]), and environmental* ***fate*** *(as defined by chemical toxicity and behaviour in the environment).*

In line with other characterisation methodologies in LCA, the potential contribution to environmental irradiation by a specific radionuclide is determined by a factor, which may be expressed as the product of an ***effect*** *factor, and* ***fate*** *factor [32].*

STAGE 3 VALIDATE FORMULA (ISO 14042)

Review formula against the criteria for a characterisation model in ISO 14042 and demonstrate that the EF values derived are robust and consistent with the scope of the study objectives (see section 3.7.4.4).

In this thesis separate EFs for water and air, which are described in detail in Section's 3.7.4.2 and 3.7.4.3 are determined. The parameters identified in Section 3.7.2.5 are summarised in the table below, which also identifies whether each parameter is considered to represent an environmental fate or effect and how dose coefficient factors relate to each of these parameters.

Table 3-32 Parameters and the Relationship Between Fate, Effect and Dose Coefficient Factors

Parameter	Effect or Fate	Covered by DCF	Method by which the parameter will be measured in the EF formula
1.Life-time in the environment based on half-life (years).	Fate	No. This parameter is covered by Section 3.7.4.1.	Life-time based on half-life of radionuclide.
2. Total activity (Bq)	Fate	No. This parameter is covered by Section 3.7.4.1.	The total amount of activity released (Bq)
3. Specific activity (Bq/g)	Effect	Yes DCF take into account specific activity.	Covered by DCF.
4. Energy (MeV)	Effect	Yes DCF take into account MeV.	Covered by DCF.
5. Linear Energy Transfer (LET)	Effect	Yes DCF take into account LET.	Covered by DCF.
6. Radiation type alpha, beta or gamma.	Effect	Yes DCF take into account radiation type.	Covered by DCF.
7. Ozone creation potential (releases to air only).	Effect	No.	Ozone creation from routine discharges has been shown to be trivial. This parameter is not applicable.
8. Bioaccumulation in soil and freshwater systems (non-living organisms).	Fate	No.	Bioaccumulation potential of stable isotope.
9. Bioaccumulation in biota (living organisms).	Effect	Yes DCF take into account the bioaccumulation in humans.	Covered by DCF.
10. Biological half-life in indicator species.	Effect	Yes DCF take into account the biological half-life of radioisotopes in humans.	Covered by DCF.
11. Residence time in soil/water.	Fate	No.	Covered by parameter 1.
12. Radio-sensitivity of indicator species.	Effect	Yes DCF take into account radio-sensitivity (humans only).	Covered by DCF.
13. Chemical behaviour and toxicity of the radionuclide.	Effect	Yes DCF take into account of toxicity.	Covered by DCF.
14. Chemical behaviour and toxicity of the stable isotope associated with the decay of the radioisotope.	Fate	No.	Chemical behaviour characteristics of the stable isotope
15. Chemical form and reactions of the species intercepted.	Effect	Yes DCF take into account reactions inside the human body.	Covered by DCF.
16. Behaviour once ingested or inhaled by species.	Effect	Yes DCF take into account biological behaviour in humans.	Covered by DCF.

Parameter	Effect or Fate	Covered by DCF	Method by which the parameter will be measured in the EF formula
17. Chemical properties of receiving media (water/air/soil).	Fate	No.	Not applicable. It is assumed that there are no unusual properties associated with the land, air of freshwater receiving media around Aldermaston.
18. Presence of other hazardous substances.	Fate and effect	No. This parameter is only valid if monitoring data reveals that the health of ecosystems is being threatened	Not applicable. Although the presence of other hazardous substances will impact upon species, this is only of interest if the health of ecosystems is being studied and a correlation between health and radionuclide releases is being sought.
19. Solubility of radionuclide.	Fate and effect	Yes DCF take into account solubility inside the human body.	The solubility of the stable isotope will be used.

Criteria that are important to both releases of radionuclides to air and to water are:

- persistency in the environment (Parameter 1);
- total activity released (Parameter 2).

Both of these criteria are described within the context of EF development in the following section.

3.7.4.1 Life-time and Total Activity of Radionuclides in the Environment

One of the most important aspects in quantifying R/A substances is to establish how persistent they are in the environment. This is consistent with methods used to assess the impact of chemicals released into the environment [85], and can out-weigh toxicity in importance. Polychlorinated biphenyl (PCB) is a chlorinated hydrocarbon that is considered to be particularly damaging in the environment because of its stability and, as a result, its tendency to accumulate in food chains. Radioisotopes remain radioactive until they decay to a stable (non-radioactive) isotope. Different nuclides have different decay rates, which, are measured in half-lives. A half-life is the time required for half the nuclei to decay. It is usually measured in years, so that an isotope with a half-life of 10 years and a concentration of 1000 Bq will decay to 500 Bq in 10 years and 250 Bq in 20 years. Nuclear physicists generally regard 10 half-lives to be the decay period after which the radioactivity is low enough not to present any further danger. This however, will depend on the magnitude of the source in the first place. Half-lives can vary from a few millionths of a second to billions of years. A radioactive nuclide may be characterised by the rate at which it disintegrates, and any one of three quantities: the decay constant; the half-life; or the mean life; may be used for this purpose [86]. Solberg-Johansen [32] proposed that the concentration of radionuclides in the environment is related to the average time duration over which a radionuclide exists in a particular form. This time being defined as the 'life-time' or mean life of the radionuclide, and is the reciprocal of the decay constant thus:

$$\tau_{(radionuclide)} = 1/\lambda_{(radionuclide)}$$

Where:

τ = The mean life or lifetime of a radionuclide (y).

λ = The decay constant for a given radionuclide which can also be defined as the probability of radioactive decay of a given nuclei (y^{-1}).

If λ, the decay constant, is the probability of radioactive decay for a given nuclide. The reciprocal of the decay constant will be the probability of what has not decayed and thus what remains in the environment. This value is a reasonable indication of the relative persistency or average residence time.

The half-life of a radionuclide is related to the decay constant thus [86]:

$$T = 0.693/\lambda$$

Where:

T = the half-life of the radionuclide (y)

λ = The decay constant for a given radionuclide.

Transposing this formula gives:

$$\lambda = 0.693/T$$

The decay constants and life-times for the radioisotopes released from AWE are given in

Table 3-33.

Table 3-33 Decay Constants

Radioisotope	Half-life (y)	λ	Life-time (y)
^{241}Am	432	1.6E-03	624
^{137}Cs	30	2.3E-02	44
^{60}Co	5	1.3E-01	8
^{85}Kr	11	6.5E-02	15
^{239}Pu	24065	2.9E-05	34726
^{241}Pu	14	4.8E-02	21
^{3}H	12	5.7E-02	18
^{234}U	247000	2.8E-06	356421
^{235}U	710000000	9.8E-10	1024531025
^{238}U	4500000000	1.5E-10	6493506494

The study of the ecological and health effects of radionuclides involves consideration of many factors [87]. Among these are the type and energy of the radiation emitted and the half-life of the source. In addition, the degree to which the particular element is absorbed by living species and the chemical interactions and transport of the element in aquatic, soil and atmospheric ecosystems are important factors [87]. Radionuclides having very short half-lives may be hazardous when produced but decay too rapidly to affect the environment into which they are released. Radionuclides with very long half-lives may be persistent in the environment but of such low activity that little environmental damage is caused [87]. Uranium is an example of a very long-lived radionuclide, which has a fairly low specific activity (24790 Bqg^{-1} for natural uranium). This specific activity value can be compared to Plutonium-239 (2.3 E9 Bqg^{-1}) and Tritium (3.4 E14 Bqg^{-1}), which are, mass for mass, considerably more radioactive. In general, radionuclides with intermediate half-lives are the most dangerous. At AWE the following isotopes can be considered to have intermediate half-lives:

- Cobalt-60 (5.27 years);
- Krypton-85 (10.72 years);

- Tritium (12.26 years);
- Caesium-137 (30.3 years);
- Plutonium-239 (24065 years); included owing to its high specific activity and chemical toxicity.
- Plutonium-241 (14.4 years);
- Am-241 (432 years)

These radionuclides persist long enough to enter living systems while still retaining a relatively high activity [87]. Those radionuclides that can be incorporated within living tissue (life elements) are particularly dangerous. Examples of life elements are strontium-90, which is interchangeable with calcium in bone, and caesium-137, which behaves much like potassium, replacing it in biological systems. For this reason the important criteria of persistency (life-time) and concentration (Bq) should be included in the method of EF development for R/A releases. Using the life-time in years directly in a formula to calculate the equivalency factor however, will greatly influence the result and it is clear that the long-lived isotopes (uranium) will be calculated as being the most serious by a disproportionate amount. There exists two alternatives to expressing life-time values either:

- Banding half-lives and scoring each band whereby those isotopes with the longest half-life are given the highest score
- Equating the half-life to a reference period of for example 100 years. This is compatible with the approach adopted in other life-cycle assessments.

In this work the latter method has been chosen and a value has been derived based on the % decay after 100 years, and used this value is used in the equivalency factor formula. To calculate the % decay the standard equation for radioactive decay is used:

$$A(t) = A(0).e^{-\lambda t}$$

Where:

A(t) = activity at some time in the future (100 years in this case)

A(0) = activity at the time of discharge

λ = the decay constant

t = time (100 years)

For the isotopes used at AWE the following values are derived:

Table 3-34 % Decayed (100 years)

Isotope	λ	Time (years)	Activity at release A(0)	Activity at time A(t)	Amount decayed in 100 years	% decay
^{241}Am	1.6 E-3	100	50	4.26 E+1	7.39 E+0	14.78
^{137}Cs	2.3 E-2	100	50	5.01 E+0	4.5 E+1	89.97
^{60}Co	1.3 E-1	100	50	1.13 E-4	5.00 E+1	99.99
^{85}Kr	6.5 E-2	100	50	7.52 E-2	4.99 E+1	99.84
^{239}Pu	2.9 E-5	100	50	4.99 E+1	1.45 E-1	0.29
^{241}Pu	4.8 E-2	100	50	4.11 E-1	4.96 E+1	99.17
^{3}H	5.7 E-2	100	50	1.67 E-1	4.98 E+1	99.66
^{234}U	2.8 E-6	100	50	5.00 E+1	1.4 E-2	0.03
^{235}U	9.8 E-10	100	50	5.00 E+1	4.9 E-6	0.00001
^{238}U	1.5 E-10	100	50	5.00 E+1	7.5 E-7	0.000001

The various parameters relevant to AWE isotopes are summarised in the following table.

Table 3-35 Parameters and AWE Isotopes

Parameter	^{241}Am	^{137}Cs	^{60}Co	^{85}Kr	^{239}Pu	^{241}Pu	^{3}H	^{234}U	^{235}U	^{238}U
1.Life-time in the environment based on half-life (years).	624	44	8	15	34726	21	18	3.5 E5	1.0 E9	6.5 E9
2. Total Activity (Bq)	-	-	-	-	-	-	-	-	-	-
3. Specific activity (Bq/g)	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
4. Energy (MeV)	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
5. Linear Energy Transfer (LET)	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
6. Radiation type alpha, beta or gamma.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
7. Ozone creation potential (releases to air only).	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8. Bioaccumulation in soil and freshwater systems (non-living organisms).	High	No data	Low	No data	High	High	Low	High	High	High
9. Bioaccumulation in biota (living organisms).	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
10. Biological half-life in indicator species.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
11. Residence time in	624	44	8	15	34726	21	18	3.5 E5	1.0 E9	6.5 E9

Parameter	^{241}Am	^{137}Cs	^{60}Co	^{85}Kr	^{239}Pu	^{241}Pu	^{3}H	^{234}U	^{235}U	^{238}U
soil/water.										
12. Radio-sensitivity of indicator species.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
13. Chemical behaviour and toxicity of the radionuclide.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
14. Chemical behaviour and toxicity of the stable isotope associated with the decay of the radioisotope.	High	No data	Low	No data	High	High	No data	High	High	High
15. Chemical form and reactions of the species intercepted.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
16. Behaviour once ingested or inhaled by species.	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF	See DCF
17. Chemical properties of receiving media (water/air/soil).	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18. Presence of other hazardous substances.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19. Solubility of radionuclide.	Low	High	In-soluble	Low	Low	Low	High	Low	Low	Low

From analysis of the above table it is clear that a number of the 19 identified parameters are included in the ICRP biokinetic model [84] used to determine DCF values. In addition the following parameters are identified as being measurable and having a direct influence on environmental **fate** and **effect**, which are essential for determining characterisation methods for LCA:

- Life-time value (100 year time-frame)
- Total activity (Bq)
- Bioaccumulation potential (ranked as either High, Medium, Low or None)
- Chemical behaviour and toxicity (measured by environmental benchmarks and ranked as either High, Medium, Low or None)
- Solubility (based on behaviour in water and ranked as either High, Medium, Low or Insoluble)

These parameters provide compatibility with other impact categories, which is a requirement in characterisation in LCA.

These last three parameters are scored as follows: High = 3; Medium = 2; Low = 1; None / Insoluble = 0. For parameters for which there is no data a score of 1 is given as a default value. Data to guide the scoring is taken from Croner's database on hazardous chemicals [88] and where there is no data for the specified radioactive nuclide a stable analogue is used instead, for example for Pu this is Pb. The justification for the Toxicity (T), Bioaccumulation (B) and Solubility (S) scores is given in **Table 3-36**.

Table 3-36 Bioaccumulation, Toxicity and Solubility Scores

Radioisotope	Stable Analogue	Environmental Information (taken from reference 88)	B	T	S
^{241}Am	Lead/ Bismuth	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
^{137}Cs	Potassium	Low bioaccumulation potential, low ecotoxicity and freely soluble in water.	1	1	3
^{60}Co	Cobalt/ Nickel	Low bioaccumulation potential, low toxicity and insoluble.	1	1	0
^{85}Kr	Krypton	Inert gas with low water solubility. Being chemically inert it does not normally get involved in biological process and is not considered to bioaccumulate.	0	0	1
^{239}Pu	Lead	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
^{241}Pu	Lead	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
^{3}H	Hydrogen / Helium	Tritium when organically bound bioaccumulates up the food chain. Tritium follows the hydrological cycle penetrating all components of the biosphere. It will exchange with non radiological isotopes of hydrogen (protium and deuterium). Hydrogen is not chemically toxic. It dissolves easily in water.	2	0	3
^{234}U	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water	3	3	0
^{235}U	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water	3	3	0
^{238}U	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water	3	3	0

The Equivalency Factor (EF) is based on a combination of fate and effect. The effect part of the formula is made up of the relevant DCF value and fate is based upon the combination of life-time, bioaccumulation, chemical toxicity and solubility. The total activity is equivalent to the mass in conventional LCA impact determinations. The EF formula is derived thus:

$$EF = Effect \times Fate$$

$$EF = Effect\ in\ Receptor\ Species \times Fate\ in\ the\ Environment$$

$$EF = DCF\ value \times Fate\ in\ the\ Environment$$

$$EF = DCF\ value \times (B + T + S) \times Life\text{-}time\ value\ for\ 100\ years$$

Where:

B = bioaccumulation score

T = chemical toxicity score

S = solubility score

The overall impact is calculated thus:

$$Sji = MiQji$$

Where:

Sji	potential contribution to environmental irradiation impact j from discharge i
Mi	Environmental quantity (total activity Bq)
Qji	characterisation factor (impact potential or equivalency factor) for radioactive substance i to environmental irradiation impact category j

Separate Equivalency Factors for discharges to water (effluent) and discharges to air (gaseous) are described in the following sections.

3.7.4.2 Application of Methodology for Radioactive Effluent Discharge

Using the formula derived above and the DCF values for ingestion (ICRP) a calculation of EF values for the various AWE isotopes can be made.

High enough exposures to ionising radiation will disrupt the reproductive ability of certain species to the detriment of the overall river quality. Values derived for EF are summarised in **Table 3-37**.

Table 3-37 EF Value for Radioactive Effluent Releases

Radioisotope	DCF [84] (Ingestion)	B	T	S	Life-time value	EF
^{241}Am	2.0 E-7	3	3	0	14.78	1.77 E-5
^{137}Cs	1.3 E-8	1	1	3	89.97	5.85 E-6
^{60}Co	6.5 E-9	1	1	0	99.99	2.8 E-7
^{85}Kr	-	0	0	1	99.84	-
^{239}Pu	2.5 E-7	3	3	0	0.29	4.35 E-7
^{241}Pu	4.8 E-9	3	3	0	99.17	2.86 E-6
^{3}H	4.2 E-11	2	0	3	99.66	2.09 E-8
^{234}U	4.9 E-8	3	3	0	0.03	8.82 E-9
^{235}U	4.7 E-8	3	3	0	0.00001	2.82 E-12
^{238}U	4.5 E-8	3	3	0	0.000001	2.7 E-13

3.7.4.3 Application of Methodology for Radioactive Gaseous Discharge

Using the formula derived above and the DCF values for inhalation (ICRP) a calculation of EF values for the various AWE isotopes can be made.

High enough exposures to ionising radiation will disrupt the reproductive ability of certain wildlife species to the detriment of air and land quality. Values derived for EF are summarised in the following table:

Table 3-38 EF Value for Radioactive Gaseous Releases

Radioisotope	DCF [84] (Inhalation)	B	T	S	Life-time value	EF
^{241}Am	4.2 E-5	3	3	0	14.78	3.72 E-3
^{137}Cs	9.7 E-9	1	1	3	89.97	4.36 E-6
^{60}Co	1.0 E-8	1	1	0	99.99	2 E-6
^{85}Kr	2.2 E-11 (Sv/Bqm^{-3})	0	0	1	99.84	-
^{239}Pu	5.0 E-5	3	3	0	0.29	8.7 E-5
^{241}Pu	9.0 E-7	3	3	0	99.17	5.36 E-4
^{3}H	4.5 E-11	2	0	3	99.66	2.24 E-8
^{234}U	3.5 E-6	3	3	0	0.03	6.3 E-7
^{235}U	3.1 E-6	3	3	0	0.00001	1.86 E-10
^{238}U	2.9 E-6	3	3	0	0.000001	1.74 E-11

These equivalency factors are relative to each of the respective isotopes and could now be normalised between 0 and 1 using the following formulae [89].

$$\textit{Normalised Value} = \frac{\textit{EF Value} - \textit{Lowest EF Value in the Range}}{\textit{Highest EF Value in the Range} - \textit{Lowest EF Value in the Range}}$$

Normalisation places the most damaging isotope, over a 100-year reference period, ^{241}Am as 1 and ^{238}U as 0 with values in between for the other isotopes. The author has not used normalised values in the analysis as this will distort the results. The normalised equivalency values are reproduced below to illustrate this:

Table 3-39 Normalised EF Values for Radioactive Releases

Radioisotope	EF (Effluent)	Normalised EF (Effluent)	EF (Gaseous)	Normalised EF (Gaseous)
^{241}Am	1.77 E-5	1	3.72 E-3	1
^{137}Cs	5.85 E-6	3.30 E-1	4.36 E-6	1.17 E-3
^{60}Co	2.8 E-7	1.58 E-2	2 E-6	5.37 E-4
^{85}Kr	-		-	
^{239}Pu	4.35 E-7	2.45 E-2	8.7 E-5	2.34 E-2
^{241}Pu	2.86 E-6	1.61 E-1	5.36 E-4	1.44 E-1
^{3}H	2.09 E-8	1.18 E-3	2.24 E-8	6.02 E-6
^{234}U	8.82 E-9	4.97 E-4	6.3 E-7	1.69 E-4
^{235}U	2.82 E-12	1.44 E-7	1.86 E-10	4.53 E-8
^{238}U	2.7 E-13	0	1.74 E-11	0

The equivalency factors derived for releases to effluent (see **Table 3-37**) do show some correlation with the environmental increment values derived by Solberg-Johansen (see **Table 3-30**). Although there are numerical differences, as expected owing to the different methodologies employed, both calculate ^{241}Am to be the most damaging isotope and the uranium isotopes, in the same order, to be the least damaging. ^{241}Pu is considered by both methods to be worse than ^{239}Pu and tritium is approximately mid-way in both ranges of values. Solberg-Johansen does not provide data for ^{137}Cs and ^{60}Co isotopes.

3.7.4.4 Compliance with International Standard ISO 14042

To ensure the developed EF is robust, a review of its appropriateness against an international standard is presented. This is to demonstrate that the method possesses the necessary qualities to meet agreed international standards for life-cycle impact assessment. The ISO standard 14042 [37] gives a number of recommendations for characterisation models, which are used to determine equivalency factors. The recommendations from Section 5.3 of the standard [37] are summarised below:

The characterisation model should be consistent with the goal and scope of the LCA study, appropriate and justified. An approved and competent body should internationally accept the model. Value choices and assumptions should be minimised during the selection of an impact category and double accounting should be avoided i.e. human health and carcinogenicity. The characterisation model should be scientifically and technically valid, based on a distinct identifiable environmental mechanism or reproducible empirical observation. The actual extent of the scientific and technical validity should be identified. Finally the fate and transport of the substances should be part of the characterisation model. These recommendations are summarised in the following table:

Table 3-40 Compliance with ISO 14042

Recommendation	Justification
Consistent with the Goal and Scope of the LCA	The goal and scope of the LCA was to incorporate EF values thus allow radioactive substances to be included in LCA impact assessments.
Approved and accepted by an international body	As this method is part of academic research, an accepted international body has not yet approved it. AWE will be invited to accept and approve the methodology.
Value choices and assumptions minimised	The method is based on the ICRP dose coefficient model and known literature about the behaviour of stable analogues to the radioactive isotopes.
Avoided double accounting	There is no double accounting the EF reflects the relative impact radioactive material will have in the environment based on fate in the environment and effect in an indicative receptor species (man).
Scientifically and technically valid	The method is based on known scientific parameters. The method relies on persistency, environmental fate and behaviour inside an indicative receptor species (effect) and is considered to be technically valid
Fate and transport of substances included	The method uses both effect and fate to derive an EF value. Solubility is a parameter used to determine the EF value.

The EF process developed is robust and it is recommended that AWE accepts the methodology presented in this thesis for the derivation of EF values.

3.7.5 Environmental Impact of Radioactive Waste

A method for comparing different categories of radioactive waste to establish relative environmental impact is now described. New categories for radioactive waste have been proposed in this work and that pertaining to solid waste is:

- Special Landfill for R/A Waste

This is a similar category to the Landfill Volume / Waste Generation category described in Section 3.4.1.9, with some significant differences. Radioactive waste will eventually have to be disposed in a repository and immobilised to protect the environment. At present the UK Government's proposed strategy for dealing with radioactive waste is pre-treatment prior to disposal in a deep land-based geological repository. This disposal strategy has been adopted in the US where plans are more advanced and work has already started on the construction of a deep mountain repository at the Yucca site in Nevada [90]. The Yucca site will have capacity for 63,000 Tonnes of Spent Nuclear Fuel (SNF) and cost an estimated \$28B (~£17.5B). This huge cost reflects the necessary engineering measures required to isolate the waste from the environment for many thousands of years until it has decayed to safe levels.

It should be recognised that SNF is the most hazardous category of radioactive waste known as High Level Waste (HLW). It is similar to ILW (see Section 3.2.3) in that the radioactive concentrations are above the same thresholds with the exception that HLW is heat generating. This heat can cause problems during storage and eventual disposal. AWE does not generate any HLW on a routine basis, although experimental reactors at Aldermaston will give rise to SNF during re-fuelling / eventual decommissioning operations.

A significant hazard with the disposal of both HLW and some types of ILW is how to manage the problems of criticality. Criticality is a sudden release of neutrons from fissionable radioactive material (most commonly ^{235}U and ^{239}Pu). If enough fissionable waste is brought to a critical mass by incorrect storage and/or the erroneous infiltration of a moderator material (water), a sustainable nuclear fission could be triggered (criticality). This reaction will lead to a huge release of additional radioactive material and heat energy. Rigorous measures are required to ensure against this possibility. These measures include specific engineering controls and geological conditions that physically prevent radioactive waste from going critical. These measures often mean that there are only a limited number of sites in the UK that are geologically suitable for a repository.

It is proposed the environmental impact, from releases of R/A waste be based on the following criteria:

- Life-time of radionuclides present in the waste;
- Total activity;
- Waste classification (high, intermediate, low or very low);
- Shielding requirements (contact or remote handled waste); Remote handled waste is considered to be worse owing to the high gamma radiation fields posing a direct risk to people and ecosystems close to the waste and the need for heavy duty transport required to move waste that is shielded in lead lined flasks. This type of waste cannot be shallow buried and will have to be stored prior to the availability of purpose built repository;
- Storage requirements and cost associated with the engineered facilities to handle radioactive waste.

It is further proposed that radioactive waste can be categorised in a similar fashion to domestic and trade waste, based on hazard. Thereby radioactive waste is multiplied by the following weighting factors reflecting the additional engineering, cost and hazardous nature of the disposal.

Table 3-41 Waste Weighting Factors

AWE Waste Type	Weighting Factor
Domestic waste (i.e. office waste)	1
Trade and toxic waste (i.e. waste covered by the Special Waste Regulations 1996)	2
Low Level Waste	10
Intermediate Level Waste (contact handled)	20
Intermediate Level Waste (remote handled)	50

Scoring systems similar to the one proposed above are often used in LCA impact assessments to account for nuclear waste [43].

3.7.6 Inventory Compilation (R/A)

All contributions, including those to radioactive aspects, are compiled as an entire inventory of data in **Appendix H**. Data is presented for each of the environmental aspects in the AWE EMS, and is built up from a series of linked spreadsheets.

3.7.7 Classification and Characterisation (R/A)

The inventory is now broken down and grouped according to appropriate impact categories (classification) so that subsequent multiplication by various factors, (characterisation, normalisation and valuation), can be performed. Characterisation is performed using the new EF values for radioactive releases to water (effluent) and air (gaseous) where releases are scored according to their damage potential. The method for calculating an impact is based on the multiplication of the quantity released (Bq or litres of R/A waste) by the appropriate EF value. Data from the inventory is grouped onto spreadsheets as a matrix of aspect contributions by environmental impact categories for each individual AWE facility. Multiplication of the contribution, (Bq for the radioactive releases and litres for special landfill R/A waste), by the equivalency factor (EF) is performed and recorded in **Appendix J**.

3.7.8 Normalisation (R/A)

The normalisation factors that are calculated for this study are presented for each impact category in **Appendix I**. The results of the calculations are summarised in **Table 3-3**, and are applied to the characterisation values and shown in the results given in **Appendix J**. Individual spreadsheets showing how the normalisation values are calculated are presented and include values for the R/A impact categories:

- *Environmental Irradiation (radioactive releases to water);*
- *Environmental Irradiation (radioactive releases to air)*;
- *Special Landfill/Radioactive Waste Generation*;

3.7.9 Valuation (R/A)

Valuation is the final step in the LCIA framework and the numerical values that are developed for application in this study, and described and presented in Section 3.3.4.3, are applied to the characterisation results after normalisation. The results of the valuation process are given in **Appendix J**.

3.8 TRANSPORT IMPACTS

AWE Aldermaston supports approximately 4000 employees most of whom, (~ 70%), travel to work using cars [91]. In addition Aldermaston has a fleet of vehicles that are used on site for transporting equipment and personnel. Within the current EMS only the impacts from congestion and noise are considered. This section reviews additional environmental impacts from road vehicle use in comparison with other site operations.

The movement of traffic on roads generates pollution [92] as a result of:

- Emissions from the vehicles themselves, due to the workings of the internal combustion engine which lead to the evolution of combustion by products as well un-burnt hydrocarbons and additives in fuels;
- Abrasion and corrosion as a result of the movement of vehicles, affecting both the vehicle and the road surface;
- Turbulence caused by vehicle, activating existing pollutants.

Vehicle emissions include volatile solids and Polynuclear Aromatic Hydrocarbons (PAHs) (derived from un-burnt fuel), exhaust gases and vapours, lead compounds, (from petrol additives), and hydrocarbon losses from the fuel, lubrication and hydraulic systems [92].

Pollutants generated by the everyday passage of traffic consist mainly of the products of abrasion from tyres and paved surfaces, corrosion of vehicles and their components, fuel and lubricant losses. Tyre wear releases lead, zinc and hydrocarbons either in particulate form or in larger pieces as a result of tyre failure. Corrosion of vehicles releases pollutants such as iron, chromium, lead and zinc from rust particles and flakes of paint; their impact, as a result of runoff, being largely dependent on particle size and chemical form. Wear of the paved surfaces will release various substances: bitumen and aromatic hydrocarbons; tar and emulsifiers; carbonate, metals and fine sediment, depending on the road construction techniques and materials used. Turbulence generated by vehicle movement can mobilise and transport particles suspended in the air; conversely deposition of particles can be induced dependent upon their size grading [92].

Some basic assumptions are made regarding annual vehicle distances travelled and these are given below:

Of the 4000 staff at AWE 70% use a car to travel to and from work and do not car share (only 10% of the remaining staff actually car share [91]). This gives 2800 staff travelling twice a day for 250 working days of the year. Most staff live in the nearby areas of Reading, Newbury, Basingstoke, Tadley and Kingsclere. A small number of staff travel from farther away including Surrey, Bristol, Oxford, London, Southampton and Wiltshire. Based on this the average distance travelled is assumed to be 15km each way making a total of 30 x 2800 x 250 (working days in a year) = 21 E6 passenger km per year. This is believed to be a conservative estimate as it does not take into account the impact from shared car use.

In addition to the staff commuting there will also be the distances covered by vehicles operating on the site. The mileage from internal transport is calculated from figures used for petrol and diesel consumption [93]. Overall consumption is given in the tabulation below.

Table 3-42 Annual Vehicle Fuel Consumption - Aldermaston

Fuel Type	Quantity (litres/year)
Diesel	216666
Unleaded Petrol	13000

Fuel consumption for the fleet of small cars on site is assumed to be 30 miles/gallon or 10.67 km/litre. Using these figures diesel vans are calculated to cover:

216666 x 10.67 = 2311104 km

Whilst petrol vans are calculated to cover:

13000 x 10.67 = 138710 km

In addition to staff transport and on-site vehicles there is also the impact from delivery vehicles (Heavy Goods Vehicles - HGV). Traffic flows onto site were measured during the in-muster as part of a study in 1995 [94] and are recorded below. The traffic was monitored on the 15 and 22 August and has been multiplied by 125 (2 days x 125 gives 250 working days in a year) and then doubled to account for out-muster movements. The tabulation below shows the estimated number of HGV movements over a one-year period.

Table 3-43 Annual HGV Flows - Aldermaston [94]

Gate	Estimated number of HGV vehicles entering / leaving Aldermaston site

Main Gate	2750
West Gate South	6250
West Gate North	500

It is not possible to determine with any accuracy the journey distance of all HGVs, so the impact from transport on-site only has been estimated. The journey distance on site is assumed to be approximately 8km (the distance to the centre of site and back). Based on these assumptions the annual delivery vehicle distances are as follows:

Table 3-44 Annual Estimated HGV Distances - Aldermaston

Gate	Annual HGV On-site Distances (km)
Main Gate	22000
West Gate South	50000
West Gate North	4000

The emissions from vehicles varies widely depending upon speeds travelled, type of vehicle (petrol or diesel), age of vehicle, nature of exhaust system (i.e. catalyst fitted or not) etc. Therefore some basic assumptions about average vehicle performance is required. Approximately 80% of all the staff cars are assumed to be petrol based and the remaining 20% to be diesel powered. All of the cars are assumed to be less than 10 years old. Values defined in the UK Emission Factors Database [95] for average speeds (45kmh $^{-1}$) are used as a guide for calculating emissions from petrol and diesel cars and HGVs. The problems of releasing finely divided lead from petrol additives has been widely recognised, however in all but a few cars alternatives to lead are now used and most petrol cars run on unleaded fuel. This study assumes that there are no lead products released during the operation of vehicles used at AWE. The emissions from petrol, diesel cars and HGVs are based on the following figures [95].

Table 3-45 Vehicle Exhaust Emission - Emission Values (gkm^{-1})

Vehicle Type	NOx	PM10	CO	VOC	Benzene	1,3-Butadiene	CH_4	SO_2	CO_2
Light Duty Petrol	1.02	0.027	6.18	0.874	0.055	0.015	0.047	0.04	205
Light Duty Diesel	0.4	0.07	0.43	0.078	0.001	0.004	0.005	0.04	173
HGV	7.08	0.5	2.31	1.9	0.039	0.010	0.063	0.14	777

It is recognised that other pollutants are released as combustion by-products, however **Table 3-45** includes those emissions that are deemed to be the most important in the UK for air quality [96]. In addition to lead other heavy metals are released in some fuel types. The increasing use of control technology including catalytic converters has reduced the emission of zinc, cadmium and copper. Without control technology the following emission rates [97] can be used:

Table 3-46 Vehicle Emission Rates for Metals (g/km/vehicle) [97]

Vehicle Type	Zn	Cd	Cu
Petrol (no control technology)	0.003	1.00E-08	5.00E-5
Diesel (no control technology)	0.003	1.00E-08	5.00E-5

This analysis in this thesis makes the conservative judgement that none of the vehicles is fitted with abatement technology.

The combustion of hydrocarbon fuel with air produces mainly CO_2 and water [98]. The figures for CO_2 given in **Table 3-45** above are based on an average figure for 1997 vehicles. Diesel engines generate approximately 20% less CO_2 than petrol cars [99]. The HGV CO_2 emission data is from the Cleaner Vehicle Task Force [100].

From all of the above distance and emission data the following life-cycle transport inventory is given:

Table 3-47 Life-Cycle Inventory - AWE Transport Use (one year - kg)

	Vehicle Types (Distances – km)				
Burdens (kg) ▼	**Staff Petrol (16.8 E6)**	**Staff Diesel (4.2 E6)**	**Site Petrol (1.4 E5)**	**Site Diesel (2.3 E6)**	**HGV (7.6 E4)**
NOx	1.71E+04	1.68E+03	1.43E+02	9.20E+02	5.38E+02
PM10	4.54E+02	2.94E+02	3.78E+00	1.61E+02	3.80E+01
CO	1.04E+05	1.81E+03	8.65E+02	9.89E+02	1.76E+02
VOC	1.47E+04	3.28E+02	1.22E+02	1.79E+02	1.44E+02
Benzene	9.24E+02	4.20E+00	7.70E+00	2.30E+00	2.96E+00
1,3-Butadiene	2.52E+02	1.68E+01	2.10E+00	9.20E+00	7.60E-01
CH_4	7.90E+02	2.10E+01	6.58E+00	1.15E+01	4.79E+00
SO_2	6.72E+02	1.68E+02	5.60E+00	9.20E+01	1.06E+01
CO_2	3.44E+06	7.27E+05	2.87E+04	3.98E+05	5.91E+04
Zn	5.04E+01	1.26E+01	4.20E-01	6.90E+00	2.28E-01
Cd	1.68E-04	4.20E-05	1.40E-06	2.30E-05	7.60E-07
Cu	8.40E-01	2.10E-01	7.00E-03	1.15E-01	3.80E-03

The inventory information summarised above is reproduced in full in **Appendix K** along with the impact assessment for transport activities.

3.9 CONCLUSIONS

This chapter gives a comprehensive analysis of the environmental impacts associated with routine activities at AWE Aldermaston. The contributions made by individual facilities has been transferred into meaningful LCA inventory data and used to perform an impact assessment. New categories have been developed and a new method presented for characterisation of environmental impacts to allow for inclusion in the LCA framework.

A detailed analysis of the impact resulting from transport activities has been included as this had not been considered within the existing AWE EMS.

CHAPTER 4 SUMMARY

In this chapter a methodology to assess accidental scenarios, which have the potential to cause an environmental impact is proposed and developed. Risk assessment, has been chosen by the author, as an effective way of measuring environmental accident conditions. A discussion of the need to assess accident conditions as part of an EMS is given along with a description of the elements of risk assessment. Definitions for consequence and frequency are presented along with a new environmental consequence classification developed specifically for AWE. A description of the current hazard categorisation and risk assessment methods used at AWE is given by way of an introduction to the development of a new 6-step screening methodology to identify Major Accidents to the Environment to comply with the requirements of the COMAH Regulations. The use of a risk matrix is described for ranking all faults and this is demonstrated on a large high hazard facility at AWE.

4 METHODOLOGY FOR THE ASSESSMENT OF ACCIDENT CONDITIONS

4.1 INTRODUCTION

In Chapter 3 an impact assessment of routine contributions at AWE is given. Aspect contributions have been converted to impact categories and a new methodology provided for R/A releases. In this chapter a methodology to assess accidental scenarios, which have the potential to cause an environmental impact is proposed and developed. It is possible that without a full assessment of accident conditions, as well as routine contributions, some important risks could be overlooked. It is therefore vital that accident scenarios are assessed to build up a complete picture of environmental impact at AWE Aldermaston. Whilst an EMS must control routine and abnormal impacts some form of assessment of accident conditions is required as the potential consequences can be very damaging to an organisation. In some cases the consequences can be disastrous as in the case of the reactor accident at Chernobyl in 1986 and the dioxin release from the Seveso incident in Italy in 1976. Without proper planning and adequate controls the probability and consequence of an undesirable event can become intolerable. Accident conditions are not normally quantified in LCA unless their frequency is relatively high [25]. If their frequency is high however, they cease to become an accident and can be considered as non-routine or even routine events. Risk assessment, has been chosen by the author, as an effective way of measuring environmental accident conditions. AWE Aldermaston is a lower tier COMAH site and is required to identify potential MATTE (Major Accident To The Environment) scenarios to comply with the 1999 COMAH Regulations [105].

A methodology for the systematic identification of potential MATTE scenarios and the assessment of environmental risk using consequence and frequency is now presented. This is developed following consideration of the subject of risk assessment in general, and then by a review of facility hazard categorisation and risk assessment techniques currently used at AWE.

4.2 BACKGROUND TO RISK ASSESSMENT

The application of risk assessment techniques to many hazardous industrial processes has become widespread as a tool that can be used to assess accident conditions. Risk assessment has two components:

1. the likelihood of a hazard being realised, or its frequency and,
2. the consequences of that event if it was realised.

Hence risk can be defined as follows:

$$Risk = Frequency \times Consequence$$

Numerical values can be applied to both frequency and consequence, giving a mathematical quantity of risk to make comparisons meaningful. Frequency can be based on a judgement of the probability over a set period, usually one year, (f) (y^{-1}). The frequency analysis can be qualitative, semi-quantitative or quantitative. An example of a semi-quantitative frequency definition is given in **Table 4-1**.

Table 4-1 Frequency Definition [101]

Frequency Classification	Definition of Likelihood of Impact	Typical Range of Event Frequency (f) (y^{-1})
Frequent	Likely to be continuously experienced.	$f > 10$
Probable	Likely to occur often.	$10^{1} > f > 10^{-1}$
Occasional	Likely to occur occasionally.	$10^{-1} > f > 10^{-3}$
Remote	Unlikely to occur.	$10^{-3} > f > 10^{-5}$
Improbable	Highly unlikely, but may exceptionally occur.	$10^{-5} > f > 10^{-7}$
Incredible	Extremely unlikely that the event will occur at all.	$F < 10^{-7}$

This table shows that different probabilities are assigned to different frequency bands. The difficulty arises in determination of which is the most appropriate band and also as the range is quite wide, differences in risk between a frequency at the limits of these bands. The method is useful however for screening those risks, which require further assessment, from those that can be disregarded on the grounds of credibility (typically this is $< 10^{-6}y^{-1}$). There is little point in carrying out in-depth analysis of non-significant or tolerable risks as effort should be focussed on those that are significant, or those for which the full extent of their tolerability has yet to be determined. The degree of complexity applied is dependent on the nature of the hazard and the degree of confidence that is required. Often value judgements are used to screen hazardous scenarios before more quantitative methods are used to calculate frequency. Sophisticated computerised systems are available to determine probability whereby initiating events, (for example valve failure), and decision gates are used to build up a numerical picture of the event and calculate the frequency of a top event. These pictures are called Fault Trees and use Boolean algebra to calculate frequency. The method allows all the engineered and managerial controls in place to be modelled. An intimate knowledge of the system being assessed is required and reliable input data are required for initiating event failure. This technique is known as Probabilistic Safety Assessment (PSA) or Probabilistic Risk Assessment (PRA) and is widely used in the nuclear, chemical, energy and rail industries.

An alternative method of risk assessment is deterministic analysis, which, as the name implies justifies acceptability based on a determination of the adequacy of the engineered design system and controls. An evaluation of the protective system is made, based on age, operating conditions, maintenance and test regimes, and the risk of failure calculated. If the system is operated within set limits then the risk of failure can be determined to be either tolerable or not. Deterministic analysis is usually qualitative but quantitative assessments can be made based on knowledge of design data and operating conditions. The two techniques are complimentary and many assessments use a combination of both probabilistic and deterministic methods. For old plant where the exact operating history and conditions are unknown deterministic techniques will not be appropriate and probabilistic methods will be required.

Consequence assessment seeks to calculate the severity of the event if it were realised, and for environmental analysis, evaluations are made concerning the following three parameters:

Source. This is where the contaminants originated from and information can be gathered on its size, its form (powder, liquid, gas or solid) and toxicity;

Pathway. This is the route by which the pollutant or burdens can move within the environment either through natural features including streams, groundwater, air masses or man-made features including, pipes, ducts, surfaces. Pathway can also include ingestion routes and respiratory airways through which pollutants can travel into the organs and tissues of various species.

Receptor. This is the area where pollutants accumulate and this can be a protected species, a lake, river, or the tissues of human or animal populations.

As with frequency assessment the consequence assessment can be based on value judgements or quantitative methods that use mathematical models to work out contaminant migration and the fate of various pollutants in the environment. These models have become very sophisticated using computer programs to predict pollutant dispersal and deposition based on weather patterns. Semi-quantitative methods use various severity classifications to grade consequence based on the extent or the reversibility of environmental damage. An example of these severity bands is given in **Table 4-2**.

Table 4-2 Consequence Definition [101]

Consequence Severity Classification	Definition
Catastrophic	Severe widespread long-term environmental damage (not reversible). Major release of R/A or toxic material. R/A dose to humans, which may result in fatalities.
Critical	Severe localised environmental damage (not reversible). Large release of R/A or toxic material to the environment. R/A dose to humans.
Marginal	Local environmental damage reversible in the short term. Small spillage of R/A material to the environment. R/A dose to humans.
Minor	Minor environmental disruption, minor spillage. Non-R/A spillage.
Negligible	Trivial damage, no long-term environmental consequence.

These consequence definitions were developed previously by the author [101] and are based purely on the severity of environmental impact. A problem with the consequence definition given above is that it is often very difficult to judge if a release of toxic or radioactive material will result in a reversible damage without applying expensive modelling. Also under the critical and marginal classifications, R/A dose to humans is given as a definition; even small discharges however, can give a dose and it is the magnitude of the dose that is important. Again modelling is required to accurately predict dose to critical groups (human or otherwise).

The author proposes in this research a more sophisticated consequence definition based on the AWE environmental aspects. This will link the risk assessment with the AWE

EMS and the wider definition of consequence based on business issues (monetary), societal preference (stakeholder concerns) as well as environmental impact. This accords with the valuation method developed in Section 3.3.4.3 for the weighting in the life-cycle impact assessment. The monetary and societal preference elements are based on the business and stakeholder scores used to determine corporate significance in the AWE EMS [13].

Environmental accidents result in impacts from one or more of:

- Accidental Releases to Air
- Accidental Releases to Water
- Additional Waste Generation

These impacts are in the main as a result of spillages, fires or explosions. The specific AWE sub-aspects that apply are given in **Table 4-3** along with their original monetary, societal and environmental impact scores that were used for corporate significance assessment [13].

Table 4-3 Air, Water and Waste Aspect Significance Scores [13]

Corporate Environmental Aspect	Environmental Impact Score (out of 9)	Monetary Value Score (out of 9)	Societal Preference Score (out of 15)	Total score	Corporate Significance
Releases to Air - R/A	7	7	15	29	High
Releases to Air – Acids	3	3	5	11	Low
Releases to Air - VOCs	5	3	5	13	Low
Releases to Air - ODSs	7	4	10	21	Medium
Releases to Air – Be	5	3	6	14	Low
Releases to Air – Pb	5	1	3	9	Low
Releases to Air - Combustion by Products	7	1	6	14	Medium
Releases to Water – R/A Effluent	7	9	14	30	High
Releases to Water – Trade Effluent	4	5	5	14	Medium
Releases to Water – Domestic Effluent	4	3	3	10	Low
Releases to Water – Engineered Surface Water	6	9	12	27	High
Releases to Water – Un-engineered surface Systems	6	8	11	25	High
Releases of Waste - R/A	9	8	14	31	High
Releases of Waste - Trade Waste	4	3	5	12	Low
Releases of Waste – Domestic Waste	2	4	7	13	Low

Based on the information given in **Table 4-3** more meaningful definitions can be derived for accidental releases, which match the corporate importance placed on different substances.

The revised consequence definition, developed by the author is presented in **Table 4-4**.

Table 4-4 Revised Consequence Definitions. Based on Environmental Impact, Monetary and Societal Preference Issues

Environmental Aspects	Corporate Significance	Definitions [Source Author]	Consequence Severity Classification
Releases to Air – R/A	High	Accidental discharge of radioactive material to air, resulting from a fire or explosion. An engulfing fire would need to breach containment systems and result in catastrophic collapse of the building structure.	Catastrophic
Releases to Water – R/A	High	Accidental release of water contaminated with radioactive effluent to the surface water systems from a fire or explosion (see footnote).	
Releases to Air – R/A	High	Accidental release of radioactive material to air (other than from a fire or explosion).	Critical
Releases to Water – R/A	High	Accidental discharge of water contaminated with radioactive effluent to the engineered or un-engineered surface water system.	
Releases of Waste – R/A	High	Accidents, which result in the generation of additional R/A waste.	
Releases to Air - ODSs & Combustion by Products	Medium	Accidental release of ODS to air from a spillage. Release of combustion by products from a fire or explosion in a building containing chemicals classed as dangerous by the COMAH regulations (see **Appendix L**).	Marginal
Releases to Water – Trade Effluent	Medium	Accidental release of water contaminated with trade effluent to the engineered or un-engineered surface water system.	
Releases to Air – Acids, VOCs, Be & Pb.	Low	Accidental release of acids, volatile organic compounds, beryllium or lead to air.	Minor
Releases to Water – Domestic Effluent	Low	Accidental release of water contaminated with domestic effluent to the un-engineered surface water system.	
Release of Waste- Trade or Domestic Waste	Low	Accidents, which result in the generation of additional trade or domestic waste.	
Releases to Water – Domestic Effluent	Low	Accidental release of water contaminated with domestic effluent to the engineered surface water system.	Negligible

Note. A release of R/A effluent to the un-engineered system is considered by the author to be worse than the engineered system as there is much reduced chance of mitigating the effects by intercepting the contamination in the on-site (engineered) drainage system. Although in a fire situation it is likely that both the engineered and un-engineered systems would be affected by firewater run-off.

The definitions given above reflect importance and concerns based on AWEs business (cost), societal preferences and environmental impact. It is important to note that physical quantities have not been used to differentiate between categories, as this is very difficult to calculate without recourse to modelling. The author recognises that as greater quantities of for example radioactive material are released to the environment in an accident, the more serious the potential consequence. It is the political reaction to any uncontrolled release (even relatively small ones) however, that will determine overall consequence. This methodology, being derived here from the EMS, takes account of these concerns. Modelling is very time consuming and expensive and is not considered to be economically viable or indeed necessary for most accident scenario assessments. As all high hazard category facilities, (category 3, 4 and 5) are required to justify their continued operation based on an assessment of faults, (contained in a Safety Case), for NII licensing purposes, a great deal of information about safety consequence already exists. The Safety Case fault schedule is derived from structured hazard identification exercises and contains details of faults with environmental consequence. As the acceptability of a fault is primarily based on safety consequences however, a methodology for environmental faults is needed. The higher hazard category facilities (Category 3, 4 and 5), Safety Cases usually contain detailed information on frequency analysis.

The consequence methodology presented in this thesis is complimentary to techniques already employed giving refinement to assist in assessing the significance and acceptability of specific environmental faults. Where there is the possibility of more than one consequence category the worst-case scenario shall be used to determine the appropriate classification.

4.3 HAZARD CATEGORISATION AND RISK ASSESSMENT AT AWE

At AWE the application of risk assessment is widespread. All work, from the operation of laboratories, workshops and offices to decommissioning of redundant facilities and the remediation of contaminated land is subject to some form of risk assessment. The concept of risk assessment is central to the regulation of the site by the Nuclear Installation Inspectorate (NII) and each operating facility is required to justify continued operation by submission of a Safety Case containing a risk assessment. The purpose of the risk assessment is to demonstrate that risks from operations are tolerable. Risks are identified on a schedule and screened and assessed to determine their category [102] as:

- **Risk Class A** Intolerable
- **Risk Class B** Tolerable with demonstration of the ALARP (As Low As Reasonably Practicable) principle
- **Risk Class C** Tolerable

Any class "A" risks carry an unacceptable risk and changes to operations must be made to reduce the risk. In practice this will mean establishing better control regimes to reduce the severity or likelihood of the risk.

The perception of risk is dependent on many different factors. It is worthwhile at this point to put risk into context, as perception is often different from reality. **Table 4-5** gives a comparison of average annual risk of death in the UK.

Table 4-5 Average Annual Risk of Death from Various Causes [103]

Activity	**Risk of death per year**
Smoking 10 cigarettes per day	1 in 200
Breathing indoor air at UK action level for radon gas	1 in 300
Cancer, all ages	1 in 350
Commercial fishing (deep sea)	1 in 500
Deep coal mining	1 in 700
Accidents in the home	1 in 10000
Accidents on the road	1 in 11000
Nuclear industry workers	1 in 20000
Exposure to the UK government public dose limit of 1 mSv per year	1 in 100000
Lightning strike	1 in 10000000
High exposure to seafood potentially contaminated with radioactive fragments around the outfall pipe at UKAEA Dounreay (see note below)	1 in 10000000

NB. A ban was imposed in 1997 around the outfall pipe because tiny irradiated nuclear fuel fragments were found on the seabed nearby. Despite the fact that no radioactive material has been found in any fish or shellfish since monitoring began in the 1960s. UKAEA affirms that it will take all reasonable measures to reduce a small risk to an even smaller risk.

Table 4-5 shows a range of risks to which humans are exposed to each year, along with the differences in probability of their occurrence. A distinction should be made between imposed and voluntary risk, as people tend to be more concerned about issues over which they have no control. This is why, exposure to man-made radiation is a major concern even though the risks can be very low. This can be compared to risk associated with voluntary lifestyle choices, e.g. smoking, which invariably carries a much higher risk of premature death.

An initial hazard assessment of facilities at AWE was carried out to determine facility categorisation. This is based on an examination of the potential accidents with the worst credible hazard being used to assign categorisation. This categorisation [104] does include some element of potential environmental impact, but is primarily focussed on nuclear safety and is based on the following, in descending order of severity:

Category 5	Hazard potential off the site.
Category 4	Hazard potential confined to the site.
Category 3	Hazard potential limited to the confines of the plant or building.
Category 2	Very minor hazard.
Category 1	No significant hazard on site i.e. office building.

Different categories dictate the varying degrees of scrutiny for which a Safety Case will be subject. It should be stressed that only credible accidents are considered. Incredible accident scenarios that have very remote frequencies, for example seismic events or plane crashes are discounted. It is not considered to be worthwhile or economically viable to base decisions on such incredible events.

4.4 METHODOLOGY FOR IDENTIFYING MAJOR ACCIDENTS TO THE ENVIRONMENT

AWE Aldermaston is classified as a lower tier COMAH site owing to its holdings of "Dangerous Substances". The COMAH regulations [105] came into force in 1999 and are the UKs response to the European Union's Seveso II Directive. The purpose of these regulations is to:

- Identify Major Accident Hazards (MAH);
- Ensure that control measures are in place to prevent a MAH;
- Ensure that mitigatory measures are in place to limit effects if MAH do occur.

The Health and Safety Executive (HSE), and the Environment Agency (EA) jointly enforce the regulations. The fundamental requirement, taken directly from the regulations, [105] is:

"Every operator shall take all measures necessary to prevent major accidents and limit their consequences to persons and the environment".

Operators are bound by the requirements of the regulations depending on their inventories of dangerous substances. AWE Aldermaston holds in excess of 10 Te of High Explosive and is a lower tier COMAH site. One of the requirements of these regulations [105] is to identify Major Accidents to the Environment (MATTE). The purpose of this identification exercise is to subsequently identify appropriate emergency response arrangements.

This section gives a methodology developed by the author to systematically identify potential MATTE scenarios. These scenarios represent the highest environmental hazard potential for which adequate emergency response arrangements need to be in place. As the identification of MATTE scenarios is a mandatory legal requirement it is considered sensible that a framework for assessing accident conditions should be built on the environmental issues associated with the COMAH regulations [105].

The development of a screening methodology is presented and described. A methodology for assessing and ranking all environmental faults is given in Section 4.5.

Patterson proposed [106] a five stage screening process, which was based on a review of environmental faults presented in environmental addenda [5]. Patterson's methodology, broken down into five stages, is described below. A critique of each stage is also given:

Screening Stage 1 [106]

Review environmental addenda and identify those facilities, which have the potential to impact off-site and collate all these accident scenarios.

Evaluation of Stage 1

It is not clear what criteria are used to determine potential to impact off-site and is assumed to be based on the hazard categorisation described above in Section 4.2. If this were the intention then only Category 5 facilities would be screened in.

Screening Stage 2 [106]

Screen out all accidents, which do not impinge on those aspects directly associated with the environment to leave the aspects defined below. Faults are sorted thus:

Conservation	Ecology – Species
	Ecology - Habitats

	Ecology – Heritage
Land Quality	Land Quality – Solvents
	Land Quality – Metals
Releases to Air	Releases - to air: Beryllium
	Releases - to air: Acids
	Releases - to air: Lead
Releases to Water	Releases - to water: engineered surface water
	Releases - to water: un engineered surface water

Patterson [106] selected these aspects as they relate to environmental Major Accident Hazards (MAH), because they are associated with events external to facilities. These groups are a subset of the corporate environmental aspects used in the EMS (**Table 3-1** in Section 3.2). The purpose of this screening stage was to allow subsequent screening according to the mechanism by which substances are released into the environment.

Evaluation of Stage 2

The drawback with this grouping stage is that faults that impact on several aspects will be duplicated leading to increased workload during analysis with the associated risk of errors during subsequent screening. For example a fire could lead to releases to air, impact on land quality via deposition, disrupt ecology and any contaminated firewater run-off could challenge surface waters. Thus fire scenarios would be duplicated into four impact scenarios.

Screening Stage 3 [106]

Screen out all incidents involving radioactive materials, leaving accidents, which involve only chemicals, oils and toxic materials. Radioactive scenarios are covered by the Radioactive Substances Act 1993 [12] and are not applicable to COMAH regulation.

Evaluation of Stage 3

This is a sensible screening stage. Radioactive releases are assessed in great detail to comply with site Nuclear Licence conditions and are not applicable to COMAH regulations. There remains some doubt over depleted uranium (DU), which owing to its chemical toxic properties is under review and debate for possible inclusion.

Screening Stage 4 [106]

Screen out those accident scenarios that do not involve dangerous substances as defined in the regulations (Schedule 1 Parts 2 and 3). This stage focuses on the specific type of substance that is released and how dangerous it is in the environment.

Evaluation of Stage 4

It is not clear what specific criteria are to be used for screening, but they are assumed to be based on the presence, however small, of a listed substance and/or one exhibiting the properties of one or more of the generic categories. The dangerous substances as defined by the COMAH regulations are reproduced in **Appendix L**.

The problem with the definition and list of dangerous substances as given by the COMAH regulations is that it is not comprehensive. There are many gaps in our knowledge of the behaviour and fate of substances in the environment and the list of generic categories that are considered dangerous to the environment only cover the following risk phrases [44].

R50	Very Toxic to the Environment
R51	Toxic to aquatic organisms
R53	May cause long-term adverse effects in the aquatic environment

There appears to be no justification in the Regulations [105] for the omission of the following substances:

R52	Harmful to aquatic organisms
R54	Toxic to flora
R55	Toxic to fauna
R56	Toxic to soil organisms
R57	Toxic to bees
R58	May cause long-term adverse effects in the environment
R59	Dangerous for the ozone layer

The author considers that the reason behind these omissions may be that they are not considered to be major. A potential problem with this stage is that some substances may be screened out that have the potential to cause a major accident. Sulphuric Acid for example is not a listed dangerous substance in the regulations and does not exhibit any of the properties in the generic category. Under CHIP (Chemical Hazard

Identification and Packing for Supply Regulations) classifications [44] it is classed as risk phrase R35 (causes severe burns) and would automatically be screened out. A bulk release of sulphuric acid into an aquatic receptor however, may well change the pH so that organisms are killed and this could be considered to be a major accident scenario, even though it is not strictly a MATTE scenario. Clearly it makes sense to assess environmental risks at the same time as identifying those hazards that are considered to be MATTE in accordance with the Regulations.

Screening Stage 5 [106]

The final stage in the screening process proposed the use of consequence modelling, both atmospheric and aquatic to determine concentrations at specific receptor sites and confirm or otherwise that the release represents a MATTE.

Evaluation of Stage 5

This stage is expensive and can be time consuming to implement especially for a large industrial site like Aldermaston. This is the method however, that is inferred in the DETR guidance [107] on MATTE identification. This guidance [107] gives threshold limits and recovery periods for different species and receptor sites for which the only method of assessing impact is to determine off-site concentrations. Ecologists would then be required to evaluate the potential damage to populations, the short and long-term effects and recovery periods.

The specific concerns with each of the stages described, has been discussed. The author considers that restricting the screening to faults that are given in the Environmental Addenda is a significant shortcoming. The Environmental Addenda were focussed on assessing routine and non-routine aspect contributions and meeting the requirements of ISO 14001 rather than a specific piece of legislation. The accident identification process in these reports was limited to obvious faults, typically fires and spills and not based on any structured hazard identification exercise. The Safety Cases, on the other hand, that are prepared to justify facility operation in accordance with the Nuclear Site Licence conditions are built on very structured hazard identification processes including hazard and operability studies (HAZOP), critical examination (CE) and Failure Modes and Effects Analysis (FMEA) and include environmental faults. The treatment of these faults for risk assessment however, is limited as justification and acceptability of all scenarios is primarily based on safety considerations.

An improved method of MATTE identification and the application of environmental risk assessment for accident conditions developed by the author is presented as a six step MATTE screening methodology.

4.4.1 6-Step MATTE Screening Methodology

Patterson's screening process has been refined and developed by the author into a new 6-step process. The approach to MATTE identification is to review individual facilities, regardless of hazard categorisation as follows:

1. Desktop review of appropriate documentation:
    - The COMAH inventory database generated by the Facility;
    - The Approved Fault Schedule from the Safety Case;
    - The Accident scenarios in the Environmental Addendum/Statement.
2. Walk-through audit of the facility using the inventory as a guide to identify further environmental hazards. A new audit methodology checklist developed by the author is used to identify environmental hazards during a facility walkthrough. The checklist is reproduced in **Appendix M**;
3. Screening and assessment of all identified environmental faults.

This approach immediately limits the review to those facilities that have holdings of chemical substances. The screening and assessment process is described detail below.

4.4.1.1 Revised Methodology Screening Step 1

Screen out those scenarios that do not impact directly on the environment. The purpose is to remove all scenarios that are non-environmental in consequence. For example a spillage of a chemical in a laboratory that results in the substance remaining contained inside the building is screened out. Although internal spills will result in additional clean-up waste that will have an environmental impact, this should be screened out, as it will not cause immediate damage. Similarly any faults with a safety consequence only (physical injury etc.) are also screened out. If it is not possible for the chemical substance to reach the environment in that particular fault sequence, it should be screened out.

4.4.1.2 Revised Methodology Screening Step 2

Screen out those scenarios that do not involve dangerous substances as defined in the COMAH regulations (Schedule 1, Parts 2 and 3) – see **Appendix L,** which reproduces the list. The regulations clearly state what is considered to be a dangerous substance.

This step will screen out some substances that are dangerous in the environment but are not listed as dangerous in the regulations. It is proposed however, that the screening process be totally transparent and all environmental faults will be subject to ranking in accordance with the risk assessment process described in Section 4.5. For the purposes of regulation only 'true' MATTE faults (i.e. those involving COMAH substances) should be identified as such. By definition this means that a COMAH substance must be involved somewhere in the fault sequence (initiator, partaker, product, bi-product or pre-cursor). Should a COMAH incident occur it would have to be reported, by the HSE & EA, to the EU. Given this, only relevant faults must be identified as MATTE (i.e. a loss of sulphuric acid from a tank to a stream, whilst environmentally significant, is not a MATTE unless a COMAH defined dangerous substance such as explosives is involved in the fault sequence that led to the release).

4.4.1.3 Revised Methodology Screening Step 3

Screen out those substances involving radioactive substances. It is important to note that this step can only be applied to faults that involve radioactive materials and no other hazardous substances. Although radioactive scenarios are screened out for MATTE identification purposes they still need to be included for subsequent risk assessment (see Section 4.5). For this reason the MATTE identification screening should be carried out after the environmental risk assessment process.

4.4.1.4 Revised Methodology Screening Step 4

Assess COMAH inventory involved in the accident to determine if the quantity released could constitute a MATTE or not. Screen out using qualitative and deterministic arguments those scenarios that do not have the potential to impact on the nearest SSSI or conservation receptor. There are 2 SSSI that lie within the Aldermaston site boundary; Decoy Ponds and Grim's bank (see **Appendix D**). The site fence is conservatively considered to be the nearest sensitive receptor when the on-site SSSI sites are not under threat.

4.4.1.5 Revised Methodology Screening Step 5

Screen out using a more detailed analysis of the accident by characterising the fault in terms of consequence and frequency. Many of the major hazards at AWE are very well controlled such that the frequency of it happening is low. Screening step 5 looks at frequency arguments for a fault to determine its credibility.

A return frequency of 1 x 10^{-6} yr^{-1} is the likelihood of a fault occurring once in 1,000,000 years. This is not considered to be a credible return frequency for classification as a potential MATTE. Any faults that can be shown to have return frequency of <1 x 10^{-6} yr^{-1} are therefore screened out. The AWE Facility Safety Case provides a calculation of frequency for fault conditions. Consequences are also evaluated in this step, where the frequency cannot be calculated or is determined to be > 1 x 10^{-6} yr^{-1}. A simple unit release model [108] is considered to be appropriate for assessing atmospheric releases and is based on the modelling tool Aermod [109] and is suitable for all gaseous releases apart from dense gas scenarios. The programme [108] results are transferred to excel spreadsheet format, which calculates the amount released. Finely divided metal releases, for example beryllium, can be used in this model as the material is assumed to be entrained in the plume and therefore a worse case. If one agrees that metals will fall to land via deposition sooner than particulates or gases, then assuming the material stays with the plume is bound to be a worse case, based on geographical spread as the plume will spread further. The atmospheric modelling programme [108] requires the following variables to calculate concentration:

- Unit release (g/s) based on the inventory involved in the fault;
- Release fraction (no unit). Credit can be taken for certain scenarios for example the re-suspension of powder in a drop scenario and the fraction of a volatile organic compound that is vaporized once it has been spilled.
- Containment factor (no unit). Credit can be taken for the effectiveness of certain containment barriers for example building fabric or a high integrity enclosure.

Care must be taken when applying these factors and values should be taken from reliable sources and fully justified. The choice of containment factor and release fraction must also be transparent.

For aquatic releases this step evaluates the nature of the fault in detail to determine the amount of material released. Dilution factors are then be applied to calculate receptor concentrations based on worse case assumptions.

For consequence assessment the predicted concentration can be compared with Environmental Quality Standards (EQS) or Environmental Assessment Levels (EAL). These are published by the EA and can be used as a benchmark to assess damage to the environment. Current guidance [110] publishes figures for routine contributions whereby a release can be considered insignificant if:

$$\text{Concentration} < 0.002 \text{ EAL}$$

This has been amended in the latest draft guidance for IPPC [111], which considers insignificance:

$$\text{Concentration} < 0.01 \text{ EAL.}$$

Only the latest guidance [111] however, gives a value for accidental releases. The actual word 'major' is used in the guidance to describe scenarios where the concentration at the receptor site is > 10 x EAL. This value is used in step 5 to evaluate consequence. Scenarios which have a return frequency of $> 1 \times 10^{-6}$ yr^{-1} and/or a receptor concentration > 10 x EAL are considered to be potential MATTE.

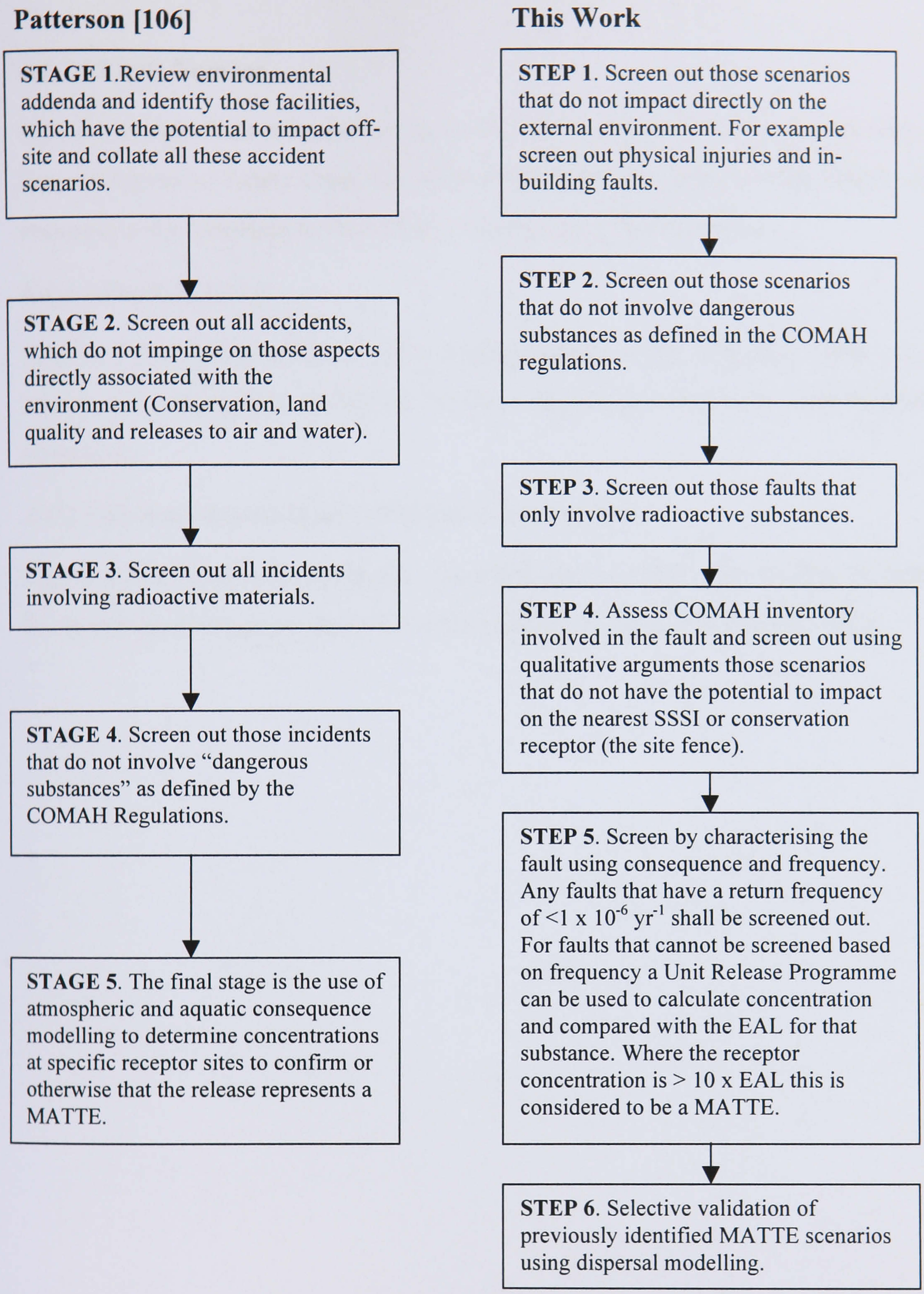
It is important to note that the purpose of step 5 is to carry out enough analysis to determine whether the scenario is a potential MATTE. Detailed quantitative consequence modelling is not carried out in this step (see step 6). AWE like many large industrial sites has a considerable number of facilities to assess and the author considers that it is not possible to justify the cost or time necessary to model all scenarios. It is not always necessary to know the exact effects on the environment in order to make a valid judgement about acceptability and industry must be able to prioritise resources for decision-making.

4.4.1.6 Revised Methodology Screening Step 6

This step is used selectively to check the validity of previous scenario assessments by dispersal modelling. Quantitative analysis, using aquatic and atmospheric dispersal modelling software is applied to a selected number of scenarios to validate by consequence that scenarios are MATTE.

4.4.2 Application of Screening

In order to apply the screening methods described in a transparent and efficient way the author proposes application of steps 1 to 4 in the form of tabulated schedule of faults, as shown in **Table 4-6**. This is because it is possible to carry out steps 1 to 4 as a parallel set of tasks not necessarily in isolation. A description of each of the column headings is given below. Any faults that are carried forward for more detailed analysis (step 5) are evaluated in the form of written discussion and do not form part of the tabulated assessment. The differences between Patterson's method [106], and that proposed in this work are illustrated in the following flow-charts:



Patterson [106]

STAGE 1.Review environmental addenda and identify those facilities, which have the potential to impact off-site and collate all these accident scenarios.

STAGE 2. Screen out all accidents, which do not impinge on those aspects directly associated with the environment (Conservation, land quality and releases to air and water).

STAGE 3. Screen out all incidents involving radioactive materials.

STAGE 4. Screen out those incidents that do not involve "dangerous substances" as defined by the COMAH Regulations.

STAGE 5. The final stage is the use of atmospheric and aquatic consequence modelling to determine concentrations at specific receptor sites to confirm or otherwise that the release represents a MATTE.

This Work

STEP 1. Screen out those scenarios that do not impact directly on the external environment. For example screen out physical injuries and in-building faults.

STEP 2. Screen out those scenarios that do not involve dangerous substances as defined in the COMAH regulations.

STEP 3. Screen out those faults that only involve radioactive substances.

STEP 4. Assess COMAH inventory involved in the fault and screen out using qualitative arguments those scenarios that do not have the potential to impact on the nearest SSSI or conservation receptor (the site fence).

STEP 5. Screen by characterising the fault using consequence and frequency. Any faults that have a return frequency of $<1 \times 10^{-6}$ yr^{-1} shall be screened out. For faults that cannot be screened based on frequency a Unit Release Programme can be used to calculate concentration and compared with the EAL for that substance. Where the receptor concentration is $> 10 \times$ EAL this is considered to be a MATTE.

STEP 6. Selective validation of previously identified MATTE scenarios using dispersal modelling.

Step 6 is only applied to a set sample of scenarios to verify the robustness of the previous steps, for assurance purposes, for example to 10% of identified MATTE scenarios. This is considered to be a more cost effective use of the expensive and time consuming modelling that is applied as step 5 in Patterson's method [106].

4.4.2.1 Fault Number

This is a unique fault reference given to each fault. Where the scenario has been taken from an approved Safety Case, the faults will already be uniquely numbered to allow a traceable audit trail back to the original hazard identification exercise.

4.4.2.2 Fault Scenario

This is a description of the fault including details of the initiating event. As much information as possible should be included in this description to help facilitate the evaluation.

4.4.2.3 Environmental Impact (Potential Consequence)

This is a description of the impact. This information is useful for helping to determine the faults significance. Quantitative information is not calculated at this stage.

Table 4-6 Example of the Proposed Tabulation for Recording Potential MATTE Faults

<table>
<tr><th colspan="10">MATTE Identification Schedule</th></tr>
<tr><th colspan="10">Accident Scenarios – Screening STEPS 1 to 4</th></tr>
<tr><th>Fault Ref.</th><th>Fault Scenario</th><th>Environmental Impact (Potential Consequence)</th><th>Risk Phrase</th><th>COMAH Substance involved in Scenario (Y/N)</th><th>Aspects</th><th>Inventory involved in the scenario</th><th>Physical Form</th><th>Off Site Impact (Yes/No) and Justification</th><th>Reason for Screening Out as non MATTE</th></tr>
<tr><td>1</td><td>Detailed description of the fault.</td><td>Description of the potential consequence in terms of environmental impact.</td><td>List phrases here R2 etc.</td><td></td><td>Identify AWE environmental aspects as appropriate, for example Land Quality, Releases to Water etc.</td><td>For example 10 kg of high explosive.</td><td>Solid, Liquid or Gas</td><td>Qualitative statement describing if the fault has the potential to impact off the AWE site.</td><td>Statement giving details and reasons for screening in (for further analysis – step 5) or out.</td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

4.4.2.4 Risk Phrase

This column is used to record the substance(s) risk phrase to demonstrate that if the substance is not classed as dangerous there is some traceable check to show this. The term risk phrase was first adopted as a definition in the CHIP 2 regulations [44] and provides information about the hazards of a chemical in normal use. Risk phrase numbers can be used to determine if a substance falls under the property headings in Schedule 1 Part 3 of the regulations (see **Appendix L**).

4.4.2.5 COMAH Substance Involved in Scenario (Y/N)

This column is to record if a COMAH substance (classed as dangerous by the regulations – see **Appendix L**) is involved anywhere in the fault sequence, either as an initiator, partaker, product, bi-product or pre-cursor. If a COMAH substance is not involved in any part of the fault sequence it should be screened out using this methodology. The column requires a yes or no input based on risk phrase and other information about the substance(s) involved.

Mineral oil is not currently considered to be a COMAH substance, however proposals are being debated to include mineral oil as a COMAH substance in the near future. For this reason the application of this methodology given in **Appendix N**, assumes that scenarios involving mineral oil should be thoroughly assessed as potential COMAH/MATTE scenarios.

4.4.2.6 Aspects

This column is used to record information about which environmental aspects the fault impacts upon. The purpose of this column is to provide a link to the AWE EMS. One or more of the following aspects will be recorded:

Releases to Air; Releases to Water; Land Quality or Ecology.

4.4.2.7 Inventory Involved In The Scenario

This is an estimate of the quantity of materials that may be involved in the scenario. As it is taken from facility inventories it is unlikely that the precise release fraction will be known at this stage. However, if only trivial quantities are stored or used in a process it is possible to make judgements about screening on a worse case basis without having to do the more detailed analysis required in step 5.

4.4.2.8 Physical Form

This column is to record the form the material is released, either, gas, solid, liquid or powder.

4.4.2.9 Off site Impact (Y/N) and Justification

This column is used to record arguments about whether the substance can cause an impact off-site or challenge on-site receptors (SSSI). The column requires a yes or no input and a justification. The justification is based on the amount of inventory released (source based) and the pathways to transfer substances in the environment.

4.4.2.10 Reason for Screening Out as a non-MATTE

This column is used to state why the scenario is not considered to be a potential MATTE. All the previous column entries are considered and a judgement made. If there is not enough information to determine if the fault is MATTE, it should be carried forward (screened-in) for further analysis. A statement needs to be made recording if the fault is screened in or out.

4.4.2.11 Treatment and Prioritisation of Identified MATTE Faults

Once MATTE faults have been identified, existing emergency response arrangements can be reviewed for adequacy. The DETR guidance [107] gives detailed information on what is considered to be best practice for emergency response as part of Risk Management strategies for environmental accidents.

As AWE Aldermaston has in excess of 60 facilities with holdings of COMAH substances, some form of prioritisation over which ones represent the most importance for the Company as a whole is required. The author proposes to use the qualifying quantities for a lower tier site to give a determination of relative harm. The regulations specify limits for the named substances and categories given in Schedule 1 Parts 2 and 3, and reproduced in **Appendix L**. If the site total holding exceeds one of these limits then it is classed as a lower tier site and specified regulations apply. If the site total holding exceeds any of the higher limits then it is classed as an upper tier site and all of the regulations apply. The lower limits reflect the HSE and EAs interpretation on what substances are most harmful. For example the lower tier limit for substances classed as flammable is 5000 Te, whereas for substances classed as explosive this limit is 10 Te and for some particularly dangerous substances including dioxins and carcinogens this limit is only 0.001 Te.

The author proposes to calculate relative harm based on these limits for each of the substances, assuming that for the maximum lower tier limit (5000 Te) the corresponding harm index value is equal to one. Therefore by dividing this maximum limit by the other lower tier limits a relative harm value can be calculated. Care must be taken when using these figures to assess risk. The wide-ranging relative harm index suggests a dramatic difference in importance, which, could be misinterpreted and some MATTE faults perceived to be a far greater risk. The relative harm index should therefore be further refined into weighting bands (**Table 4-7**), used only as a guide to prioritise emergency response planning arrangements.

Table 4-7 Proposed Scores for Relative Harm Index Values

Relative Harm Index Range	Harm Score
Above 50000	10
10000-50000	5
1000-9999	4
100-999	3
10-99	2
1-9	1

The application of these harm scores is given in **Table 4-8** of named substances and **Table 4-9** specific categories.

Table 4-8 Relative Harm Index and Scores for Named Substances

Named COMAH Substance	Notification Limit [105] Te	Relative Harm Index	Harm Score
Ammonium nitrate	350	14	2
Ammonium nitrate conforming to Fertiliser Regulations 1991.	1250	4	1
Arsenic pentoxide, arsenic (V) acid and/or salts	1	5000	4
Arsenic trioxide, arsenious (III) acid and/or salts	0.1	50000	5
Bromine	20	250	3
Chlorine	10	500	3
Nickel compounds in inhalable powder form (nickel monoxide, nickel dioxide, nickel sulphide, nickel disulphide, nickel trioxide)	1	5000	4
Ethyleneimine	10	500	3
Fluorine	10	500	3
Formaldehyde (concentration ≥ 90%)	5	1000	4
Hydrogen	5	1000	4
Hydrogen chloride (liquefied gas)	25	200	3
Lead alkyls	5	1000	4
Liquefied extremely flammable gases (including LPG) and natural gas (whether liquefied or not)	50	100	4
Acetylene	5	1000	4
Ethylene oxide	5	1000	4
Propylene oxide	5	1000	4
Methanol	500	10	2
4, 4-Methylenebis (2-chloraniline) and/or salts in powder form	0.01	500000	10
Methylisocyanate	0.15	33333	5
Oxygen	200	25	2
Toluene diisocyanate	10	500	3
Carbonyl dichloride (phosgene)	0.3	16667	5
Arsenic trihydride (arsine)	0.2	25000	5
Phosphorus trihydride (phosphine)	0.2	25000	5
Sulphur dichloride	1	5000	4
Sulphur trioxide	15	333	3
Polychlorodibenzofurans and Polychlorodibenzodioxins (including TCDD), calculated in TCDD (Tetra Chloro Dibenzo p Dioxin) equivalent	0.001	5000000	10
The following CARCINOGENS: • 4-Aminobiphenyl and/or its salts • Benzidine and/or salts, Bis(chloromethyl) • Ether, Chloromethyl methyl ether, • Dimethylcarbamoyl chloride, • Dimethylnitrosomine, • Hexamethylphosphoric trimide, • 2-Naphthylamine and/or salts, • 1,3 Propanesultone and 4-nitrodiphenyl	0.001	5000000	10
Automotive petrol and other petroleum spirits	5000	1	1

Table 4-9 Relative Harm Index and Scores for Specific Categories

Specific COMAH Category	Notification Limit [105] Te	Relative Harm Index	Harm Score
Very Toxic	5	1000	4
Toxic	5	1000	4
Oxidising	50	100	3
Explosive plus pyrotechnics or explosives contained in an article	50	100	3
Explosive	10	500	3
Flammable	5000	1	1
Highly Flammable Flash point less than 55°C	50	100	3
Highly Flammable Liquids Flash point less than 21° C	5000	1	1
Extremely Flammable	10	500	3
Dangerous to the environment Very toxic to the environment	200	25	2
Dangerous to the environment Toxic to the environment	500	10	2
Reacts violently with water	100	50	2
Liberates toxic gas on contact with water	50	100	3

Once the 6-step screening methodology has been applied across the relevant facilities *all* potential MATTE faults for the AWE Aldermaston site can be prioritised using these values as a guide. For faults that have been fully characterised in terms of frequency and consequence a 3 dimensional expression of the fault can be mathematically calculated thus:

MATTE Fault Risk = Frequency x Consequence Score x Relative Harm Score

Where frequency is either estimated or modelled in "likelihood" per year (y^{-1}) and a consequence score is given to reflect severity (**Table 4-4**) as defined below:

Table 4-10 Suggested Consequence Scores

Consequence Severity Classification	Score
Catastrophic	5
Critical	4
Marginal	3
Minor	2
Negligible	1

By way of illustration this prioritisation method has been applied to an analysis of a specific AWE Aldermaston facility (H Area – **Appendix N**) and is presented in **Table 4-11**.

Table 4-11 Summary of Potential MATTE Faults for H Area Facility

Fault Ref.	Fault	Frequency	Consequence	COMAH Category	Frequency (numerical)	Consequence Score	Relative Harm Index Score	MATTE Fault Risk	Priority Order
L24	Initiation of HE (explosion)	Frequency not calculated but based on the strong Lines of Defence (LOD) this is considered to be < 1 x 10^{-6}. This is an **improbable** frequency classification	Potential for toxic explosive by products to be released into the atmosphere. The nearby oil tanks could be ruptured releasing oil into surface water systems. This is a **marginal** consequence classification.	Explosive	1.00E-06	3	3	9.00E-06	6
F11 to F16	Explosion of HE during preparation or storage	A bounding frequency of between 10^{-4} and 10^{-6} (**remote**) is considered to be the worse case frequency for these scenarios.	Potential for toxic explosive by products to be released into the atmosphere. These faults are all classed as **marginal** consequence classification.	Explosive	1.00E-05	3	3	9.00E-05	4
F31	Fire: Propane leak – flammable gas ignited.	The Safety Case [112] calculates a return frequency of < 1.4 x 10^{-5} for this fault.	A number of solvents and asbestos fibres, used in building construction, could be released in the event of an explosion. This is a **marginal** consequence classification.	Named substance (extremely flammable gas)	1.40E-05	3	4	1.68E-04	2

Fault Ref.	Fault	Frequency	Consequence	COMAH Category	Frequency (numerical)	Consequence Score	Relative Harm Index Score	MATTE Fault Risk	Priority Order
F33	Fire: leak from high pressure gas system – flammable gas ignited.	The Safety Case [112] calculates a return frequency of < 1.4 x 10^{-5} for this fault. This is a **remote** frequency.	This could lead to a fire, which in a worse case would result in solvents and asbestos fibres, used in building construction, being released to the environment. This is a **marginal** consequence classification.	Named substance (extremely flammable gas)	1.40E-05	3	4	1.68E-04	2
F34	Fire: acetylene gas leak	The Safety Case [112] calculates a return frequency of < 1.4 x 10-5 for this fault. This is a **remote** frequency	A worse case consequence would be an engulfing fire that leads to a loss of combustion by products to the external environment. This is a **marginal** consequence classification.	Named substance - acetylene	1.40E-05	3	4	1.68E-04	2
F41	Loss of containment DU and beryllium detonation of round during a move.	The frequency is pessimistically considered to be **remote.**	Ground level concentration of Beryllium at the site fence of 5.1 E-6g/m^3. There will also be a small quantity of DU released. This is a **minor** consequence classification.	Explosive	1.00E-05	2	3	6.00E-05	3

Fault Ref.	Fault	Frequency	Consequence	COMAH Category	Frequency (numerical)	Consequence Score	Relative Harm Index Score	MATTE Fault Risk	Priority Order
NH10	Failure of gas system pipework leading to hydrogen explosion into an occupied area outside the firing chamber.	The frequency was determined as 3.3 x 10^{-7} i.e. **Improbable** [112].	Evolution of hydrogen and rupture of gas bottles containing hydrogen. A secondary fault could be the release of building fabric material (asbestos) to atmosphere. This is a **marginal** consequence classification.	Named substance - hydrogen	3.30E-07	3	4	3.96E-06	5
A3	Major fire inside toxic chemical store.	The Safety Case calculated the toxic store fire frequency of 6 x 10^{-4}/yr [113]. This is a **remote** frequency classification.	This will result in the evolution of combustion by products. This is therefore a **marginal** fault classification.	Very toxic	6.00E-04	3	5	9.00E-03	1
D2	Failure of transfer pipe from the LINX pipework.	The frequency of this fault is considered to be **remote** [112].	This runs above ground and failure would result in oil leaking onto the ground. This fault has occurred in the past whereby the consequence was a loss of oil killing fish. This is a **marginal** consequence classification.	Not currently a named COMAH substance but considered by the author to be dangerous to the environment.	1.00E-05	3	2	6.00E-05	3
WT1	Underground oil pipeline leak. Pipeline runs underground for approximately 7m from H1 to storage tank.	In the absence of any known frequency information this fault is pessimistically assumed be **remote**.	Contamination of land or water systems with mineral oil. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	Not currently a named COMAH substance but considered by the author to be dangerous to the environment.	1.00E-05	3	2	6.00E-05	3
WT2	Above ground oil leak during transfers from tank to machine.	This is the same fault as D2.	See Fault D2.	N/A	N/A	N/A	N/A	N/A	N/A
WT5	Fire in H8 Beryllium store	The frequency of this fire is calculated as <1 x 10^{-6} [112]. This is an **improbable** frequency.	Toxic chemicals (beryllium) and combustion by products released to atmosphere. This is a **marginal** consequence classification.	Very toxic	1.00E-06	3	4	1.20E-05	3

Fault Ref.	Fault	Frequency	Consequence	COMAH Category	Frequency (numerical)	Consequence Score	Relative Harm Index Score	MATTE Fault Risk	Priority Order
WT6	Rupture of potential PCB bearing capacitor tanks.	This fault is dominated by human error faults (vehicle impact) and is pessimistically assumed to be **improbable**.	Toxic chemicals released to water systems. This is a **marginal** consequence classification.	Dangerous to the environment.	1.00E-06	3	2	6.00E-06	6

4.4.2.12 Application of Methodology

Application of the 6-step screening methodology to a specific AWE Aldermaston facility (H Area) is given in **Appendix N**. The return frequencies for those scenarios identified from the fault schedule are taken from the H Area Safety Case [112].

4.5 SIGNIFICANCE TESTING FOR ACCIDENT SCENARIOS

As stated in Section 4.2 accident scenarios are assessed to identify impacts under emergency conditions. This section uses a Risk Matrix, based on the frequency and revised consequence methodology definitions shown in Section 4.2, to rank the faults and identify significance. Section 4.4 has shown how to identify which accident scenarios are judged to be potential MATTE, however a method of ranking *all* environmental accidents is required. Step 5 in the MATTE screening process uses either consequence or frequency to identify which fault represents a potential Major Accident Hazard. Instead of assessing faults to identify which ones are tolerable this section will identify significance based on *both* consequence and frequency. Fault conditions are assessed on frequency and consequence and placed into one of the following categories [101]:

Class A:	Highly significant
Class B:	Significant
Class C:	Not significant

The risk assessment methodology described in this thesis should be carried out prior to the MATTE identification process. For each fault condition identified an evaluation is made of the likely frequency and consequence (impact). Each fault condition is assigned a category by using a Risk Matrix (**Table 4-12**).

Table 4-12 Risk Matrix [102]

IMPACT CLASS	Frequency Classification					
Consequence Classification	Frequent	Probable	Occasional	Remote	Improbable	Incredible
	$F > 10$	$10^{1} > f > 10^{-1}$	$10^{-1} > f > 10^{-3}$	$10^{-3} > f > 10^{-5}$	$10^{-5} > f > 10^{-7}$	$f < 10^{-7}$
Catastrophic	A	A	A	A	B	C
Critical	A	A	A	B	B	C
Marginal	A	A	B	B	C	C
Minor	A	B	B	C	C	C
Negligible	B	B	C	C	C	C

Risks are either categorised as being Class A, Class B or Class C. Application of this risk assessment matrix to the H Area facility at AWE Aldermaston, which includes the auxiliary buildings is given in **Appendix O** [113].

4.6 CONCULSIONS

This chapter provides a background to Risk Assessment and its use at AWE. A refined method of consequence definition compatible with the AWE EMS is presented and demonstrated on the entire schedule of environmental faults from the AWE Aldermaston H Area facility. This same facility was used to pilot the MATTE identification methodology and demonstrate the 6-step screening process. From a total of 110 faults assessed in **Appendix O** the following classes were identified:

Class A	5
Class B	11
Class C	30

Obviously Class A and B risks (highly significant and significant risks) should be targeted first and subject to the most control (procedural and engineered). It is interesting to note that faults involving radioactive materials tend to fall into the highly significant category reflecting the high political profile and public interest in radiological risk. The vast majority of faults are Class C reflecting the broad range over which these different faults occupy.

The results of the MATTE identification applied to the 'H Area' facility are presented in **Appendix N** and the number of potential MATTE faults summarised in the table below.

Table 4-13 MATTE Identification, Summary Of Findings (H Area)

Hazard ID Source ▼	Total Number of Environmental Faults Reviewed/Identified (109)	Total Number of MATTE Identified (18)
Safety Case Fault Schedule (See Note)	94	13
Environmental Addenda	10	1
Walkthrough Audit	5	4

NB the original schedule contained a total of 150 safety and environmental faults.

A total of 18 potential MATTE faults were identified and have been summarised in **Table 4-11**. The faults have been sorted into a priority order using the MATTE fault risk equation given in Section 4.4.2.11, using consequence and relative harm scores. Where an exact numerical frequency has not been calculated the mid-way value in the range has been used, for example faults F11 to F16 are considered to have a frequency of between 1×10^{-4} and 1×10^{-6} yr^{-1} so a value of 1×10^{-5} yr^{-1} has been used.

AWE Aldermaston is a lower tier COMAH site and the author has developed a robust, transparent method of identifying potential MATTE faults to comply with these regulations [105]. The methodology is applied to an actual facility at AWE where the author carried out a walkthrough/audit and reviewed existing AWE documentation [112, 114 & 113]. The combination of environmental risk assessment and MATTE identification, collectively provide much improved methods of assessing environmental faults compatible with the existing AWE EMS and SMS whilst complying with a specific piece of legislation (COMAH - 1999). Although these methodologies have been developed specifically for use at AWE they could be applied to processes on any large industrial site that uses chemical and/or radioactive substances.

CHAPTER 5 SUMMARY

The results of the routine assessment presented in Chapter 3 are interpreted in this chapter. The facilities and buildings at AWE that are causing the most environmental damage are identified along with the corresponding impact categories, which need to be targeted for improvement. A comparison of the impact from transport activities against various facilities is also made. Various techniques for improvement are presented for the impact categories that have been identified as causing the most concern. A sensitivity analysis is presented for those particular elements in the LCA impact assessment methodology, which, have a major influence on the results. The sensitivity analysis demonstrates that the methods developed are robust.

5 APPLICATION OF METHODOLOGY AND RESULTS

In Chapters 3 and 4 the environmental impact of AWE operations for routine conditions has been assessed and a methodology for assessing accident conditions proposed. The results of the routine assessment are now used to identify the processes and facilities that are causing the most environmental damage. This chapter explores the results of the assessments in Chapter 3 and what it means in relation to environmental management at AWE. This chapter represents the Improvement Analysis phase of the LCA process.

The objective of this chapter is to identify the most damaging processes and activities and to explore the adequacy of the current methods for significance testing at both corporate and facility level. As a reminder it is now worthwhile reiterating the significance testing methods.

At the corporate level aspects are classified into one of three different categories: High, medium or low, depending upon weightings applied to local community concern, regulatory concern, company priority and environmental damage [13].

At the facility level contributions against each of these aspects is compared to the site total thus:

- If a building or facility contributes >5% of the site total to a medium significance corporate aspect this contribution is considered to be a significant contribution;
- If a building or facility contributes >10% of the site total to a low significance corporate aspect, this is considered to be a significant contribution;
- If a building or a facility contributes to any high significant corporate aspects, this is automatically considered to be a significant contribution.

5.1 IDENTIFICATION OF FACILITIES CAUSING THE MOST ENVIRONMENTAL IMPACT

The following facilities contributed to 10 or more separate impact categories (**Table 5-1** extracted from the detail presented in **Appendix J**):

A1, A19, A37, A38, A4/A82, A45, A50, A6, A8, A90 and CTF. All of these facilities should be targeted in the first instance as collectively they are making the largest contribution to environmental impact. The highest contributors to individual impact categories are given in **Table 5-1**.

Table 5-1 Facilities Identified to be Causing the Most Environmental Impact

Highest Impact - Descending	Global Warming	Ozone Depletion	Human Toxicity	Aquatic Ecotoxicity	Terrestrial Ecotoxicity	Smog Formation	Acidification	Nutrification	Trade to Landfill	Domestic to Landfill	Env. Irradiation Air	R/A Waste to Landfill
1	MBH	A2	C8.1	H Area	H Area	MBH	MBH	MBH	A90	A90	A37	Trade Effluent
2	A90	A91	MBH	C8.1	CTF	C8.1	A90	A90	MBH	A45	A90	A23
3	A91	B2A1/B2 A4	A90	CTF	C8.1	A90	A91	A91	H Area	H Area	B8A	A19
4	MISC	C15	A4/A82	A4-A82	A4/A82	A91	MISC	MISC	A97	OWMG	A1	A45
5	A45	A45	A91	A90	A90	MISC	A45	A45	ESSPH	A37	A50	A37
6	A1	A36	MISC	A45	A45	XTF	A1	A1	A38	CTF	A12C	H Area
7	A37	A19	H Area	XTF	XTF	A45	A37	A37	A1	A1	A12K	A1
8	ESSPH	C15	A45	C15	C15	A1	ESSPH	ESSPH	A37	A50	A91	A90
9	A2	A4/A82	A1	A38	A6	A37	A38	A4/A82	A50	R61 M	A2	A4/A82
10	A4/A82A5/A9		A37	A6	A38	ESSPH	A4/A82	A2	A4/A82	A5/A9	A41	OWMG

MISC – This is a group of buildings that make up a facility.

It is clear from the analysis of the results that the same facilities are causing the most environmental impact. The facilities that should be targeted for improvements are not surprisingly the main boiler house and the large nuclear processing buildings: A90, A1, A37, A45, A4/A82 and A5/A9. In addition the plating shop C8.1, CTF, H Area and ESSPH among others are significant contributors. It is the buildings and facilities identified that should be targeted for making improvements.

In comparing the contributions between impact categories it is clear that the radioactive discharges resulting in the environmental irradiation to air and radioactive waste are judged to be the most important. Unfortunately as the exact isotopic composition from each facility is unknown it is not possible to calculate impacts for environmental irradiation to water. To measure this impact however, a weighting factor of 10 has been applied and included in the radioactive waste category. Radioactive categories are large due to the high valuation weighting on these impacts, nevertheless these results should be acted upon. It is the discharge of radioactive material that attracts most attention from the regulators and the local community. Often to the point whereby decisions are made based on the perception of the risk associated with radioactivity in the environment and not necessarily on the pure cost benefits of discharge reduction. The results of the analysis are plotted and reproduced (see attached CD-ROM for the entire analysis of results) in **Appendix J**. The results are plotted on a logarithmic scale and priority should be directed at reducing the impact in the following categories (descending order):

- Radioactive impacts
- Impact associated with trade and domestic waste production leading to landfill.
- Global warming and climate change
- Human toxicity and nutrification
- Acidification
- Photochemical smog formation
- Ecotoxicity
- Ozone Depletion

5.2 TRANSPORT IMPACTS

In addition it should be noted that the contribution from transport activities is judged to be significant. **Table 5-2** (extracted from **Appendices J** and **K**) shows the results of the impact assessment, for three large facilities, (A37, A1 and A45), compared with those from transport activities. The results from the Main Boiler House (MBH) are also included as this is largest site contributor to global warming, smog formation, acidification and nutrification.

Table 5-2 Comparison of Transport Impacts v Selected Facility Impacts

	Transport	A37	A1	A45	MBH
Global Warming	2.33 E+8	3.67 E+7	5.5 E+7	6.43 E+7	7.81 E+9
Ozone Depletion	0	1.62 E+1	1.65 E+1	4.87 E+1	0
Human Toxicity	8.55 E+6	8.15 E+3	1.22 E+4	2.91 E+4	2.3 E+6
Aquatic Toxicity	5.35 E+3	0	0	2.98 E-1	0
Terrestrial Toxicity	2.99 E+3	0	0	3.18 E-2	0
Smog Formation	1.23 E+3	8.77 E+6	1.32 E+7	1.57 E+7	6.42 E+8
Acidifcation	1.26 E+10	6.03 E+9	9.05 E+9	1.05 E+10	3.19 E+11
Nutrification	7.95 E+3	7.51 E+3	1.13 E+4	1.31 E+4	2.33 E+6

The global warming impact is higher than A37, A1 and A45, which are in the top 10 contributors to this aspect. Furthermore, the contribution to human toxicity from transport activities is higher than any facility assessed in this study. Clearly efforts should be made in targeting a reduction in transport emissions.

5.3 TECHNIQUES FOR IMPROVEMENT

5.3.1 Radioactive Impacts

The author suggests the following techniques be considered to help improve the EMS. Radioactive impacts are controlled by legislation and authorisations issued by the Environment Agency under the Radioactive Substances Act 1993. The emission targets for radioactive discharges is constantly being driven down and AWE is already applying the principles of Best Practical Means to reduce emissions. The process of BPM application is a transparent tool for assessing options for discharge reduction and should be applied across site for all processes and proposed changes to processes. Radioactive waste is a major environmental problem and as shown by the results of this study represents one of the most significant impacts. Waste minimisation techniques are already applied across site and the application of the BPM process is helping to minimise unnecessary generation. It is suggested that AWE maintains an active interest in research techniques for decontamination so that waste can be declassified ideally to free release levels. This would allow expensive materials, particularly metals, to be recycled thus yielding a double benefit. Often difficulties associated with monitoring components to determine contamination levels means they are routinely streamed as radioactive waste as it is impossible to confirm otherwise. This approach is leading to unnecessary environmental impact. Efforts should be targeted at finding suitable decontamination methods. At AWE there are vast amounts of ventilation ducting that are awaiting decommissioning, most of which is destined for disposal as low level waste at BNFLs Drigg facility. The internal surfaces of the ducting could be etched clean or decontaminated using foam agents allowing the surfaces to be uncovered for monitoring. BNFL have recently developed state of the art smelting facilities to reclaim otherwise contaminated metal material for clean recycling. Radioactive slag is produced as a by-product but this is only a fraction of the original volume allowing for a 95% recycling rate. AWE needs to be aware of the techniques available for recycling radioactive waste.

5.3.2 Landfill Impacts

AWE Aldermaston generates a considerable volume of trade and toxic waste, which is controlled by recycling schemes and the actions of local waste minimisation officers. Currently paper production is the subject of a company Key Performance Indicator, and all offices have bins available for recycling paper waste. Metal waste is also recycled at a central facility. Further efforts should be directed at measuring waste generation at a local level and segregation of waste at source to facilitate re-use. A chemical user group has been established and the terms of reference for this group should be expanded to include cross facility trading of unwanted chemicals. The new appointment of a Resource Technical Authority will help focus on specific initiatives to reduce resource consumption. Inter departmental trading of unwanted materials will help reduce resource consumption and hence the generation of waste.

5.3.3 Global Warming and Climate Change Impacts

The main contributor to this impact is from the centralised main boiler house, which provides site wide steam heating and the larger process buildings including A90. The boiler house is gas fired and controlled under the IPC regime. The current system uses a network of old distribution pipes, which leaks, accounting for 700 Te of water loss as steam each day. These inefficiencies are resulting in unnecessary environmental impact. A study is being carried out into alternative options and a decentralised supply is favoured. Decentralisation and more metering will help to reduce this impact along with the installation of better insulation and greater awareness of energy consumption.

5.3.4 Human Toxicity, Nutrification and Acidification

These impacts are associated with the release of chemicals into the environment and can be reduced by seeking out less harmful alternatives. The contribution to acidification and nutrification at AWE are not particularly significant.

5.3.5 Ecotoxicity

Ecotoxic impacts are again associated with the release of chemicals into the environment and can be reduced by seeking out to replace those substances with less harmful alternatives. Risk phases give a good indication of danger and reducing the reliance on substances with risk phrases R50 to R59 will help to reduce the contribution to this impact category.

5.3.6 Ozone Depletion

AWE has taken measures to identify all of the contributions and inventories of ozone depleting substances and phase out their replacement with ozone friendly alternatives. The contribution to this impact is not considered to be significant.

5.4 SENSITIVITY ANALYSIS

This section describes some of the elements within the LCA framework, which are sensitive to the results of the study. The purpose here is to establish the robustness of the results achieved. The following are considered to influence the results and are hence regarded as sensitive.

5.4.1 Characterisation Factors

The factors used in this study have been taken from reliable, published and accepted sources. The factors developed for calculating the impact from radioactive releases are based on known parameters about the behaviour of radioisotopes in the environment and are considered to be representative of the environmental harm potential. As described in Section 3.7.4 the formula derived for calculating Equivalency Factors used a half-life component based on how much of each isotope had decayed in a 100-year period. This approach ensures that those isotopes with short to medium half lives and correspondingly give up a lot of their energy in the first 100 years, are, weighted accordingly. A sensitivity analysis, to calculate the EF based on % decayed for 1000 and 10,000 years, for the 10 AWE isotopes has been carried out. The results of this sensitivity are given in **Table 5-3** and **Table 5-4**.

Table 5-3 Sensitivity Applied to Life Time Values (1000 and 10,000 years) to Determine EF Values for Radioactive Effluent Releases

Radioisotope	DCF (Ingestion) [84]	B	T	S	Life-time value (% Decayed in 100 yrs)	EF Value (100 yrs)	Life-time value (% Decayed in 1000 yrs)	EF Value (1000 yrs)	Life-time value (% Decayed in 10000 yrs)	EF Value (10000 yrs)
^{241}Am	2.0 E-7	3	3	0	14.78	1.77 E-5	79.1803	9.58 E-5	100	N/A
^{137}Cs	1.3 E-8	1	1	3	89.97	5.85 E-6	100	N/A	100	N/A
^{60}Co	6.6 E-9	1	1	0	99.99	2.8 E-7	100	N/A	100	N/A
^{85}Kr	-	0	0	1	99.84	-	100	-	100	-
^{239}Pu	2.5 E-7	3	3	0	0.29	4.35 E-7	2.8584	4.29 E-6	25.1736	3.78 E-5
^{241}Pu	4.8 E-9	3	3	0	99.17	2.86 E-6	100	N/A	100	N/A
^{3}H	4.2 E-11	2	0	3	99.66	2.09 E-8	100	N/A	100	N/A
^{234}U	4.9 E-8	3	3	0	0.03	8.82 E-9	0.2796	8.22 E-8	2.7612	8.12 E-7
^{235}U	4.7 E-8	3	3	0	0.00001	2.82 E-12	0.001	2.76 E-11	0.0010	2.76 E-10
^{238}U	4.5 E-8	3	3	0	0.000001	2.7 E-13	0.000015	4.04 E-12	0.00015	4.05 E-11

Where:
B = Bioaccumulation Score
T = Toxicity Score
S = Solubility Score

After complete decay (life time value of 100) the isotope no longer poses a threat to the environment

The effects of decay daughters are included in the analysis for Americium, Plutonium and Uranium Isotopes. The decay of the parent isotope dominates the overall decay patterns in the timescales considered (up to 10000 years) except for ^{238}U and ^{235}U which are in secular equilibrium

Table 5-4 Sensitivity Applied to Life Time Values (1000 and 10,000 years) to Determine EF Values for Radioactive Gaseous Releases

Radioisotope	DCF (Inhalation) [84]	B	T	S	Life-time value (% Decayed in 100 yrs)	EF Value (100 yrs)	Life-time value (% Decayed in 1000 yrs)	EF Value (1000 yrs)	Life-time value (% Decayed in 10000 yrs)	EF Value (10000 yrs)
^{241}Am	4.2 E-5	3	3	0	14.78	3.72 E-3	79.1803	2.01 E-02	100	N/A
^{137}Cs	9.7 E-9	1	1	3	89.97	4.36 E-6	100	N/A	100	N/A
^{60}Co	1.0 E-8	1	1	0	99.99	2 E-6	100	N/A	100	N/A
^{85}Kr	2.2 E-11 (Sv/Bqm^{-3})	0	0	1	99.84	-	100	-	100	-
^{239}Pu	5.0 E-5	3	3	0	0.29	8.7 E-5	2.8584	8.58 E-4	25.1736	7.55 E-3
^{241}Pu	9.0 E-7	3	3	0	99.17	5.36 E-4	100	N/A	100	N/A
^{3}H	4.5 E-11	2	0	3	99.66	2.24 E-8	100	N/A	100	N/A
^{234}U	3.5 E-6	3	3	0	0.03	6.3 E-7	0.2796	5.87 E-6	2.7612	5.8 E-5
^{235}U	3.1 E-6	3	3	0	0.00001	1.86 E-10	0.001	1.82 E-9	0.0010	1.82 E-08
^{238}U	2.9 E-6	3	3	0	0.000001	1.74 E-11	0.000015	2.61 E-10	0.00015	2.61 E-09

Where:
B = Bioaccumulation Score
T = Toxicity Score
S = Solubility Score

After complete decay (life time value of 100) the isotope no longer poses a threat to the environment.

The effects of decay daughters are included in the analysis for Americium, Plutonium and Uranium Isotopes. The decay of the parent isotope dominates the overall decay patterns in the timescales considered (up to 10000 years) except for ^{238}U and ^{235}U which are in secular equilibrium.

After 1000 years ^{137}Cs, ^{60}Co, ^{85}Kr, ^{241}Pu and ^{3}H have given up all of their energy and no longer pose a threat to the environment. After 10,000 years only ^{239}Pu and the Uranium series isotopes remain to pose a threat. The general order of most damaging isotopes is unchanged. The 100-year reference period has the following benefits:

1. it ensures that all of AWEs isotopes are included in the formula;
2. the period approximates with the biokenetic models used by the NRPB in their Dose Coefficient Factors (human age derived);
3. is compatible with timeframes used in LCA for other impact categories;
4. is the most realistic timeframe upon which to base environmental decision-making, in this context. Organisations including nuclear industries do not make strategic decisions on environmental policy over very long time periods, except for issues concerning solid radioactive waste disposal.

The method used to calculate the equivalency factors and the resulting sensitivity has also taken into consideration the effects of the decay chain for Plutonium, Americium and Uranium isotopes. As these isotopes decay they change into other radioisotopes, which have different half-lives, until the chain ends with a stable (non-radioactive) element. To estimate daughter in-growth, and hence the validity of the EF formula, will depend on the half-life of the parent isotope with respect to the half-life of the daughter. There will also be a point during the decay times where the daughter is at a maximum [115]. For ^{241}Am its daughter is ^{237}Np which, has a much longer half-life and is said to be a *no-equilibrium* case because the daughter build-up, (due to decay of the parent), is faster than its loss due to decay. This is also the case for ^{239}Pu and ^{241}Pu. The Uranium isotopes ^{235}U and ^{238}U are examples where the parent is much longer-lived ($>10^4$ times) than the daughter. These cases are said to be in *secular equilibrium* [115] and there is no significant change in the number of parent nuclei present, although several half-lives of the daughter may occur. In short the activity of the parent and daughter are the same during the period of observation [115], in this case up to 10,000 years.

For ^{241}Am its daughter is ^{237}Np which then decays to ^{233}Pa, and then to ^{233}U, ^{229}Th, ^{225}Ra, ^{225}Ac etc. until it reaches stable isotope ^{209}Bi. The decay process has been modelled using simplified decay chains for a pure sample, (assumes an initial zero daughter presence), of 100 Bq of ^{241}Am, ^{239}Pu, ^{241}Pu, ^{235}U, ^{238}U and ^{234}U using the following formulae [taken from Ref. 115 formula 3-22 on page 12]:

$$A(d) = \frac{\lambda p \lambda d}{\lambda d - \lambda p} . \frac{Ap}{\lambda p} (e^{-\lambda pt} - e^{-\lambda dt}) + A_2^0 e^{-\lambda dt}$$

Where:

A(d) = activity of the daughter product;

A(p) = activity of the parent;

A_2^0 = initial activity of the daughter which is assumed to be zero;

λp = the decay constant for the parent radioisotope;

λd = the decay constant for the daughter radioisotope;

t = time (years);

5.4.1.1 Decay Chain Modelling Results

^{241}Am

The decay is modelled using excel spreadsheets for 10,000 years and peak ^{237}Np in-growth occurs 435 years later at 5.13 E-3 Bq. The modelling demonstrates that the results of the sensitivity analysis are still valid.

^{241}Pu

The decay is modelled using excel spreadsheets for 10,000 years and peak ^{241}Am in-growth occurs 15 years later at 0.8 Bq. The modelling demonstrates that the results of the sensitivity analysis are still valid, although the first daughter is ^{241}Am and is much more damaging that ^{241}Pu.

^{239}Pu

The decay is modelled using excel spreadsheets for 10,000 years and the ^{235}U steadily increases to 6 E-4 Bq at 10,000 years (^{239}Pu is at 75 Bq). The modelling demonstrates that the results of the sensitivity analysis are still valid.

^{238}U and ^{235}U

These isotopes are in secular equilibrium and the daughter activity is approximately the same as that of the parent (^{234}Th from ^{238}U and ^{231}Th from ^{235}U).

^{234}U

The decay is modelled using excel spreadsheets for 10,000 years and the ^{230}Th steadily increases to approximately 8 Bq at 10,000 years (^{234}U is at 97.24 Bq). The modelling demonstrates that the results of the sensitivity analysis are still valid.

5.4.1.2 Decay Chain Modelling Findings

The quantities discharged from individual facilities and buildings at AWE are in the kBq region and thus the in-growth quantity from daughter products is not significant. Sensitivity should be used to determine the reference period, if this method is used to calculate the EF for other radioisotopes, which have different half-lives.

5.4.2 Normalisation Factors

These factors were derived from actual AWE data compared with a total contribution and then calculated to person equivalents. Although the normalisation factor will influence the results the method selected to calculate the factor is considered to be appropriate for this study.

5.4.3 Valuation

The valuation weighting will have a major influence on the outcome of the study. It is considered however, that the method chosen, which is based on the stakeholder and business (cost) issues of the EMS is the correct weighting factor. Even if the factors were adjusted up or down by one value (i.e. 6 to 5) the results would not be altered significantly to change the outcome of which facilities or impacts should be targeted for improvement.

It is concluded that the methodology presented in this thesis is robust and gives an accurate indication of environmental impact and clearly identifies areas for prioritisation to improve the effectiveness of the EMS.

CHAPTER 6 SUMMARY

In this chapter the conclusions are presented. The reasons for choosing AWE as a case study are given and the key contributions to knowledge identified. The advances to LCA methodology and the research findings are also described. The original aims and objectives are re-assessed in light of the research carried out and a demonstration given to show that these have been met. Flow-charts are presented to show how the important areas of research carried out in Chapters 3 and 4 were developed. The appropriateness of the AWE corporate environmental aspects is discussed and recommendations for further work presented.

6 CONCLUSIONS

AWE Aldermaston is an ideal industrial site and organisation for use as a case study for research on the development of life-cycle methodology. The site has been developed over many years and includes a wide variety of nuclear and chemical processes. The current AWE EMS has only recently been implemented and there is clear scope to develop a means of quantifying all environmental burdens and impacts to facilitate decision-making within the EMS to target those processes that are generating the greatest impact for improvement first.

6.1 KEY CONTRIBUTIONS TO KNOWLEDGE

This research work has resulted in the following key contributions to knowledge:

- A method has been devised for the inclusion of radiological releases within the framework of LCA methodology by developing equivalency factors for nine radionuclides released to air and water media.
- New applications of the LCA approach to investigate the links between environmental aspects and impacts within an EMS are reported.
- An LCA valuation method for weighting environmental impacts in an EMS has been developed including site-specific normalisation factors.
- Use LCA methodology to determine the impact arising from vehicle use is reported and the results discussed within the context of an EMS.
- New consequence definitions based on environmental aspects of an EMS for use in risk assessment have been developed. These consequence definitions are based on business issues (monetary), societal preference (stakeholder concerns) as well as on environmental impact. The method developed does not rely on dispersal modelling and offers an economical alternative to existing consequence assessments.
- A six-step screening methodology has been built up to identify potential Major Accidents To The Environment (MATTE) to ensure compliance with the requirements of the COMAH Regulations (1999).

- Methodology is reported to prioritise MATTE scenarios based on the relative harm of dangerous substances as defined by quantity limits given in the COMAH Regulations (1999).

By way if illustration these methods have been demonstrated on facilities at AWE Aldermaston.

6.2 ADVANCES FOR LCA

The development of the new LCA methodologies have been successfully demonstrated for use at a large nuclear / chemical site and the results have clearly identified which facilities and hence which processes are causing the most damaging environmental impacts. AWE has been used as a case study to allow the development of a methodology that is very important to the advancement of LCA methods. The equivalency factors developed have been validated using criteria defined in ISO 14042 [37] and sensitivity analysis has been applied to confirm that the 100-year reference period is the most appropriate for use in calculating the half-life component within the formula derived. The nature of radiological pollutants encountered at AWE allowed this type of sensitivity to be performed.

The equivalency factors values derived for radioisotopes now make it possible to include isotope specific radiological discharges within LCA methodology.

Gathering the data required to compile the LCA inventory was a major undertaking in this research but the accuracy and extent of these data were absolutely vital in enabling the author to perform a detailed impact assessment. Without accurate inventory data, assumptions and estimates have to be made which will undermine the accuracy of the results and /or limit the extent to which the analysis could be performed. LCA impact assessment cannot be performed without an accurate and comprehensive inventory.

6.3 RESEARCH FINDINGS

The research described in this thesis has shown that, whilst the aspect contribution method used in the AWE EMS gives an indication of environmental impact, it does not provide enough sophistication for a site as complex as AWE Aldermaston. Furthermore, in the development of a good significance testing procedure [3] the following factors should be considered:

- It should force the organisation to consider environmental impacts;
- Be industry specific and derived for that organisation;
- Give the complexity to suit that organisation.

The current method of significance testing at the corporate level does include an environmental impact component along with business and stakeholder issues. The impact is based, however, on subjective views of the magnitude discharged rather than actual scientific analysis of the measured impact. Although the significance testing procedure that has been reviewed in this work was derived specifically for AWE and based on aspects considered important to the AWE business, the concepts are no different from other environmental management systems used in other industry sectors. Those developed for other industries do not, however, give the complexity required to match AWEs diverse range of activities, which include many chemical and nuclear processes.

The original aim of this study was:

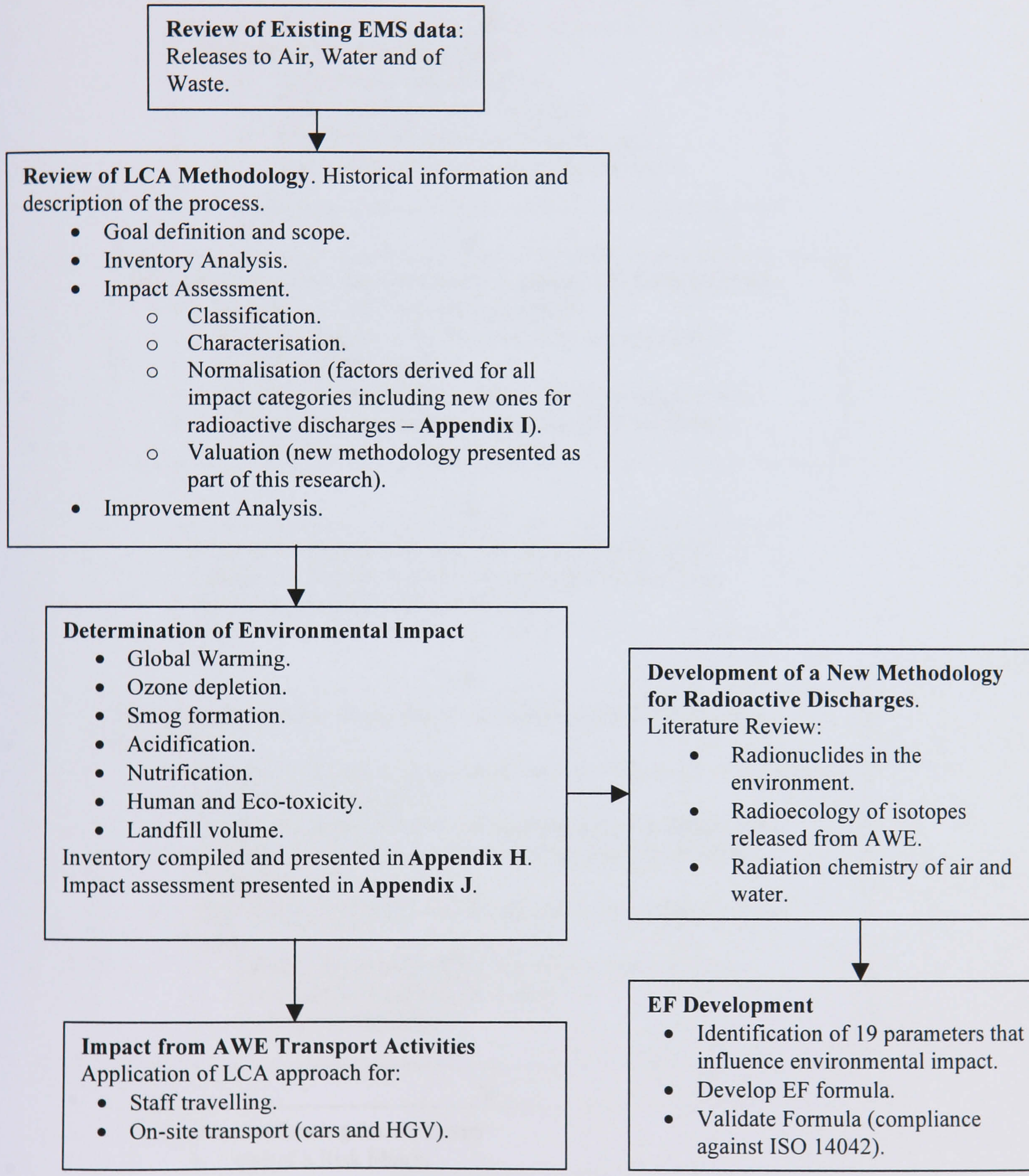
To develop a generic methodology to establish which processes and activities and associated environmental aspects are causing the most environmental damage, and to use this information to determine where best to target efforts for continual improvement within relevant Industrial Environmental Management Systems.

This was to be achieved by the completion of the following objectives:

1. To use the methodology of LCA to identify appropriate impact categories;
2. To consider how the impact from radioactive substances fits into current LCA methodology and develop company specific parameters to cover these aspects;
3. To develop a method of integrating existing environmental indices and criteria to calculate and measure the severity of the impact;
4. To develop Risk Assessment methods to evaluate environmental impact from accident scenarios;
5. To integrate and link the LCA impact assessment with the AWE EMS where appropriate;
6. To determine if current methods of significance testing, based on aspect contribution, are fit for purpose.

These objectives have been met and the results are summarised in this concluding chapter. Flow-charts are presented to summarise the research results derived from the work described in Chapters 3 and 4.

ASSESSMENT OF ROUTINE ASPECT CONTRIBUTIONS (CHAPTER 3)



Review of Existing EMS data: Releases to Air, Water and of Waste.

Review of LCA Methodology. Historical information and description of the process.

- Goal definition and scope.
- Inventory Analysis.
- Impact Assessment.
  - Classification.
  - Characterisation.
  - Normalisation (factors derived for all impact categories including new ones for radioactive discharges – **Appendix I**).
  - Valuation (new methodology presented as part of this research).
- Improvement Analysis.

Determination of Environmental Impact

- Global Warming.
- Ozone depletion.
- Smog formation.
- Acidification.
- Nutrification.
- Human and Eco-toxicity.
- Landfill volume.

Inventory compiled and presented in **Appendix H**.
Impact assessment presented in **Appendix J**.

Development of a New Methodology for Radioactive Discharges.
Literature Review:

- Radionuclides in the environment.
- Radioecology of isotopes released from AWE.
- Radiation chemistry of air and water.

Impact from AWE Transport Activities
Application of LCA approach for:

- Staff travelling.
- On-site transport (cars and HGV).

EF Development

- Identification of 19 parameters that influence environmental impact.
- Develop EF formula.
- Validate Formula (compliance against ISO 14042).

METHODOLOGY FOR THE ASSESSMENT OF ACCIDENT CONDITIONS (CHAPTER 4)

Definition of Requirement
Define need to assess accident conditions in an EMS.

Background to Risk Assessment
- Definition of risk assessment.
- Risk = Consequence x Frequency.
- Numerical definitions for frequency and descriptions of consequence classifications.

Development of New Environmental Consequence Classifications.
- Matched to AWE corporate importance.
- Based on Scores used to rank the importance of AWE Environmental Aspects.
- Accords with the valuation method developed in Chapter 3.
- No need for expensive and time-consuming modelling.

Hazard Categorisation and Risk Assessment at AWE.
Discussion of risk perception, tolerability of risk and the hazard categorisation system at AWE.

Methodology for Identifying Major Accidents to the Environment (MATTE).
- Discussion of COMAH regulations and the importance of Dangerous Substances (**Appendix L**).
- Critical evaluation of an existing screening methodology [106].
- Development and presentation of new screening methodology (**Appendix N**).
- Prioritisation of MATTE faults based on a robust scoring system using:
  1. Relative Harm Index (RHI) for dangerous substances.
  2. A consequence classification score.
  3. A numerical frequency.

Significance Testing for all Faults
- Use of a Risk Matrix.
- Application to a large high hazard facility at AWE (**Appendix O**).

The methodology of LCA has been applied to measure environmental impact based on aspect contribution data. A specific goal and scope for the study has been defined based on a functional unit of:

"Nuclear deterrent component manufacture at AWE Aldermaston in One Year".

Data originally used to populate facility aspect registers have been used to form the basis of an LCA inventory. An impact assessment has been performed on this inventory using known characterisation values, normalised to person equivalents using total AWE site figures and finally weighted using a new valuation method derived by the author from business and societal scores used in the corporate significance testing procedure.

A new methodology has been developed to include the release of AWE specific radionuclides discharged into either water, air or as waste. The method chosen to include radioactive substances is based on the development of equivalency factors (EF) and the methodology has been compared with the requirements of ISO 14042 [37] to demonstrate effectiveness and compliance. The development of equivalency factors is a significant achievement for the advancement of LCA methodology. Unlike other methods developed [32 and 78] it can be applied without having to establish background radioactive concentrations in receiving media (soil and water).

The methodology developed in this work can be applied to the wide range of other radionuclides that are encountered and used across the nuclear industry to measure environmental irradiation.

A new methodology has been developed for the assessment of accident conditions based on risk assessment techniques. The method includes a revised system for the identification of Major Accident Hazards to comply with the COMAH Regulations 1999. A more sophisticated consequence definition and a ranking system to prioritise potential Major Accidents is also presented. Collectively these refined methods of risk assessment provide a much-improved technique for assessing environmental faults.

The original assumption made in the AWE EMS was that the magnitude of the contribution to a corporate aspect is proportional to its impact. Whilst this is a reasonable assumption for energy use and some resource use aspects this is not always the case for different chemical and radioactive isotopes that are released from the AWE site. The research carried out has shown that it is the scale of the impact that gives the most reliable indication of environmental damage and that use of scale of impact data in LCA methodology, can be applied to the operations and activities of a large industrial site to calculate impact.

The current AWE EMS, in common with other EMSs, makes no allowance for the environmental impact from the various transport activities on the site and from employee commuting. This research has included an impact assessment on the gaseous emissions from employee commuting and transport activities on the site.

6.4 APPROPRIATENESS OF AWE CORPORATE ENVIRONMENTAL ASPECTS

The results of this study indicate that some of the corporate aspects are not adding a great deal of value to the EMS. Contributions to the following aspects are negligible:

Release to Air – Beryllium. Despite AWE recently submitting its first IPPC submission for a permit to operate a non-ferrous process using beryllium this aspect adds little to the EMS. Beryllium is only used in a couple of facilities and could be incorporated into a broader aspect namely Releases to Air - Metals

Releases to Air – Lead. As with beryllium this aspect does not add a great deal to the EMS and could also be included in Releases to Air – Metals.

Releases to Air – Combustion by-products. This aspect applies only to the boiler houses on site and for the main boiler house this is adequately managed and controlled under an existing IPC arrangement.

The **Releases to Water – Domestic Effluent** aspect is effectively duplicated by the Resource Use – Water aspects so one or the other should be removed.

Resource Use – Gas. This aspect is applicable to one facility only, the main boiler house. It would be more sensible to have a Resource Use – Steam aspect, which can be used to indirectly measure gas consumption in individual buildings.

Resource Use – Chemical and Oil Storage. This aspect is largely superfluous as chemical and oil consumption is not measured to any degree of accuracy in any facility on site. This situation could be remedied as the site has recently introduced a database of all its chemical holdings to comply with the COMAH 1999 Regulations. It would be fairly straightforward to augment the system so that actual consumption is monitored.

The remaining aspects are entirely appropriate and should be retained in the EMS. A new aspect covering Releases to Air – Transport Emissions would be useful in managing the contributions from this activity in addition to the difficult to measure

Nuisance – Congestion aspect. Further the nuisance aspects in general provide little of use to the EMS. A single complaints aspect could replace the existing suite of nuisance aspects covering odour, noise, visual, light and congestion, which could focus on specific issues that are of real concern to the local community.

The contribution to global impacts including climate change is relatively high compared to local impacts. Current legislation including COMAH and the IPPC regime tend to place emphasis on local impacts as these are under the direct control of individual industrial sites. However, whilst the EMS must help ensure that an organisation meets legislation it should not preclude the EMS focussing on the challenges of reducing its contribution to global impacts, which in the longer term may have a greater importance. The impacts associated with radioactive discharges (to air, water and as waste) are given the highest weighting which largely reflects the concern of the major stakeholder groups (local community, regulatory bodies and pressure groups). Radiological releases are subsequently very well measured and controlled.

6.5 RECOMMENDATIONS FOR FURTHER WORK

The methods developed in this research can be applied to improve environmental reporting in an EMS. Actual environmental impact, based on the annual environmental profile generated using this developed LCA methodology, can be compared with an organisations total impact as part of the process of continual improvement. The information used in this thesis can be readily transferred into an Excel spreadsheet workbook allowing simple calculations of impact based on annual contributions suitably characterised, normalised, weighted and plotted.

Transport activities make a significant contribution to the overall environmental impact of site operations and any large industrial facility should consider alternatives to help reduce this impact that also contributes to local congestion. Initiatives include:

- Utilisation of a dedicated bus service from major towns close to the site.
- Encourage more professional staff to work from home where the majority of their work is office based. The Confederation of British Industry predicts that in 15 years time 40% of professional workers will be operating from home. With modern communication technology including e-mail, telephone and

video conferencing a major proportion of office-based staff are able to work effectively from home.

- Reward for those employees that car share, use public transport or cycle or walk to walk.
- Adopt a four-day working week by extending the working day to ten hours. This would also reduce congestion as staff would be mustering outside normal rush hours.

Estimating the reduction in journey mileages and calculating the corresponding reduction in environmental impact can measure the effectiveness of these initiatives.

The accident assessment did not use LCA methodology and instead focussed on the use of risk assessment for more major hazards. Further work should investigate high frequency accidents using LCA to link with the work described for routine assessments.

In summary, the aims of this research have been met through the development of equivalency factors for radionuclides to allow inclusion in LCA methodology and by developing improved risk assessment methods to assess industrial environmental accident scenarios.

Equivalency factors have been developed for nine radioisotopes encountered at AWE. Application of this methodology to other radioisotopes will enable LCA to be applied to other sites and organisations. The inclusion of radiological releases will benefit the continuing use of LCA as an environmental management tool. This research has shown that LCA methodology can be used to measure the environmental impact of a large nuclear and chemical site.

REFERENCES

---

1. International Standards Organisation ISO 14001: 1996 Environmental Management Systems - Specifications with Guidance for Use.

2. "Evaluating Environmental Effects as part of an Environmental Management System". D J A Brown published in Clean Air journal Volume 25 No.2.

3. Environmental Aspect Evaluation D J A Brown – Lecture Notes for the Systems for Environmental Management course (CD 5035) Brunel University July 1998.

4. Report of the World Commission on Environment and Development – "Our Common Future". Gro Harlem Bruntland. Published in 1987.

5. Aspect contributions for facilities at AWE, taken from environmental addenda and statements. Private Communication 2000.

6. AWE Major Accident Prevention Policy (MAPP). AWE/DSDG/A/PS/AD/007. Issue 1 April 2000. Private Communication.

7. Information on the history and capabilities of AWE. Taken from the AWE Intranet site – 2001. http://www.awe.co.uk/.

8. Environment Site Setting Exercise: Aldermaston AWE/DSDG/B/GN/AD/016 November 1999 Issue 1. Claire Perks. Private Communication.

9. National Rivers Authority Policy and Practice for the protection of Groundwater. Groundwater vulnerability 1:100,000 map series, sheet 38 Upper Thames and Berkshire Downs 1995.

10. AWE SRCT Survey (Phase 1) Factual Report. AEA Technology August 1997 Reference DD/DOX/H0169/011/3/4

11. NRPB Volume 9 No.1 1998 - Revised Generalised Derived Limits for Radioisotopes of Strontium, Ruthenium, Iodine, Caesium, Plutonium, Americium and Curium - Application of Generalised Derived Limits.

12. The Radioactive Substances Act 1993 HMSO. ISBN 0105412937

13. Environmental Aspects Register - Significance Assessment Process. AWE/DSDG/B/RP/EDP/244. Neil Reilly 1998. Private Communication.

14. AWE Company Restricted and Prohibited Substances List. OH/A/400-T/OH/98.117/C99.224 Issue 4 January 2003. Private Communication.

15. 1999 Pollution Handbook - National Society for Clean Air and Environmental Protection ISBN 090 3474 425

16. AWE Montreal Protocol Baseline Study Report and Action Plan DSD01/B/RP/ES/AAVD/001 Issue 1 March 2000. N Croxford and P Bradbeer. Private Communication.

17. "Global Warming and Nuclear Power" - P E Hodgeon, Paper presented at the BNES Nuclear Congress, London, December 1998.

18. AWE Public Information Leaflet. An alternative to the Pangbourne pipeline. Summary of the Best Practicable Environmental Option Study. Issued by AWE Corporate Communications, October 2000 Telephone 01189 824811/5602.

19. Department of Environment, Transport and Regions, Report No. DETR/RAS/99.001 - An Assessment of the Radiological Significance of Historic Discharges into the River Thames.

20. Special Waste Regulations 1996 (SI 972). ISBN 0110545656

21. Lecture notes on Integrated Pollution Science as part of the MSc in Environmental Management at Brunel University - Mr B Weald, October 1999.

22. Life-cycle Analysis. Professor J D Donaldson, Centre for Environmental Research, Brunel University.

23. Fundamentals of Environmental Chemistry. S E Manahan. 1993 Lewis Publishers. ISBN 0-87371-587-X.

24. Revise Chemistry. R McDuell. Letts Study Aids. Published 1983. ISBN 0-85097-598-0.

25. "Nordic Guidelines on Life-cycle Assessment", Nord. 1995:20. L G Lindfors, K Christiansen, L Hoffman, Y Virtanen, V Juntilla, O J Hanssen, A Ronning, T Ekvall & G Finnveden. Nordic Council of Ministers, Copenhagen, Denmark.

26. World Population based on logarithmic equation obtained through statistical analysis. Taken from the World Wide Web site. http://sunsite.unc.edu/lunarbin/worlpop.

27. Dr Lewis Roberts article on "Radioactive Waste Management" published in 'Nuclear Energy' the journal of the British Nuclear Energy Society (BNES) Volume 39 No.1 February 2000.

28. International Standards Organisation ISO 14040 series, Environmental Management – Life-cycle Assessment.

29. D P Francis, Research Paper, Centre for Environmental Research, Brunel University 1999 – "Complex Life-cycle Assessment".

30. J Donaldson and D P Francis, Research Paper D2, Centre for Environmental Research, Brunel University 1999 – "Selection of Industry Specific Burdens for Life-cycle Inventories – Examples and a Selection Criteria from the Electronics Industry".

31. D P Francis, EngD, Brunel University 1999 – "Models for Applying Complex Life-cycle Assessment in the Telecommunications Industry".

32. B Solberg-Johansen, PhD, Surrey University 1998 – “Environmental Life-cycle Assessment of the Nuclear Fuel Cycle”.

33. Paper presented by Westlakes Scientific Consulting criticising the Environment Agency for not using a risk-based approach to regulation. Fourth annual BNES/BNIF Nuclear Congress. December 1999.

34. A guide to Risk Assessment and Risk Management for Environmental Protection. Department of the Environment, Transport and the Regions. HMSO 1995 ISBN 011 7530913.

35. “Accounting for the Environment” (Page 88) Rob Gray. Published in association with the Chartered Association of Certified Accountants (ACCA). ISBN 1-85396-223-6

36. AWE Environmental Safety and Health Policy issued April 2000, AWE/MAN.S/01 PSEH01. Available from the AWE web site. http://www.awe.co.uk/.

37. International Standard ISO 14042: 2000(E) Environmental management - Life-cycle assessment - Life-cycle impact assessment.

38. LCA Impact Assessment Method - Spreadsheet database of characterisation and normalisation factors. Centre of Environmental Science, Section Substances and Products - Leiden University in the Netherlands. Lauren Van Oers. Updated August 2001.

39. Lecture notes on Integrated Pollution Science (Atmospheric Chemistry) as part of the MSc in Environmental Management at Brunel University - Dr S Mullins, November 1999.

40. World Meteorological Organisation 1991. http://www.wmo.ch/index-en.html

41. UN Environmental Programme Montreal Protocol Agreement on Substances that Deplete the Ozone Layer 1987.

42. IAEA Bulletin 39/1 – “Radiation and the Environment”: Assessing effects on plants and animals. Gordon Linsley. March 1997. http://www.iaea.or.at/worldatom/periodicals/bulletin/Bull391/linsley.hml

43. Environmental Assessment of Products Volume 1 Wenzel, Hauschild and Alting. 1997 Volume 1: Methodology, tools and case studies in product development. ISBN 0 412 80800 5. Published by Chapman and Hall, London.

44. Health and Safety Executive, Approved Supply List (Fifth Edition). Information approved for the classification and labelling of substances and preparation dangerous for supply. Chemicals (Hazard Identification and Packaging for Supply) Regulations 1994 (as amended). HSE Ref: ISBN 0 7176 1725 4.

45. The Environmental Protection Act 1990 Part 1 HMSO. ISBN 0105443905

46. Oxford Concise Science Reference Dictionary 2nd edition 1991 ISBN 0-19-866167-3

47. Impact of Radiation on the Environment D. Robeau – IPSN. From Environment on CD-ROM Technical Indexes product. November 2000.

48. Royal Commission of Environmental Pollution 6th Report Nuclear Power and the Environment Cm 6618.

49. Environmental Health Criteria 025 - Selected Radionuclides, World Health Organisation 1983.

50. The oxidation state of plutonium in the Irish Sea. D M Nelson and M B Lovett. Nature 276: p599 - 601 (1978).

51. "Plutonium in drinking water: effects of chlorination on its maximum permissible concentration". R P Larsen and R D Oldham. Science 201: p1008-1009 (1978).

52. "Synthesis of the research literature in transuranic elements in the environment" (W C Hanson, ed.) R L Watters, D N Edgington, T E Hakonson et al. DOE publication series, TID-22800, Washington, D.C 1980.

53. "Physiochemical characterisation of mobile plutonium species in soils", T R Garland and R E Wilding in p254-263 of Biological Implications of Metals in the Environment (H Drucker and R E Wildung, eds). DOE symposium series, Richland, Washington, 1975. CONF-750929 NTIS (1977).

54. "Plutonium, americium and uranium concentration in Nevada Test Site soil profiles". E H Essington, E B Fowler, R O Gilbert et al, in p157- 173 of Transuranium Nuclides in the Environment. Proceedings of a symposium, San Fransisco, 1975. IAEA publication STI/PUB/410, Vienna, 1976.

55. Chemical Analysis Operations at AWE Aldermaston. Private Communication 2000.

56. "Distribution of plutonium in trinity soils after 28 years". J. Environ. Qual. 5(4): p431-437 (1976).

57. "Environmental processes leading to the presence of organically bound plutonium in plant tissues consumed by animals in biological implications of radionuclides released from nuclear industries". Proceedings of symposium, IAEA, Vienna 1978.

58. "The behaviour of plutonium and other long-lived radionuclides in Lake Michigan. II. Patterns of deposition in the sediments". D N Edgington and J A Robbins. P245-260 in Impacts of Nuclear Releases into the Aquatic Environment. Proceedings of a symposium. Otaniemi, Finland 1975. IAEA publication STI/PUB/406, Vienna, 1975.

---

59. International Atomic Energy Agency. The radiological basis of the IAEA revised definition and recommendations concerning high level radioactive waste unsuitable for dumping at sea IAEA-211 (1978).

60. T K Manners and C C Fleischer. EUR 17888, 1994 “Large-scale demonstration of dismantling techniques under realistic conditions on the LIDO biological shield”.

61. Testimony of Dr Edward Radford to the Select Committee on Ontario Hydro Affairs 10 July 1979.

62. “Distribution and reaction of tritiated hydrogen and methane”, Burger L L P 47-64 in Behaviour of Tritium in the Environment. IAEA, Vienna 1979.

63. International Commission of Radiological Protection. Report of the task group on reference man. ICRP publication 23. Pergamon Press, 1975.

64. Discussion with Sean Amos AWE Aldermaston. Private Communication 2000.

65. “Caesium-137 in Radioactivity and Human Diet” (p 317-352). L Fredriksson, R J Garner and R S Russel. Pergamon Pre 1966.

66. “A trophic level effect of Cs-137 concentration”. R C Pendleton, C W Mays, R D Lloyd et al. Health Physics 11. p 201-205 1962.

67. “A model for the approximate calculation of safe rates of discharge of radioactive wastes into marine environments”. Health Physics 13. P 743 - 758 1967.

68. CRC Handbook of Chemistry and Physics. David R Lide 73rd Edition. ISBN 0849304717.

69. National Council on Radiation Protection and Measurements. Krypton-85 in the atmsophere - accumulation, biological significance and control technology. NCRP No.44 (1975).

70. “Effects of Nuclear Explosions” Carey Sublette May 1997. http://www.fas.org/man/dod-101/navy/docs/fun/nfaqs.htm.

71. Ionising Radiation. http://www.photobiology.com/educational/len/index.htm. Leonard I. Grossweiner.

72. “Releases of Radionuclides from Nuclear Facilities (Impact on Non-Human Biota)”. Priority Substances List Assessment Report. Environment Canada July 2000.

73. Scottish Environmental Protection Agency Variation Notice to the Rosyth Royal Dockyard changing its discharge authorisation for Cobalt 60 and Tritium. Issued 22 December 1997 Ref. 46/97.

74. “Towards a methodology for Life-cycle Impact Assessment”. Udo de Haes H A (ed). SETAC Europe Brussels September 1996.

75. B Solberg-Johansen, R Clift, and A Jeapes, (1997) "Irradiating the environment - radiological impacts in Life-cycle Assessment", The International Journal of Life-cycle Assessment, 2, No. 1, pp.16-19.

76. The UK Sustainability Development Strategy as defined in Sustainable Development The UK Strategy Cm 2426 HMSO 1994 ISBN – O –10-124262-X.

77. S Shiels and D Garner, "Adopting a Life-Cycle Perspective to Inform Decisions". A paper presented at the one day conference on Best Practicable Environmental Option studies, Sponsored by BNES and held at the NRPB Oxfordshire on the 25 October 2001.

78. "Protection of the environment from nuclear fuel waste radionuclides": a framework using environmental increments. B D Amiro. The Science of the Total Environment, 128 (1993) 157 - 189 Elsevier Science Publications B.V., Amsterdam.

79. R Frischknecht, A Braunschweig, P Hofsetter & P Suter 1999. "Human health damage due to ionising radiation in life-cycle impact assessment". Paper accepted for publication in Environmental impact assessment review.

80. "Human Health Damages Due to Ionising Radiation in Life-cycle Impact Assessment". R Frischknecht, A Braunschweig, P Hofstetter and P Suter. Environmental Impact Assessment Review 20 (2000) 159-189.

81. "Environmental Assessment of Nuclear Power Generation in Korea". Young Eal Lee, Kun Jai Lee and Byong Whi Lee. Published in Progress in Nuclear Energy, Vol. 37, No 1-4, pp. 113-118, 2000.

82. "Health Risks from Low Level Environmental Exposure to Radionuclides", K F Eckerman. Environmental Protection Agency, EPA 402-R-97-014 (1998).

83. "Impact Assessment of Ionising Radiation on Wildlife (R & D Publication 128)". Published by the Environment Agency with financial support from English Nature June 2001. ISBN 1 85705590X.

84. Annals of the ICRP. Publication No. 72. "Age Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients". ISBN 0 08 04. ISBN 0 08 042737 5.

85. Environmental Sampling after a Chemical Accident DETR report. ISBN 011 753 4951.

86. Irving Kaplan – "Nuclear Physics" 1956.

87. Stanley E Manahan, "Fundamentals of Environmental Chemistry". Lewis Publishers, 1993 ISBN 0-87371-587-X.

88. Substances Hazardous to the Environment – Croner's March 2003 No. 23

---

89. BPEO Decision Makers Guide. Prepared by Environmental Resources Management Ltd in conjunction with the Environment and Heritage Service. June 2001 – www.ehsni.gov.uk

90. Office of Civilian Radioactive Waste Management – Total System Life-cycle Cost Programme for the Yucca Mountain Project. December 1998.

91. AWE Infrastructure Support Services Information Leaflet on Transport and Nuisance.

92. CIRIA (Construction Industry Research and Information Association), Report 142. Control of Pollution from Highway Drainage Discharges 1994.

93. AWE Motor Transport Section Environmental Addendum to the Safety Case Issue 1 March 2000 DSD08/E/EV/017. Private Communication.

94. Draft Environmental Statement for the Toxic Waste Transfer Station at AWE AM2888/1995/SEPTEMBER W S Atkins September 1995. Private Communication.

95. The UK Emission Factors Database http//www.rsk.co.uk

96. The UK National Air Quality Strategy. Figures and pollutants are reproduced in http://www.seiph.umds.ac.uk/omni/naqs.htm.

97. Page 868 Table 20.5 of Environmental Engineering by G Keily. Published by McGraw-Hill. 1996, pp628. ISBN 0-07-709127-2.

98. Design Manual for Roads and Bridges Volume 11: Environmental Assessment. DETR Publication 1993.

99. M Harrison, Letters to The Independent. Saturday 14 July 2001.

100. The environmental impacts of road vehicles in use, air quality, climate change and noise pollution DETR. http://www.roads.dft.gov.uk/cvtf/impact/1/htm.

101. T K Manners, MSc Dissertation, Brunel University, 2000. "An Evaluation of the Environmental Influences and Future Strategy of Dumped Nuclear Fuel in the Arctic Sea".

102. AWE Approved Risk Assessment Methodology. Private Communication.

103. Scottish Environmental Protection Agency (SEPA) and the UK National Radiological Protection Board (NRPB).

104. AWE Hazard Categorisation Procedure Dated 1998. Private Communication.

105. Health and Safety Executive, A guide to the Control of Major Accident Hazard Regulations 1999, HMSO 1999 ISBN 0 7176 1604 5.

106. M S Patterson, MSc Dissertation, Surrey University. 1999 – "A Methodology for the Identification of Major Accident Hazards at a Typical Industrial Site".

107. Guidance on the Interpretation of Major Accident to the Environment for the Purposes of the COMAH Regulations. DETR 1999.

108. Microsoft Excel modelling programme for a unit release based on the results Aermod. Mark Bussell, Oxford Biosphere Ltd. August 2001. Private Communication.

109. Aermod gaseous dispersion modelling software. Aermod Meteorological Office College Shinfield Park Reading. www.metoffice.com/environment.

110. Technical Guidance Note (Environmental) E1. Best Practicable Environmental Option Assessments for Integrated Pollution Control. Environment Agency publication 1997 – ISBN 0-11 – 310126-0

111. Horizontal Guidance Note (H1). Integrated Pollution Prevention and Control (IPPC) Environmental Assessment and Appraisal of BAT. Environment Agency Publication ISBN 0113101082.

112. H Area Safety Case AWE/HDFM/A/0003/006 Issue 2 January 2001. Private Communication.

113. AWE Aldermaston H Area Auxiliary buildings Full Safety Case. Private Communication 2000.

114. HD Area Full Safety Case Environmental Addenda Issue 1 March 2001 AWE/HDFM/B/0103/041. David Stapleton. Private Communication.

115. Radioactive Decay Kinetics, Chapter 3 of the Oregon State Department of Nuclear Chemistry Textbook Chapter 3. http//oregonstate.edu/dept/nchem/textbook/chapter3.pdf.

Appendix A
Surface Watercourses

The following list of surface watercourse should be read in conjunction with O/S 1:25,000 series Explorer Maps for the Reading, West Berkshire and North Hampshire.

- West End Brook - flows to the south of the site in an easterly direction, approximately 1 km from the centre.
- Silchester Brook - flows to the south of the site in an easterly direction, approximately 3 km from the centre.
- Fishermans Brook - flows to the north of the site in an easterly direction, approximately 2 km from the centre and meets Padworth Stream.
- Church Brook - flows to the south of site in an easterly direction approximately 3.25 km from the centre.
- Bishops Wood Stream - flows to the south of site in an easterly direction approximately 2.25 km from the centre.
- Wasing Stream - flows to the west of the site approximately 2.25 km from the centre and meets the River Enborne, before it joins the Kennet, approximately 2.75 km north west of the centre of site.
- Padworth Stream - flows north from the northeastern site boundary, meeting the River Kennet approximately 3 km from the centre of site.
- Aldermaston Stream - flows from the Blue Circle Lake at the north of site to meet the River Kennet 2.5 km from the centre of site.
- River Enborne - dominates the drainage for the western side of the site area flowing in a northeasterly direction to meet the River Kennet approximately 2.5 km to the north west of the site centre.
- River Kennet - the largest river in the site area flowing in a north easterly direction approximately 2.5 km to the north of the site centre and eventually joins the River Thames.
- The Kennet and Avon canal also flows through the area, paralleling the flow of the River Kennet to the north of the site.

Under the Environmental Agency's GQA (Chemistry) scheme six of the surface water features in the area have been assessed and awarded grades according to their water quality:

- River Enborne (Baughurst Brook to Kennet) - 'Fairly Good' (95-97 & 96-98).
- Fisherman's Brook (Source to Padworth Stream) - ' Fairly Good' (95-97, 'Fair' (96-98).
- Padworth Stream (Old Warren to Kennet) - 'Fairly Good' (95-97), 'Fair' (96-98).
- Kennet and Avon Canal (Woolhampton to Ufton) - 'Fair' (95-97), 'Fairly Good' (96-98).
- Silchester Brook (Tadley to Silchester Sewage Treatment Works) - 'Good' (95-97 & 96-98).
- River Kennet (Aldershot Stream to Enborne) - 'Good' (95-97), 'Very Good' (96-98).

Appendix B
Surface Water Abstractions

The following list of surface water abstractions should be read in conjunction with O/S 1:25,000 series Explorer Maps for the Reading, West Berkshire and North Hampshire Areas.

Appendix B

- SU 577639 (2.5 km west) Wasing Farm is licensed to abstract 9092 m^3 yr^{-1} water from Lake and River Enborne for spray irrigation.
- SU 590617 (1.25 km southwest) Tadley is licensed to abstract 2273 m^3 yr^{-1} from un-named inland water for use in lake filling.
- SU 586645 (1.75 km northwest) Forsters Farm is licensed to abstract 22730 m^3 yr^{-1} from an un-named inland water for use in lake filling.
- SU 605666 (3 km north) Mill Lane is licensed to abstract 39528000 m^3 yr^{-1} from the River Kennet for use in fish farming.
- SU 587638 (1.5 km west) Harris Gully is authorised to abstract 5800 m^3 y^{-1} from an un-named inland water course for use in spray irrigation.

Appendix C
Ground Water Abstractions

The following list of ground water abstractions should be read in conjunction with O/S 1:25,000 series Explorer Maps for the Reading, West Berkshire and North Hampshire Areas.

Appendix C

- AWE Burghfield abstract water from the chalk at Grazely 4-km east of site.
- TWU abstract groundwater from the chalk 3 km northwest at Ufton Bridge.
- SU 601630 (0.75 km south) - Mrs J Rayner is authorised to abstract 1659m^3 yr^{-1} from the Bagshot Beds for agricultural purposes.
- SU 591666 (3.25 km north) - W Owen is authorised to abstract 1659 m^3 yr^{-1} from the River Gravels for agricultural purposes.
- SU 591662 (2.5 km north) - The Old Mill Hotel is authorised to abstract 909 m^3 yr^{-1} from the Chalk.
- SU 601628 (1 km south) - The Environment Agency is authorised to abstract 55000 m^3 yr^{-1} from the chalk for flow augmentation.
- SU 594646 (1 km north) - Blue Circle plc is authorised to abstract 22457 m^3 yr^{-1} from the chalk for use in university spray irrigation.
- SU 606666 (3 km north) - Padworth Trout Farm is authorised to abstract 935859 m^3 yr^{-1} from the River Gravels for use in fish farming.

Private Groundwater abstractions within 3 km of AWE Aldermaston:

- SU 606667 (3 km north) - P Waugh is authorised to abstract water from the River Gravels for domestic purposes.
- SU 593663 (2.5 km north) - I Davies and M Taylor are authorised to abstract water from the River Gravels for domestic use.
- SU 593663 (2.75 north) - M R Whitty is authorised to abstract water from the River Gravels for domestic use.
- NGR unknown - T F and U Dracup are authorised to abstract water from the River Gravels for domestic use.
- NGR unknown - Clappers Farm, Silchester: authorised to abstract water for own use.
- NGR unknown - The Hut, Ash Lane, Silchester: authorised to abstract water for own use.
- NGR unknown - Rimes Gigot, Rimes Lane, Baughurst: authorised to abstract water for own use.
- NGR unknown - Stoney Croft, Baughurst: authorised to abstract water for own use.
- NGR unknown - Shaw Lane, Baughurst: authorised to abstract water for own use.

Appendix D
SSSI around AWE Aldermaston

West Meadow - SU 597626, 1 km south of site. This site is made up of two fields of unimproved pasture, bounded by hedgerows and a stream. This type of habitat, which supports diverse plant and invertebrate communities, is rare and rapidly declining in Great Britain. West Meadow contains over 80 species of grassland plant, their distribution reflecting the varying moisture content of the soil, and interesting hedge boundaries composed of a variety of trees and shrubs.

Pamber Forest and Silchester Common - SU 615608, SU 605623, 2.5 km south east of site. Pamber forest is an extensive ancient oak woodland (185.4 ha) managed as a Local Nature Reserve. The West Side of the forest is bounded by a series of unimproved, neutral to acid wet meadows. To the north of the site are two heathland commons, representing the best remaining examples of this type of ecosystem in the area. Silchester is registered and Tadley common has been designated a Countryside Heritage Site by Hampshire County Council. The interface between ancient woodland, heath and grassland supports a wide range of animal and plant species, including many nationally rare species (equivalent to those listed in the British Red Data Book) and three species of bird listed in Annex 1 of the EC Directive on the Conservation of Birds.

Brimpton Pit SU 566651, 3.75 km north west. This is a working gravel pit considered important by geologists because it provides evidence for environmental change in the Ice Age. It is also an important site used to track the development of the Thames and its tributaries.

Woolhampton Reed Bed SU 575667 3.5 km north west. This site consists of dense reedbeds with smaller areas of tall fen vegetation and carr woodland. It is notable for its nesting passerine bird populations and the diversity of insects, which it supports, including several uncommon species. In particular, it is an important site for flies one species of which is listed as rare in the British Red Data Book [Ref].

Aldermaston Gravel Pits SU 596668 3 km north. The site consists of mature flooded gravel workings surrounded by dense fringing vegetation, trees and scrub. This site provides a variety of habitats for breeding birds such that it is regarded as being of regional importance for the quality of its breeding bird community.

Decoy Pit, Pools and Woods SU 616632 1 km east adjacent to site boundary. This site is comprised of many different types of habitat including woodland, heathland, grassland and small water bodies. The site is particularly important as it includes alder woodland, which is nationally uncommon, and a declining habitat. It also supports the largest known number of breeding dragonfly and damselfly species in Berkshire, as well as other nationally uncommon insects and birds. Decoy Pit is also a BBONT Nature Reserve.

Wasing Woods Ponds SU 578636, SU 583633 1.75 km south west. The site is made up of a group of ponds, wet ditches and marshy areas, partly situated in Wasing Wood and partly on open ground previously excavated for gravel. The site is especially important for dragon flies, some species of which are nationally uncommon.

Ron Ward's Meadow and Tadley Pastures SU 601606 3 km south. Ron Ward's Meadow is made up of an unimproved, herb rich grassland, managed traditionally as a hay meadow with after-math cattle grazing. The adjacent meadows have been included in the boundary as their species composition contrasts markedly as they support grasslands managed by grazing alone. Some species present at the site that are indicative of ancient grassland are also regionally uncommon.

Ashford Hill Woods and Meadows SU 563620 3.25km south east. This site comprises an extensive and varied complex of woodlands and agriculturally unimproved meadows. The habitat quality, diversity of communities and number of rare and threatened species ensures this site is without comparison in central and southern England. 2.36 ha of the site has been purchased by the Nature Conservancy Council and is now a National Nature Reserve, attracting 5000 visitors each year.

River Kennet SU 203692 to SU 572667 4.25 km north west. The River flows through many undisturbed areas of marshy grassland, wet woodland and reed beds and supports rich and diverse species. Clear succession in plant communities can be seen, reflecting variations in geology, flow rate and the influence of the Kennet and Avon Canal. The river also sustains abundant and diverse aquatic invertebrates, including the nationally scarce cranefly and caddis fly, as well as good populations of kingfisher, grey wagtail, mute swan and little grebe and a healthy and mixed fishery.

Appendix E
Environmental Monitoring for Radioactive Material (Ref. Year 2000)

Appendix Summary

Chapter 2 provides environmental information on the AWE Aldermaston site including the radiological monitoring regime. This Appendix reproduces the results from radiological monitoring carried out in 2000. Comparisons with the Generalised Derived Limits for protection of humans are made in the text of section 2.6 of Chapter 2. The results are in all cases below GDL's for AWE's radioisotopes.

Contents

Table E-1 High Volume Air Sample Results (Quarterly – Q3 2000)

Location	$^{238}Pu + ^{(239+240)}Pu$ $nBqm^{-3}$ (max. in air)	Total Uranium $nBqm^{-3}$ (max. in air)
Hannington	<30	134 ± 45
Thatcham	<30	151 ± 38
Reading	<30	277 ± 55
Basingstoke	<30	191 ± 45
Tadley	<30	78 ± 25
Silchester	<30	109 ± 26
Mortimer	94 ± 38	146 ± 45
Aldermaston	<30	41 ± 21

This table clearly shows that the levels of contamination over a 3 month period are very low and in the case of the plutonium samples was, except in Mortimer, below the limit of detection.

Table E-2 Surface Water Results (Quarterly – Q3 2000)

Location (OS Grid Ref.)	Total Alpha Bqm^{-3} (max.)	Total Beta Bqm^{-3} (max.)	Total Tritium Bqm^{-3} (max.)
Aldermaston Fishermans Lane	<20	206 ± 33	18 ± 4
Aldermaston Bridge	<20	117 ± 26	<6
Wasing	<20	308 ± 32	277 ± 55
Wasing Lower	<20	244 ± 32	7 ± 4
Padworth Bridge	<20	104 ± 41	<6
Aldermaston Stoke	<20	200 ± 33	9 ± 4
Silchester Sewage Works	<20	401 ± 35	7 ± 4
Bowmonts Bridge	21 ± 9	223 ± 30	<6
Tadley Pump House	<20	361 ± 34	7 ± 4
Church Brook Tadley	<20	999 ± 51	<6
Red Lane	<20	247 ± 32	7 ± 4
Pangbourne Upstream	26 ± 24	266 ± 55	<6
Pangbourne Downstream	23 ± 16	300 ± 32	<6
Fobney Works	21 ± 11	267 ± 35	<6

Table E-3 Rainwater Results (Quarterly - Q3 2000)

Location (OS Grid Ref.)	Total Alpha Bqm^{-3} (max.)	Total Beta Bqm^{-3} (max.)	Total Tritium Bqm^{-3} (max.)
AWE(A) R001C	<20	48 ± 22	16 ± 4
AWE(A) R003C	<20	140 ± 39	<6
AWE(A) R003C	<20	106 ± 30	13 ± 4
AWE(A) R003C	<20	51 ± 28	<6
Tadley	<20	78 ± 29	13 ± 4

Table E-4 Onsite Groundwater Borehole Results

Internal Location	**Total Alpha Bqm^{-3} (max.)**	**Total Beta Bqm^{-3} (max.)**	**Total Tritium Bqm^{-3} (max.)**
AWE(A) R406W July 2000	<20	260 ± 34	<6
AWE(A) R042W August 2000	<20	297 ± 35	26 ± 5
AWE(A) R410W September 2000	<20	59 ± 26	7 ± 4

Table E-5 Silchester Sewage Works Sampling Results

Location	**Total Alpha in dry sample kBqkg^{-1}**	**Total Beta in dry sample kBqkg^{-1}**	**^{239}Pu + $^{(239+240)}$Pu dry sample kBqkg^{-1}**	**Total Uranium in dry sample kBqkg^{-1}**	**Total Tritium in dry sample kBqkg^{-1}**
SSTW August 2000 - solid sample	0.29 ± 0.04	0.14 ± 0.01	<0.001	<0.0015	50 ± 8
Location	**Total Alpha Bqm^{-3}**	**Total Beta Bqm^{-3}**	**^{239}Pu + $^{(239+240)}$Pu Bqm^{-3}**	**Total Uranium Bqm^{-3}**	**Water bound Tritium Bqm^{-3}**
SSTW August 2000 - liquid sample	N/R	N/R	<3.2	<6.7	<6

N/R - No result. Analysis not carried out.

Table E-6 Soil Sampling Results (July 2000)

Location (OS Grid Ref.)	**Soil Depth cm**	**Total Alpha in dry soil kBqkg^{-1}**	**Total Beta in dry soil kBqkg^{-1}**	**Tritium in free water kBqm^{-3}**	**Total Uranium alpha in dry soil Bqkg^{-1}**	**^{239}Pu + $^{(239+240)}$Pu in dry soil Bqkg^{-1}**
Tutts Clump	0-1	0.12 ± 0.03	0.32 ± 0.03	6.0 ± 2.8	21.8 ± 1.8	<0.5
	1-5	0.19 ± 0.04	0.26 ± 0.03	10.3 ± 2.6	23.8 ± 1.8	<0.5
Sulhamstead	0-1	<0.1	0.30 ± 0.03	<6	15.5 ± 1.5	0.5 ± 0.10
	1-5	0.12 ± 0.03	0.51 ± 0.05	7.9 ± 2.4	28.4 ± 2.1	0.85 ± 0.11
Mortimer	0-1	0.17 ± 0.04	0.34 ± 0.03	<6	38.4 ± 3.2	<0.5
	1-5	0.24 ± 0.05	0.47 ± 0.05	<6	50.8 ± 3.4	<0.5
Reading	0-1	0.20 ± 0.04	0.27 ± 0.03	<6	29.2 ± 2.3	<0.5
	1-5	0.15 ± 0.04	0.28 ± 0.03	6.4 ± 3.2	22.5 ± 1.8	<0.5
Sherfield-On-Loddon	0-1	0.29 ± 0.06	0.40 ± 0.04	<6	40.4 ± 3.1	<0.5
	1-5	0.22 ± 0.04	0.45 ± 0.04	16.3 ± 3.5	20.7 ± 1.7	<0.5
Basingstoke	0-1	0.19 ± 0.04	0.42 ± 0.04	<6	49.3 ± 3.3	<0.5
	1-5	0.18 ± 0.04	0.38 ± 0.04	9.0 ± 2.7	42.1 ± 2.8	<0.5
Hannington	0-1	0.21 ± 0.04	0.25 ± 0.02	<6	44.3 ± 3.2	<0.5
	1-5	0.22 ± 0.04	0.23 ± 0.03	6.6 ± 3.5	41.3 ± 2.9	<0.5
Kingsclere	0-1	0.23 ± 0.05	0.52 ± 0.05	<6	55.6 ± 2.7	<0.5
	1-5	0.21 ± 0.04	0.55 ± 0.05	<6	34.9 ± 1.6	<0.5
Thatcham	0-1	0.29 ± 0.06	0.38 ± 0.04	<6	39.6 ± 2.2	<0.5
	1-5	0.29 ± 0.06	0.34 ± 0.03	17.2 ± 6.9	33.1 ± 1.6	<0.5
AWE Burghfield	0-1	0.25 ± 0.05	0.68 ± 0.07	7.6 ± 2.6	54.7 ± 3.1	<0.5
	1-5	0.29 ± 0.06	0.62 ± 0.06	12.2 ± 2.7	49.9 ± 2.9	<0.5
Silchester	0-1	0.24 ± 0.05	0.46 ± 0.05	8.3 ± 3.2	55.8 ± 2.7	1.05 ± 0.14
	1-5	0.30 ± 0.06	0.58 ± 0.06	6.5 ± 2.9	58.3 ± 3.3	1.08 ± 0.01
Aldermaston	0-1	0.16 ± 0.04	0.47 ± 0.05	<6	47.3 ± 2.4	<0.5
	1-5	0.27 ± 0.05	0.55 ± 0.05	10.2 ± 2.6	41.4 ± 2.5	<0.5

Table E-7 Vegetation Sampling Results (July 2000)

Location	Total Alpha in dry sample kBqkg^{-1}	Total Beta in dry sample kBqkg^{-1}	Tritium in free water kBqm^{-3}	Total Uranium alpha in dry sample Bqkg^{-1}	^{239}Pu + $^{(239+240)}$Pu in dry sample Bqkg^{-1}
Tutts Clump	<0.03	1.29 ± 0.24	<6	<0.3	<0.1
Sulhamstead	<0.03	1.40 ± 0.26	<6	0.7 ± 0.1	<0.1
Mortimer	<0.03	0.98 ± 0.18	<6	<0.3	0.17 ± 0.06
Reading	<0.03	0.89 ± 0.16	<6	<0.3	<0.1
Sherfield-On-Loddon	<0.03	0.79 ± 0.14	<6	<0.3	<0.1
Basingstoke	<0.03	0.75 ± 0.14	<6	<0.3	<0.1
Hannington	<0.03	0.96 ± 0.18	<6	<0.3	<0.1
Kingsclere	<0.03	1.20 ± 0.22	<6	<0.3	<0.1
Thatcham	<0.03	1.84 ± 0.34	<6	<0.3	<0.1
AWE Burghfield	<0.03	0.66 ± 0.12	<6	<0.3	<0.1
Silchester	0.05 ± 0.01	0.84 ± 0.15	<6	0.8 ± 0.1	<0.1
Aldermaston	<0.03	1.19 ± 0.22	<6	<0.3	<0.1

Table E-8 Milk Sampling Results (July 2000)

Farm Location	Tritium Activity in Free Water kBqm^{-3}	^{239}Pu + $^{(239+240)}$Pu Bqm^{-3} (milk)	Total Uranium alpha Bqm^{-3} (milk)
Tadley	<6*	<2.6	<3
Aldermaston	<6*	<2.5	<3
Mortimer	<6*	<5.2	<3

* NB these values are below the limit of detection for tritium

Appendix F
Example of a blank FREA

Appendix Summary

This Appendix reproduces the type of tabulated register that is used at AWE to record routine contributions to environmental aspects. The register has provision for aspect significance assessment and the procedural and engineered controls used to manage the aspect.

Facility Register of Environmental Aspects (FREA)

CORPORATE ASPECT	CORPORATE SIGNIFICANCE	SIGNIFICANT FACILITY CONTRIBUTION	DESCRIPTION (QUANTITY)	CONTROLS (ENGINEERED AND MANAGERIAL)
Releases to Air - R/A	High	*Yes or No*	*What quantities and isotopes are released?*	*What are the controls i.e. filters and monitoring arrangements.*
Releases to Air – Acids	Low		*Type of acid?*	*Scrubbers?*
Releases to Air – VOC's	Low		*Type and quantity?*	
Releases to Air – ODS's	Medium		*Type and quantity?*	
Releases to Air – Be	Low		*Concentrations?*	*IPC/IPPC authorisation and monitoring regimes and abatement systems?*
Releases to Air – Pb	Low		*Concentrations?*	
Releases to Air – Combustion by Products	Medium		*What volumes?*	
Releases to Water – R/A Effluent	High		*What volumes?*	
Releases to Water – Trade Effluent	Medium		*What volumes?*	
Releases to Water – Domestic Effluent	Low		*What volumes?*	
Releases to Water – Engineered Surface Water	High			
Releases to Water – Un-engineered surface Systems	High			
Releases of Waste – R/A	High		*What volumes?*	
Releases of Waste –Trade Waste	Low		*What volumes?*	
Releases of Waste – Domestic	Low		*What volumes?*	
Resource Use – Electricity	Low		*KWh/year consumption.*	*Metering? Energy warden appointed.*
Resource Use – Gas	Low		*KWh/year consumption.*	
Resource Use – Water On – site	Medium		*Volumes used per person.*	*Metering?*
Resource Use – Water Off – site	Low		*Volumes used per person.*	*Water savers?*
Resource Use – Chemical/Oil Storage and Use	Medium		*Types and volumes stored.*	*Bunds? Storage arrangements. COSHH assessments.*
Resource Use - R/A Use and Storage	High		*Special Nuclear Material?*	*Inventory and storage arrangements.*
Resource Use – Other	Low			

Facility Register of Environmental Aspects (FREA)

CORPORATE ASPECT	CORPORATE SIGNIFICANCE	SIGNIFICANT FACILITY CONTRIBUTION	DESCRIPTION (QUANTITY)	CONTROLS (ENGINEERED AND MANAGERIAL)
Land Quality - R/A	High		*Presence of contamination, survey results.*	*Surveys and monitoring well. Remediation programme?*
Land Quality – Solvents	High		*Records of solvent spillages.*	
Land Quality – Metals	Medium			
Nuisance – Odour	Low			
Nuisance – Noise	Low			
Nuisance – Visual	Low			
Nuisance – Light	Low			
Nuisance – Congestion	Low		*Number of people travelling to and from work.*	*Traffic restrictions.*
Ecology – Species	Medium			*Register of protected species on site.*
Ecology – Habitats	Medium			
Ecology – Heritage	Medium			

Appendix G
Environmental Indices (Equivalency Factors)

Appendix Summary

This Appendix reproduces the environmental indices (Equivalency Factors) used to interpret inventory information in Life Cycle Impact Assessment. The data is taken from published sources (as identified in the main text of the thesis). The indices are used to calculate the environmental impact of AWE site operations (Appendix J gives the plotted results). Equivalency Factors (EFs) are reproduced for Global Warming, Photochemical Ozone Creation, Stratospheric Ozone Depletion, Acidification and Nutrification.

Contents

Table G-1 Global Warming Potentials

Substance	Formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Others		
HFC – 23	CHF_3	11700
HFC – 32	CH_2F_2	650
HFC – 41	CH_3F	150
HFC – 43 - 10mee	$C_4H_2F_{10}$	1300
HFC – 125	C_2HF_5	2800
HFC – 134	$C_2H_2F_4$	1200
HFC - 134a	CH_2FCF_3	1300
HFC - 152a	$C_2H_4F_2$	140
HFC – 143	$C_2H_3F_3$	300
HFC - 143a	$C_2H_3F_3$	3800
HFC - 227ea	C_3HF_7	2900
HFC - 236fa	$C_3H_2F_6$	6300
HFC - 245ca	$C_3H_3F_5$	560
Chloroform	$CHCl_3$	4
Methylene chloride	CH_2Cl_2	9
Sulphur hexaflouride	SF_6	23900
Perfluoromethane	CF_4	6500
Perfluoroethane	C_2F_6	9200
Perfluorocyclo-butane	$C\text{-}C_4F_8$	8700
Perfluoropentane	C_5F_{12}	7500
Perfluorohexane	C_6F_{14}	7400
Carbon tetrachloride	CCl_4	1400
Methyl chloroform	CH_3CCl_3	110
CFCs		
CFC – 11	$CFCl_3$	4000
CFC – 12	CF_2Cl_3	85000
CFC – 13	$CClF_3$	11700
CFC – 113	$C_2F_3Cl_3$	5000
CFC – 114	$C_2F_4Cl_2$	9300
CFC – 115		9300
HCFCs		
HCFFC – 22	CF_2HCl	1700
HCFC – 123	$C_2F_3HCl_2$	93
HCFC – 124	C_2F_4HCl	480
HCFC - 141b	$C_2FH_3Cl_2$	630
HCFC - 142b	$C_2F_2H_3Cl$	2000
HCFC - 225ca	$C_2F_2H_3Cl$	170
HCFC - 225cb	$C_3F_5HCl_2$	530
Bromocarbons		
H – 1301	CF_3Br	5600
Carbon monoxide	CO	2

Substance	**Formula**	**GWP**
Hydrocarbons		3
Partly oxidised hydrocarbons		2
Partly halogenated hydrocarbons		1

Table G-2 Photochemical Ozone Creation Potential (POCP)

Hydrocarbon	Formula	POCP (relative to ethylene)
Alkanes		
Methane	CH_4	3.4
Ethane	C_2H_6	14
Propane	C_3H_8	41.1
n-butane	C_4H_{10}	59.9
i-butane		42.6
n-pentane	C_5H_{12}	62.4
i-pentane		59.8
n-hexane	C_6H_{14}	64.8
2-methylpentane	$CH_2CH(CH_3)C_3H_7$	77.8
3-methylpentane	$C_2H_5CH\ (CH_3)CH_3$	66.1
2,2 - dimethylbutane	$CH_3C(CH_3)_2C_2H_5$	32.1
2,3 - dimethylbutane	$CH_3CH(CH_3)CH(CH_3)CH_3$	94.3
n-heptane	C_7H_{16}	77
2-methylhexane	$CH_3CH(CH_3)C_4H_{10}$	71.9
3 - methylhexane	$C_2H_5CH(CH_3)C_3H_7$	73
n – octane	C_8H_{18}	68.2
2 - methylheptane	$CH_3CH(CH_3)C_5H_{12}$	69.4
n – nonane	C_9H_{20}	69.3
2 - methyloctane	$CH_3CH(CH_3)C_6H_{14}$	70.6
n – decane	$C_{10}H_{22}$	68
2 - methylnonane	$CH_3CH(CH_3)C_7H_{16}$	65.7
n – undecane	$C_{11}H_{24}$	61.6
n – dodecane	$C_{12}H_{26}$	57.7
Cyclohexane		59.5
Methyl cyclohexane	C_7H_{14}	73.2
Alkenes		
Ethylene	C_2H_4	100
Propylene	C_3H_6	107.9
1 – butene	$CH_2CHC_2H_5$	113.2
2 – butene	$C_2H_5CHCH_2$	99.3
2 – pentene	$C_2H_5CHCHCH_3$	95.3
1 – pentene	$CH_2CHC_3H_7$	104.1
2-methylbut - 1 -ene	$CH_2C(CH_3)C_2H_5$	83
3-methylbut - 1 -ene	$CH_2CHCH(CH_3)CH_3$	118.4
2-methylbut - 2 -ene	$CH_3C(CH_3)CHCH_3$	77.1
Butylene		70.3
Isoprene	C_5H_8	117.8
Styrene		7.7
Alkynes		
Acetylene	C_2H_2	28
Aromatics		
Benzene	C_6H_6	33.4
Toluene	$(C_6H_6)CH_3$	77.1
o – xylene	$(C_6H_6)(CH_3)_2$	83.1

Hydrocarbon	**Formula**	**POCP (relative to ethylene)**
m – xylene	$(C_6H_6)(CH_3)_2$	108.8
p – xylene	$(C_6H_6)(CH_3)_2$	94.8
Ethylbenzene	$(C_6H_6)C_2H_5$	80.8
n - propylbenzene	$(C_6H_6)C_3H_7$	71.3
i - propylbenzene		74.4
1,2,3 - trimethylbenzene	$(C_6H_6)(CH_3)_3$	124.5
1,2,4 - trimethylbenzene	$(C_6H_6)(CH_3)_3$	132.4
1,3,5 - trimethylbenzene	$(C_6H_6)(CH_3)_3$	129.9
o - ethyltoluene	$(C_6H_6)(CH_3)(C_2H_5)$	84.6
m - ethyltoluene	$(C_6H_6)(CH_3)(C_2H_5)$	98.5
p - ethyltoluene	$(C_6H_6)(CH_3)(C_2H_5)$	93.5
3,5 - dimethylethylbenzene		124.2
3,5 - diethyltoluene		119.5
Aldehydes		
Formaldehyde	$HCHO$	55.4
Acetaldehyde	CH_3CHO	65
Propionaldehyde	C_2H_5CHO	75.5
Butyraldehyde	C_3H_7CHO	77
i - butyraldeyde		85.5
Valeraldehyde	C_4H_9CHO	88.7
Benzaldehyde		-5.6
Ketones		
Acetone	$(CH_3)_2CO$	18.2
Methylethylketone	$CH_3COC_2H_5$	51.1
Methyl - i - butylketone	$CH_3COC(CH_3)_3$	84.3
Cyclohexanone		52.9
Alcohols		
Methyl alcohol	CH_3OH	20.5
ethyl alcohol	C_2H_5OH	44.6
i-propanol	$CH_3CHOHCH_3$	21.6
n – butanol	C_4H_9OH	62.8
i – butanol		59.1
s – butanol		46.8
t – nutanol		19.1
Diacetone alchol		61.7
Cyclohexanol		62.2
Esters		
Methyl acetate	CH_3COOCH_3	4.6
ethyl acetate	$CH_3COOC_2H_5$	32.8
n - propyl acetate		48.1
i - propyl acetate	$CH_3COOCH(CH_3)_2$	29.1
n - butyl acetate	$CH_3COOC_4H_9$	51.1
s - butyl acetate		45.2
Organic acids		
Formic acid		0.3

Hydrocarbon	**Formula**	**POCP (relative to ethylene)**
Acetic acid		15.6
Propionic acid		0
Ethers		
butyl glycol		62.9
Propylene glycol methyl ether		51.8
Dimethyl ether	CH_3OCH_3	26.3
Methyl - t - butyl ether	$CH_3CHOCH_2OCH_3$	26.8
Halocarbons		
Chloromethane		3.5
Methylene chloride	CH_2Cl_2	3.1
Methylchloroform	CH_3CCl_3	0.2
Tetrachloroethylene		3.5
Trichloroethylene	$C_2H_3Cl_3$	7.5
vinyl chloride		27.2
1, 1 - dichloroethane		23.2
cis 1,2 - dichloroethylene		17.2
trans 1,2 - dichloroethylene		10.1
Other Pollutants		
nitric oxide	NO	-42.7
Nitrogen dioxide	NO_2	2.8
Sulphur dioxide	SO_2	4.8
Carbon monoxide	CO	2.7

Table G-3 Equivalency Factors for POCP for VOC Mixtures

VOC Source	**EF**	
	(low NO_x) g C_2H_4/g VOC	**(high NO_x)g C_2H_4/g VOC**
Petrol powered car, exhaust	0.5	0.6
Petrol powered car, vapour	0.4	0.5
Diesel powered car, exhaust	0.5	0.6
Power plants	0.4	0.5
Combustion of wood or twigs	0.6	0.6
Food industry	0.4	0.4
Surface coating	0.5	0.5
Chemical cleaning of clothes	0.3	0.3
Refining and distribution of oil	0.4	0.5
Natural gas leakage	0.02	0.02
Coal mining	0.007	0.007
Farmimg	0.4	0.4
Controlled landfilling	0.007	0.007

Table G-4 Stratospheric Ozone Depletion Potentials

Substance	**Formula**	**5 yrs**	**20 yrs**	**100 yrs**	**Infinity**
CFC11	$CFCl_3$	1	1	1	1
CFC12	CF_2Cl_2				0.82
CFC113	$CF_2ClCFCl_2$	0.55	0.59	0.78	0.9
CFC114	CF_2ClCF_2Cl				0.85
CFC115	CF_2ClCF_3				0.4
Tetrachloromethane	CCl_4	1.26	1.23	1.14	1.2
HCFC22	CHF_2Cl	0.19	0.14	0.07	0.04
HCFC123	CF_3CHCl_2				0.014
HCFC124	CF_3CHFCl				0.03
HCFC141b	$CFCl_2CH_3$	0.54	0.33	0.13	0.1
HCFC142b	CF_2CLCH_3	0.17	0.14	0.08	0.05
HCFC225ca	$CF_3CF_2CHCl_2$				0.02
HCFC225cb	CF_2ClCF_2CHFCl				0.02
1,1,1 - trichlorethane	CH_3CCl_3	1.03	0.45	0.15	0.12
Methyl chloride	CH_3Cl				0.02
Halon 1301	CF_3Br	10.3	10.5	11.5	12
Halon 1211	CF_2ClBr	11.3	9	4.9	5.1
Methyl bromide	CH_3Br	15.3	2.3	0.69	0.64

Table G-5 Equivalency Factors (EF) for Acidification

Substance	Formula	EF
Sulphur dioxide	SO_2	1
sulphur trioxide	SO_3	0.8
Nitrogen dioxide	NO_2	0.7
Nitrogen oxides	NO_x	0.7
Nitric oxide	NO	0.7
Hydrochloric acid	HCl	0.88
Nitric acid	HNO_3	0.51
Sulphuric acid	H_2SO_4	0.65
Phosphoric acid	H_3PO_4	0.98
Hydrofluoric acid	HF	1.6
Hydrogen sulphide	H_2S	1.88
Ammonia	NH_3	1.88

Table G-6 Equivalency Factors (EF) for Nutrification

Substance	Formula	EF (N)	EF (P)	EF (ne)
N-compounds				
Nitrate	NO_3^-	0.23	0	1
Nitrogen dioxide	NO_2	0.3	0	1.35
Nitrite	NO_2^-	0.3	0	1.35
Nitrogen oxides	NO_x	0.3	0	1.35
Nitrous oxide	N_2O	0.64	0	2.82
Nitric oxide	NO	0.47	0	2.07
Ammonia	NH_3	0.82	0	3.64
Cyanide	CN-	0.54	0	2.38
Total N	N	1	0	4.43
P-compounds				
Phosphate	PO_4^{3-}	0	0.33	10.45
Pyrophospate	$P_2O_7^{2-}$	0	0.35	11.41
Total P	P	0	1	32.03

Where EF (N) is the separate impact potential for nutrient enrichment relative to Nitrogen

Where EF (P) is the separate impact potential for nutrient enrichment relative to Phosphorus

Where EF (Ne) is the combined impact potential for nutrient enrichment relative to Nitrate NO_3^-

Appendix H
Environmental Burdens (Life-Cycle Inventory)

Appendix Summary

This Appendix gives the inventory by AWE facility for each of the environmental aspects in the AWE EMS. The inventory is built up from a series of linked Excel spreadsheets and is submitted separately on a CD-ROM. The Appendix is broken down by aspect as follows:

Releases to Air - R/A

Each facility and /or building that has an R/A discharge is listed (92 in total). Some buildings did not make a discharge in the reference year (2000).

For each facility an annual contribution (Bq) and the isotope are given. For some facilities only the type of radiation is known (alpha or beta) and not the actual radioisotope. In this case the author has assumed that it is either Plutonium 239 (alpha) or Tritium (beta). The discharge data is taken from estimated or measured discharges that are presented to the Environment Agency as a requirement of the Radioactive Substances Act 1993.

Releases to Air – VOC

Information is given for the annual routine discharge of Volatile Organic Material (VOC) by facility or building, during the reference year (2000). Annual contribution (kg) and VOC name is given along with the equivalency factor (Appendix G). For the majority of the contributions the data is taken from the environmental addenda (reports), which have been subject to internal peer review and endorsement, by individual AWE Facility Managers. For other contributions the data has been taken from the IPPC/BAT justification report or estimated by Facility Managers after discussion with the Author based on simple Mass Balance assessments.

Releases to Air – Acid

Information is given for the annual routine discharge of acids by facility or building, during the reference year (2000). Annual contribution (kg) and acid type is given along with the equivalency factor (Appendix G). For the majority of the contributions the data is estimated by Facility Managers after discussion with the Author based on simple Mass Balance assessments.

Releases to Air – ODS

Information is given for the annual routine discharge of Ozone Depleting Substances (ODS) by facility or building, during the reference year (2000). The Author has made extensive use of the Montreal Protocol Substance Baseline Study Report [Referenced in the main body of the Thesis], for identifying the building, plant, inventory (kg), trade type, chemical group, type and name, leak rate, and total annual losses in terms of CFC11 equivalents per year.

Releases to Air – Be

Information is given for the annual routine discharge of beryllium by facility or building, during the reference year (2000). Annual contribution (kg) and the source of the data are given. For the majority of buildings this information comes from the IPPC/BAT Justification Report for Beryllium Processes.

Releases to Air – Pb

Information is given for the annual routine discharge of lead by facility or building, during the reference year (2000). Annual contribution (kg) and the source of the data are given. For the majority of buildings this information comes from the IPPC/BAT Justification Report for Beryllium Processes, which requires an assessment of the amount of lead or other toxic material discharged into the environment.

Releases to Air – Other Metals

This aspect is not included in the EMS but was added by the author when AWE submitted its IPPC/BAT Justification Report for Beryllium Processes. Information is given for the annual routine discharge of Titanium Dioxide and Aluminium Oxide by facility or building, during the reference year (2000). Annual contribution (kg) and the source of the data are given.

Releases to Air – Combustion by Products

Information is given for the annual routine discharge of combustion by products (CO, CO_2, NO_2). The only facility that currently measures NO_2 is the Main Boiler House.

Releases to Water – R/A

Information is given for the annual volumes (litres) of radioactively classified effluent discharged by facility or building, during the reference year (2000). The quantity of radioactivity by building is not available, however, the total volumes of treated effluent that are discharged from the site to the River Thames and to the local Water Utility (sewers) is given along with the quantity of alpha, beta and tritium radioactivity.

Releases to Water – Trade Effluent

Information is given for the annual volumes (litres) of effluent classified as "trade water" to Thames Water Utilities by facility or building, during the reference year (2000). The type of trade effluent by building is not available as the drainage is treated on site at a centralised facility. AWE carries out pH balancing, settling and monitoring prior to discharge to the public sewer.

The following volumes are also given:

- Annual site trade effluent inputs, based on what can be measured;
- Annual site trade effluent treated which includes a contribution from groundwater in-leakage;
- Annual site solid sludge outputs arising from the treatment processes and which are assumed to be 10% of the total trade effluent treated;
- Total quantities of chemical substance that was quantified in the IPPC/BAT report submission for Beryllium and associated processes.

Releases to Water – Domestic Effluent

Information is given for the annual volumes (litres) of domestic discharged to Thames Water Utilities by facility or building, during the reference year (2000).

Releases of Waste – R/A (Solid)

Information is given for the annual contribution (litres) of Intermediate Level Waste (ILW) and Low Level Waste (LLW) that is generated by facility or building, during the reference year (2000). The total site contributions are also given (m^3) along with the total activity (GBq) by isotopic breakdown.

Releases of Waste – Trade Waste

Contributions from individual facilities or buildings are not measured. Information is given on the annual site chemical collections, which are disposed of as separate Special Waste consignments. The actual volumes of individual consignments is given for one year from quarter 2 1999 to quarter 1 2000. Some chemicals are used for pH balancing in the AWE trade effluent treatment facility.

Releases of Waste – Domestic Waste

Contributions from individual facilities or buildings are not measured. Information is given on the annual site total (tonnes) that is estimated based on a 3-month measurement taken in the summer of 2001.

Resource Use - Electricity

Information is given on annual consumption (kWh) by facility where this is metered or estimated, during the reference year (2000). Information is also given on the CO_2 conversion factor used (0.44 kg/kWh) and the other pollutants associated with electricity production (particulates, SO_2, Hydrocarbons, NO_2, N_2O and CO).

Resource Use - Gas

Information is given on annual consumption (kg and kWh) for the site Main Boiler House, during the reference year (2000). The consumption by month is also given.

Appendix I
Normalisation Factors for Life-Cycle Impact Assessment

Appendix Summary

This Appendix gives details of normalisation factors used in the Life Cycle Impact Assessment. A summary showing the derived person equivalent factor for each impact category is presented in the main body of the thesis (see Chapter 3). Individual calculation sheets that detail how the author derived normalisation factors for each category is given in the accompanying CD-ROM. Individual sheets are given for the following impact categories:

- Environmental Irradiation (radioactive releases to water);
- Environmental Irradiation (radioactive releases to air);
- Special Landfill/Radioactive Waste Generation;
- Radioactive Dose to Humans (not used for impact assessment in this thesis but reproduced in the appendix for information);
- Global Warming/Climate Change;
- Stratospheric Ozone Depletion;
- Photochemical Smog Formation;
- Acidification;
- Nutrification (it is not possible to calculate with any reliability AWE Aldermaston's contribution to Phosphate and Nitrate discharge and therefore a default factor of 1 is used);
- Ecotoxicity (it is not possible to calculate with any reliability AWE Aldermaston's contribution to ecotoxicity and therefore a default factor of 1 is used);
- Human Toxicity (it is not possible to calculate with any reliability AWE Aldermaston's contribution to human toxicity and therefore a default factor of 1 is used);
- Domestic Waste;
- Toxic/Special Waste;
- Fossil Reserve Depletion.

Appendix J
Results of Characterisation, Normalisation and Valuation
(Life-Cycle Impact Assessment)

Appendix Summary

This Appendix gives detailed information on the calculated environmental impact by facility and impact category for all aspect contributions. Reproduced are the results as graphical plots by impact category, after characterisation, normalisation and valuation.

Additional information is included on the CD-ROM, in Excel spreadsheet form, for each individual facility's impacts as a numerical value in a matrix form. These matrices give details of:

- The facility number;
- Annual contribution to each aspect;
- Chemical species;
- Chemical name;
- Equivalency factors;
- Calculated contributions to each impact category;
- Summed totals by impact category modified by normalisation and valuation factors.

In addition the CD-ROM also gives a summary of all contributions and a spreadsheet for Site Impacts that cover aspect contributions that are not recorded at facility level. It is important to note that the Site Impacts spreadsheet does quantify the environmental impact from Radioactive Effluent discharges from the entire site (litres per annum based on gross alpha (^{239}Pu and ^{241}Pu) and gross beta (^{3}H). The Site Impacts spreadsheet has not been plotted graphically and has not been included in the discussion of results in Chapters 5 and 6, to avoid any possibility of double accounting.

Environmental Impact Profile for Global Warming


ODS
1.00E+03
1.00E+02
1.00E+01
1.00E+00
A2
A91
B2A1B2A4
C1.5
A45
A36
A19
C15
A4-82
A5A9
A1
B8A
A37
A8
A90
Harea
EXT
C6
A29
CTF
B8A1
R61 M
F127
ESSPH
A38
Blacknest
A6
A70.2
A23
Viper
A50
C5
IM
ODS

Environmental Impact Profile for Human Toxicity

Environmental Impact Profile for Aquatic Ecotoxicity

Environmental Impact Profile for Terrestrial Ecotoxicity

Impact Profile for Photochemical Smog Formation

Environmental Impact Profile for Acidification


NUTRI
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
MBH
A90
A91
MISC
A45
A1
A37
ESSPH
A4-82
A2
A38
A5A9
A50
CTF
R61 H
A8
A6
A29
C6
C15
Viper
NUTRI


LTRADE
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
A90
MBH
Harea
A97
ESSPH
A38
A1
A37
A50
A4-82
CTF
A8
F74
C6
A19
LTRADE

Environmental Impact Profile for Landfill Volume - Domestic Waste

Environmental Impact Profile for Environmental Irridiation to Air

Environmental Impact Profile for Environmental Irradiation as Waste

Appendix K

Results of Characterisation, Normalisation and Valuation for Transport Activities (Life-Cycle Impact Assessment)

Appendix Summary

This Appendix gives detailed information of the impacts associated with transport activities at AWE Aldermaston. The environmental impact from vehicle emissions is not included in the AWE EMS but the author felt that this omission should be quantified and discussed as part of the thesis. Information in the CD-ROM, in Excel spreadsheet form covers:

- Vehicle type and the associated g/km pollutants;
- Burdens (kg) by pollutant for staff vehicles and HGV and mileage;
- Valuation factors by impact category (already described in detail in the main body of the thesis text).

Appendix L

List of Dangerous Substances as Specified by the COMAH Regulations

Appendix L

List of Specific Substances Classed as Dangerous under COMAH Regulations Schedule 1 Part 2

SUBSTANCE
Ammonium nitrate
Ammonium nitrate conforming to Fertiliser Regulations 1991.
Arsenic pentoxide, arsenic (V) acid and/or salts
Arsenic trioxide, arsenious (III) acid and/or salts
Bromine
Chlorine
Nickel compounds in inhalable powder form (nickel monoxide, nickel dioxide, nickel sulphide, nickel disulphide, nickel trioxide)
Ethyleneimine
Fluorine
Formaldehyde (concentration ≥ 90%)
Hydrogen
Hydrogen chloride (liquefied gas)
Lead alkyls
Liquefied extremely flammable gases (including LPG) and natural gas (whether liquefied or not)
Acetylene
Ethylene oxide
Propylene oxide
Methanol
4, 4-Methylenebis (2-chloraniline) and/or salts in powder form
Methylisocyanate
Oxygen
Toluene diisocyanate
Carbonyl dichloride (phosgene)
Arsenic trihydride (arsine)
Phosphorus trihydride (phosphine)
Sulphur dichloride
Sulphur trioxide
Polychlorodibenzofurans and Polychlorodibenzodioxins (including TCDD), calculated in TCDD (Tetra Chloro Dibenzo p Dioxin) equivalent
The following CARCINOGENS: • 4-Aminobiphenyl and/or its salts • Benzidine and/or salts, Bis(chloromethyl) • Ether, Chloromethyl methyl ether, • Dimethylcarbamoyl chloride, • Dimethylnitrosomine, • Hexamethylphosphoric trimide, • 2-Naphthylamine and/or salts, • 1,3 Propanesultone and 4-nitrodiphenyl
Automotive petrol and other petroleum spirits

List of Categories Classed as Dangerous under COMAH Regulations Schedule 1 Part 3

SUBSTANCE	Associated Risk Phrase
Very Toxic	**Not Specified**
Toxic	**Not Specified**
Oxidising	**Not Specified**
Explosive plus pyrotechnics or explosives contained in an article	**R2**
Explosive	**R3**
Flammable	
Highly Flammable Flash point less than 55°c	**R17**
Highly Flammable Liquids Flash point less than 21°c	**R11**
Extremely Flammable	**R12**
Dangerous to the environment Very toxic to the environment	**R50**
Dangerous to the environment Toxic to the environment	**R51 & R53**
Reacts violently with water	**R14**
Liberates toxic gas on contact with water	**R29**

Appendix M

Environmental Audit Checklist (Hazard Identification for Facility Walk-through)

Appendix M

ENVIRONMENTAL AUDIT CHECKLIST (HAZARD IDENTIFICATION PROCESS)

This guidance is developed to assist with the identification of potential MATTE scenarios during the walkthrough stage of the process.

The audit process is carried out using the following sequence of procedures:

1. Identify dangerous substances (See **Appendix L**) from the "Facility Hazardous Materials Database";

2. Locate each dangerous substance during the facility tour and determine how it is used in facility processes.

3. Use the Seven S's (see tabulation below) for identifying major hazards (FIRES, EXPLOSIONS & SPILLAGES). Concentrate on the largest sources first

Appendix M

THE SEVEN S's CHECKLIST

No.	'S' Prompt	Guidance questions	Evaluate Facility Operations Under:
1	Stacks	• What is the condition? • Is it filtered (filter failure)? • Is there a palliative damper (failure)? • Are there any scrubbers? • Is there any stack drainage?	• **Normal conditions** • **Maintenance operations** • **Delivery operations** • **Transport operations** • **Silent hour failures** • **Shift operations** • **Shutdown modes** • **Revealed faults** • **Un-revealed faults**
2	Sinks	• Where does it drain to? • Is it possible to discharge toxic effluents down the wrong drain?	
3	Stains	• Staining is a good indication of past problems. • How far is to the nearest surface water drain for stored chemicals? • Look for missing drip trays? • What is the state of nearby vegetation and trees?	
4	Sewers	• Where is the nearest engineered surface water system? • Does any trade effluents go to Silchester sewage works? • Where does process effluent go? • Are there any R/A effluents generated (delay tank failures)?	
5	Storage	• Is it waste (is it stored appropriately)? • Is it labelled and marked? • Check the adequacy of chemical storage arrangements. • Where are raw process materials stored (bins & drums)? • ISO containers used to store R/A and other hazardous waste. • Check access and egress routes to deposit and remove waste.	
6	Spillage's	• What are the liquid handling procedures (potential for spills)? • Are bulk liquids bunded? • What is the capacity of the bunds (at least 110%)? • What is the bund made of (breeze blocks are porous, sand bags do not constitute adequate bunding)? • What are the delivery and filling arrangements of bulk chemicals?	
7	Skips	• Have they been overfilled? • Are the skips secure / locked? • Who has access? • Are they marked or labelled? • If not what controls prevent erroneous fly tipping to the wrong skip? • What are the arrangements for collection when full (Duty Of Care)?	

Appendix N
Identification of Major Accidents to the Environment (Application of the 6 Step Screening Methodology)

CONTENTS

- **Table N1 Accidents From the Fault Schedule**
- **Table N2 Accidents From the Environmental Addenda**
- **Table N3 Accidents From the Walkthrough (Hazard Identification Audit)**
- **Results of the analysis for Step 5**
- **Conclusions**

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
P1	Explosion of HE in firing chamber	6 kg explosion – no external impact	R2/3	Y	N/A	6 kg HE	Solid	No. In building fault	Chamber structure would contain all but jet blast (contained within building).
P7 to P14 inclusive	Loss of Containment Oil from: Pipe leaks Marx tank breach Overfilling	Environmental contamination	-	N	Release to Water Land Quality	Associated tank containing a bank of capacitors immersed in 40 m^3 transformer oil. Oil pumped from tank to capacitor.	Liquid	Yes. If released and not revealed. This could happen during silent hours or during the day as the area is not densely populated and the location of some of the pipe-work is remote.	Screened in for further assessment.
P15	Failure to empty the oil sump of rainwater.	Could result in environmental contamination as a result of release of oily water from the sump	-	N	Releases to Water Land Quality	Residual in tank only.	Liquid	No. This is mostly rainwater with only trace oil residues	Not enough oil to present a major accident to the environment. Oil is not a COMAH substance.
P16	Leak of SF_6	Release of a cylinder of SF_6 to atmosphere. Greenhouse gas with a high Global Warming Potential (24900).	-	N	Releases to Air	In one standard BOC gas cylinder.	Gas	No. Dilution with the atmosphere.	Small volume (200 bar approx. per cylinder). There is no immediate local impact. This release will contribute to the global impact of warming/climate change.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
P33	Fire due to flammable solvents or electrical fault	Toxic chemicals released to atmosphere	-	Y	Releases to Air Land Quality	Chemicals are only used in small quantities – see also inventory information. The inventory of flammable solvents is in litre quantities. Total recorded on the inventory for the whole of H Area is less than 150 litres (excluding 150 l of photographic fixer) spread across several buildings and stores.	Liquid	No. Low volumes contained within in building. Chemicals present no more of a fire risk than other materials and plant within the buildings. Gas products dispersed and diluted to atmosphere.	Small volumes (litre quantities only).
L1	Fire ignition of ethanol in solvent fire (during preparation of BMI Dye)	Toxic chemicals released to atmosphere	R11	Y	Releases to Air Land Quality	1 litre of solvent maximum.	Liquid	No. Low volume of solvent (1 litre) not considered enough to cause a building fire.	Small volume (1 litre).
L2	Fire – over heating laser	Toxic chemicals released to atmosphere	-	Y	Releases to Air Land Quality	No information available	All	Yes. Combustion by products could be dispersed off-site.	This fire is included as potential COMAH MATTE.
L3	Fire – laser beam ignition	Toxic chemicals released to atmosphere	-	Y	Releases to Air Land Quality	No information available	All	Yes. Combustion by products could be dispersed off-site.	This fire is included as potential COMAH MATTE.
L4	Fire – faulty electrical equipment	Toxic chemicals released to atmosphere	-	Y	Releases to Air Land Quality	No information available	All	Yes. Combustion by products could be dispersed off-site.	This fire is included as potential COMAH MATTE.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
L9	Spillage of BMI laser dye	Carcinogenic material released into lab.	-	-	N/A	25 litres is stored in external bin 2 (H36). The spillage scenario uses less than this.	Liquid	No. Although pump failure or human error could lead to a significant spillage (1 in 15 spills), dye is retained in the laboratory.	Dye enclosed within locked cabinet and prepared in a fume cupboard. This fault is contained within the laboratory and therefore not an environmental release.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
L24	Initiation of HE (explosion)	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	The maximum amount of HE is 20 kg – This is amount is the mitigated maximum (building packed with thermalite blocks to withstand blast). A worst case scenario would be accidental detonation of 20 kg of HE in chamber H1, H2 or H4 without the thermalite packing, resulting in catastrophic damage to the building. The maximum in other buildings is as follows: H10.1 (6 kg) H10.2 (4 kg) H10.3 (4 kg)	Solid	Yes – depending upon inventory of other material in these buildings. There are litre quantities of oil H10.1 – 56 litres of oil actual H10.1 – 55 litres of solvent actual (20 litres acetone, 2.5 litres alcohol, 30 litres of Evoclean, 2.5 litres of MIBK). H2 – 73 litres of oil actual H2 – 40 litres of solvent actual (5 litres of absolute alcohol, 10 litres of acetone, 5 litres ethanol, 5 litres of evolclean 191, 7 litres evostik, 7.5 litres of MIBK). Other Buildings may contain substances (asbestos), which could be released in an explosion.	Screened in for further assessment.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F1 to F5	Explosion of Round during transportation due to: Lightening Electrostatic discharge Vehicle impact	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of HE within a round is approximately 6 kg.	Solid	No. Although explosion takes place in a van outside of a building – 6kg of HE with no other hazardous material involved is not considered to be large enough to cause an off-site impact. At least 10kg in an accidental explosion with other hazardous materials is considered to be the threshold required to cause an off site hazard. This justification is based on discussions with explosive safety specialists [Discussion between Tim Manners and Nick Prout AWE September 2001].	Quantity of explosive is relatively small. No additional chemical assumed to be involved in fault scenario.
F6 to F10	Explosion of unassembled HE during transportation due to: Lightening Electrostatic discharge Vehicle impact	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of unassembled HE within the van is 0.5 kg up to approximately 6 kg.	Solid	No. Bounded by F1 to F5. It is assumed that there are no additional hazardous materials that could be re-suspended.	Bounded by Faults F1 to F5.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F11 to F16	Explosion of HE during preparation or storage Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of unassembled HE within the storage containers in H3, H6 and H7 is as follows: H7 Room 13 = 4.619 kg Room 12 = 0.34 kg Room 6 = 5.561 kg Room 3 = 2.024 kg Room 18 = 0.12 kg Room 16 = 2.554 kg Room 7 = 0.787 kg Room 4 = 64.624 kg Room 10 = 64.62 kg	Solid	Yes. The quantities held in Rooms 4 and 10 are in excess of the 20 kg amount in fault L24. The explosion of this quantity could cause an off site impact.	Screened in for further assessment.
F17 to F22	Inadvertent explosion of HE in firing chamber Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact Premature firing Human error	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of HE within the firing chamber is assumed to be 6 kg.	Solid	6kg is not considered to be large enough to cause an off-site impact	Bounded by fault P1.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F23 to F24	Pressure vessel explosion	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of HE within the firing chamber, within the pressure vessel is assumed to be one round (6 kg).	Solid	6kg is not considered to be large enough to cause an off-site impact.	Bounded by fault P1.
F26	Flammable gas explosion caused by leak in chamber	Gas explosion could lead to a fire, which is a bounding case. Toxic chemicals released to atmosphere	R2/3	Y	Releases to Air Land Quality	Asbestos fibres could be released which are particularly toxic.	Gas	Yes. Combustion by products could be dispersed off-site including asbestos particles.	This fire is included as potential COMAH MATTE and screened in for further analysis.
F27 to F40	Fires Involving HE Hydrogen leak Propane leak Vehicle impact with gas bottle High pressure gas systems Acetylene gas Electrical faults Weld sparks Heating of hot rounds	Potential for toxic explosive by products to be released into the atmosphere and associated chemical inventory	-	Y	Releases to Air Land Quality	A number of gases and oils could be released in the event of a major fire. Asbestos fibres could be released which are particularly toxic. A small amount of solvent (see L24) is stored external to the facility.	Gas Liquid Solid	Yes. Combustion by products and asbestos fibres could be dispersed off-site.	This fire is included as potential COMAH MATTE and carried forward for further analysis.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F41 to F56 and F60 and F61	Loss of containment of Be – various scenarios to both air and water.	Potential for toxic release to air and water. Release to air of beryllium particulate.	-	Y	Releases to Air Land Quality Releases to Water	Beryllium, like DU, is not machined in the HD firing area and its powder form is not allowed into the facility. It is used as a component in rounds fired in the toxic chambers, as well as in X-Ray windows. Typically a round might contain between 100 g and 2 Kg of beryllium. This will be pulverised after detonation. Various quantities of beryllium could be released to the environment (air and water) from these fault scenarios.	Solid/ particulate	Yes. Beryllium is highly toxic and further assessment is required to determine if any of these scenarios are potential MATTE.	All faults are carried forward for further analysis.
F57	Lithium Hydride reaction due to water (used for cleaning) reaction with lithium.	Evolution of hydrogen – no environmental release contained within the building.	-	N	N/A	No lithium recorded in the COMAH inventory.	Gas	No. Fault contained within the building as the volumes of gas generated are considered to be very low.	This fault is contained within the laboratory and therefore not an environmental release. Screened out.
F58	Loss of containment release of lead contamination after firing	Potential for toxic release to air and water	R61, R62 R20/22 R33	N	Releases to Air Land Quality Releases to Water	Lead is a toxic material – no information in the COMAH inventory. Likely form will be lead nitrate.	Particulate	Further assessment is required to determine if this is MATTE. Need to establish quantity released and if it challenges the external environment.	This fault is carried forward for further assessment.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F59	Loss of containment release of fluorine from explosives	Potential for toxic release to air and water	R7, R26, R35	Y	Releases to Air Land Quality Releases to Water	Fluorine is a toxic material – no information in the COMAH inventory.	Gas/liquid	Further assessment is required to determine if this is MATTE. Need to establish quantity released and if it challenges the external environment.	This fault is carried forward for further assessment.
NH1	Release of K10 (coagulant used to bind explosive) during handling of HE (Normal Operations)	No environmental release as it is normal operations and not a fault scenario.	-	-	N/A	N/A	-	N/A	Not a fault condition.
NH2 to NH6	Explosion of detonators during transport Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact Premature firing Human error	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Detonators contain only small quantities of HE (typically not more than 0.5 kg).	Solid	No. Gram quantities of explosive are not considered to be big enough to cause an off-site impact.	Screened out based on the arguments given in the column to the left.
NH8 to NH9	Inadvertent explosion of HE in firing chamber – operation of shredder and lightening strike.	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Typical mass of HE within the firing chamber, is assumed to be one round (6 kg).	Solid	6kg is not considered to be large enough to cause an off-site impact	Bounded by F17 – F22.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
NH10	Failure of gas system pipework leading to hydrogen explosion into an occupied area outside the firing chamber.	Evolution of hydrogen and rupture of gas bottles containing hydrogen. A secondary fault could be the release of building fabric material to atmosphere.	-	Y	Releases to Air	3 standard pressurised BOC cylinders of hydrogen.	Gas	Hydrogen is not considered to represent a hazard to the environment unless secondary substances are involved.	Screened in for further analysis owing to the possibility of asbestos being present in the building(s) fabric.
NH11	Methane leak leading to a fire	Toxic chemicals released to atmosphere	-	-	Releases to Air Land Quality Releases to Water	Unknown inventory discharged to the environment. Firewater and combustion by products.	All	Yes. Combustion by products could be dispersed off-site.	This fire is included as potential COMAH MATTE.
NH15 to 17	Inadvertent initiation of the proof test charge /detonator during assembly	Potential for toxic explosive by products to be released into the atmosphere	R2/3	Y	Releases to Air Land Quality	Detonators contain only small quantities of HE. Typically gram quantities and not kilogram.	Solid	No. Gram quantities of explosive are not considered to be big enough to cause an off-site impact.	Screened out based on the arguments given in the column to the left.
NH19	Ignition of hydrogen gas release during LiH reaction with water leading to a fire within firing chamber	Toxic chemicals released to atmosphere	-	Y	Releases to Air Land Quality Releases to Water	Firewater and combustion by products if fire becomes engulfing. No other chemicals apart from LiH are involved in this scenario. Lithium limited to 2 kg.	All	Yes. Combustion by products could be dispersed off-site.	This fire is included as potential COMAH MATTE.
AUXILIARY BUILDING FAULTS									
A1	HEPA filter failure could result in a release of R/A (DU) material to air.	This accident condition could result in contaminated land and/or groundwater pollution.	-	N	Releases to Air	150 g of DU held up in a filter.	Gas	Yes. R/A material could be dispersed off site.	Screened out as no COMAH materials involved.

Appendix N Table N1

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE FAULT SCHEDULE – Appendix 1 of AWE/HDFM/A/0003/006 Issue 2 January 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
A2	HEPA filter changes in the "red filter" room are carried out in a temporary containment structure.	A dropped filter may lead to an airborne release that could challenge the unfiltered extract system.	-	N	Releases to Air	150 g of DU held up in a filter.	Gas	Yes. R/A material could be dispersed off site.	Screened out as no COMAH materials involved.
A3	Major fire inside toxic chemical store.	Release of toxic chemicals to air.	-	Y	Releases to Air Land Quality Releases to Water	Less than 200 kg of toxic and very toxic chemicals.	All	Yes. Combustion by products could be dispersed off site.	This fire is included as potential COMAH MATTE.
A4	Major fire that breeches the existing containment systems for waste oil and MnO.	Release of combustion by products.	-	N	Releases to Air Land Quality Releases to Water	Approximately 1100 kg of MnO and 200 litres of waste oil.	All	Yes. Combustion by products could be dispersed off site.	Screened out as no COMAH materials involved.

Appendix N Table N2

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4

ACCIDENTS FROM THE ENVIRONMENTAL ADDENDA

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
A	Overfilling Marx tank	Leak within building – creation of clean-up waste.	-	N	Releases of Waste	Unknown size of leak.	Liquid	No. Contained in building due to internal bund (110% capacity).	Small quantity of oil involved, which will be contained by the bund, therefore screened out.
B	Leaking Marx tank	Leak within building and generation of clean up waste.	-	N	Releases of Waste	Unknown size of leak.	Liquid	No. Contained in building due to internal bund (110% capacity)	Tank leaks into the bund – no environmental release, therefore screened out.
C	Leaking storage tank	Leak into bund & generation of clean up waste. Potential water contamination during rainwater pump out.	-	N	Releases of Waste	Unknown size of leak.	Liquid	No.	Tank leaks into bund and therefore there is no environmental release. This fault is screened out.
D1	Failure of transfer pipe- isolated.	Leakage into pipe trench and generation of clean up waste.	-	N	Land Quality Releases to Water	If this is an un-revealed fault it could involve the entire oil inventory within the pipe on transfer.	Liquid	No. It is considered that this fault will be revealed before a major environmental release occurs. Transfers are not carried out very frequently (once every 2 – 3 years).	The transfer pipework is run in pipe trenches. This will provide containment for minor leaks and when the pipework is isolated from the storage and Marx tanks - which is the normal plant condition. This scenario is screened out on the grounds of very low probability and also because oil is not a COMAH substance.

Appendix N Table N2

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE ENVIRONMENTAL ADDENDA

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
D2	Failure of transfer pipe from the LINX pipework.	This runs above ground and failure would result in oil leaking onto the ground	-	N	Land Quality Releases to water	If this is an un-revealed fault it could involve the entire oil inventory on transfer.	Liquid	Yes. If undetected a large quantity of oil could challenge the groundwater and lead to an off-site problem.	This scenario is screened in for further analysis.
D3	Failure of transfer pipe from the MOGUL D & E pipework.	The MOGUL D & E pipe trench is connected to the machine bunding and oil leaking into the trench will flow into the bund. These machines are therefore fully bunded.	-	N	N/A	Unknown size of leak	Liquid	No. Fully bunded system.	Fully bunded system and therefore not an environmental release.
E	Dropped Drum	Contamination of land and water systems.	-	N	Land Quality Releases to water	Some drums (200 litres of OM16 mineral oil) are stored outside.	Liquid	No. Volumes in these containers would not be large enough to challenge the off-site environment. Unless they were near to a surface water drain. Even then 200 litres is not considered to be large enough to cause enough long term damage to aquatic ecosystems.	Screen out based on reasons given in previous box. Not currently a COMAH substance.

Appendix N Table N2

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE ENVIRONMENTAL ADDENDA

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
F	Leaking drum	Contamination of land or water system	-	N	Land Quality Releases to water	Some drums (200 litres of OM16 mineral oil) are stored outside	Liquid	No. Volumes in these containers would not be large enough to challenge the off-site environment. Unless they were near to a surface water drain. Even then 200 litres is not considered to be large enough to cause enough long term damage to aquatic ecosystems.	Screen out based on reasons given in previous box. Not currently a COMAH substance.
G	Impact damage to tank or pipework	Leak into a bund or leak into the ground causing contamination of land and water systems.	-	N	Land Quality Releases to water	Unknown size of leak. It is considered that this type of leak will be revealed limiting the amount of oil that would be released.	Liquid	No. It is considered unlikely that any impact scenario will not be known about and a catastrophic impact (aircraft crash or similar) would be required to lead to a major loss of oil.	Screen out based on low volumes likely to be released in this type of impact scenario. Oil is not a COMAH substance.

Appendix N Table N2

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS FROM THE ENVIRONMENTAL ADDENDA

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
H	Failure of both MOGUL storage tanks would exceed the capacity of the MOGUL sump. This would only happen if the two MOGUL tanks were drained of oil and there was coincident failure of the storage tank.	Contamination of land or water systems	-	N	Land Quality Releases to water	380 000 litres of oil if both tanks simultaneously failed.	Liquid	Yes. As the bund can only hold the contents of one tank a significant volume of oil would be released into the off site environment.	Screened in for further analysis.

Appendix N Table N3

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS IDENTIFIED FROM THE WALK-THROUGH ON THE 19 September 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
WT1	Underground oil pipeline leak. Pipeline runs underground for approximately 7m from H1 to storage tank.	Deterioration of land quality and potential for groundwater and river pollution. This arrangement currently breeches the Oil Storage Regulations 2001. Rectification of these arrangements will need to be built into future action plans.	-	N	Releases to Water Land Quality	34000 litres OM16 maximum. This fault may not be revealed for some time as the pipe is buried.	Liquid	Yes. Any major oil spillages to soil may challenge groundwaters that could transport the oil off site. Very slow biodegredation.	Mineral oil is a list 1 substance under the Groundwater Regulations 1998. This volume of oil lost to the environment is significant and should be screened in at this stage.
WT2	Above ground oil leak during transfers from tank to machine.	Deterioration of land quality and potential for groundwater and river pollution.	-	N	Releases to Water Land Quality	Approximately 30,000 litres of OM16 oil in each tank.	Liquid	Yes. Any oil spillages to soil may challenge groundwaters that could transport the oil off site. Very slow biodegredation.	Mineral oil is a list 1 substance under the Groundwater Regulations 1998 and should be screened in at this stage. This is the same fault as D2 above.
WT3	Spillage during emptying trade effluent tanks (R/A effluent)	Deterioration of land quality and potential for groundwater and river pollution.	-	N	Releases to Water Land Quality	Unknown volumes	Liquid	N/A	All R/A scenarios are screened out of the COMAH assessment.

Appendix N Table N3

Accident Scenarios from H Area Inventory – Screening STEPS 1 to 4
ACCIDENTS IDENTIFIED FROM THE WALK-THROUGH ON THE 19 September 2001

Fault Ref.	Fault Scenario	Environmental Impact (Potential Consequence)	Risk Phrase	COMAH Substance involved in Scenario (Y/N)	Aspects	Inventory involved in the scenario	Physical Form	Off Site Impact (Yes/No) and Justification	Reason for Screening Out as non MATTE
WT4	Spillage during pumping of trade effluent from tanks (non R/A contaminated washings)	Deterioration of land quality and potential for groundwater and river pollution.	-	-	Releases to Water Land Quality	Unknown volumes will be released – depending on the nature of the fault. This effluent will be combustion by product washings diluted with large volumes of water. The trade effluent contains un-quantified amounts of firing chamber wash-down, developer liquid from film processing and µg/litre quantities of iron and lead.	Liquid	No. A spillage is likely to be detected and dealt with during the transfer operation. It is not considered likely that this would result in a release big enough to cause major disruption to ecosystems and hence be regarded as MATTE.	Screened out based on reasons given in previous box. However it recommended on good practice grounds that nearby surface water drains be protected during pumping and transfer operations.
WT5	Fire in H8 Beryllium store	Toxic chemicals and combustion by products released to atmosphere	R25, R26 R48/23 R36/37/38 R43	Y	Releases to Air Land Quality	2.14 kg of Beryllium in solid form.	Solid – oxidising under combustion	Yes – Fire could distribute the oxidised Beryllium off site.	This fire is included as potential COMAH MATTE and taken forward for further analysis.
WT6	Rupture of potential PCB bearing capacitor tanks. As a result of a recent Abnormal Event, the contents and storage arrangements are under review. The potential risk from the un-bunded storage of this substance represents an environmental hazard.	Toxic chemicals released to water	R33, R50, R53.	Y. Owing to its persistence and toxicity	Releases to Water	Quantity estimated to be approximately 25 litres of PCB bearing material.	Liquid	Yes – Poor storage arrangements for some insulators awaiting disposal, are close to surface water drains and are not adequately protected. Evidence of leaks.	It is unclear at this stage how much capacitor oil contains PCB material and what the risk is. This is carried further for further analysis.

RESULTS OF THE ANALYSIS FOR STEP 5

This section describes the results of the detailed analysis carried out on those faults that have been carried forward for further analysis. Some faults that were previously grouped have now been split into individual faults as described in the Safety Case.

Fault Ref: P7 **Oil leak from a flexible pipe during a transfer**

Loss of oil failures from pipe faults has already been covered under the following faults conditions:

D1 (See Table N2)
D2 (See Table N2)
D3 (See Table N2)
WT2 (See Table N3)

Fault Ref: P8	**Spurious high-energy discharge within Marx tank**
Fault Ref: P9	**Fragment from explosion penetrates vacuum X-Ray tube**
Fault Ref: P10	**Corrosion of tank**
Fault Ref: P11	**Tank collapse due to blocked breather vent**
Fault Ref: P12	**Overfilling Marx tank**
Fault Ref: P13	**Opening of Marx tank**
Fault Ref: P14	**Water leak from heat exchanger, displacing oil in Marx tank**

All of these faults will result in a loss of containment of oil. The frequency of all types of failure of a storage vessel has been estimated to be of the order of 10^{-4} per year for a robust engineered system. However, the frequency of catastrophic failure will be at least an order of magnitude lower (10^{-5} per year). If environmental contamination were to be realised the bunding would also need to fail, therefore the frequency has been categorised as $< 10^{-6}\ y^{-1}$ and therefore these faults are not considered to be credible and not MATTE.

Fault Ref: L2	**Fire – Over heating laser**
Fault Ref: L3	**Fire – Laser beam ignition**
Fault Ref: L4	**Fire – Faulty electrical equipment**

The frequency of various fires has been calculated as follows: precursor/initial fires - $\sim 0.1\ y^{-1}$ per building; medium fires - $\sim 10^{-4}\ y^{-1}$ per building; large fires $\sim 10^{-5}\ y^{-1}$ per building. It is considered that only a large (engulfing) fire will result in a potential MATTE. Owing to the design and procedures that minimise the potential for fire in an explosive facility like H Area, it is considered reasonable to reduce the expected fire frequency by a factor of 10 compared with the average building on site. This scenario is therefore considered to be $\sim 10^{-6}\ y^{-1}$ per building and improbable, and is not considered to be MATTE based on frequency.

Fault Ref: L24 **Initiation of High Explosive (HE) explosion**

The Safety Case does not calculate frequency for this scenario. However strong lines of defence based on the procedural control system are given. The large tanks of insulating mineral oil are sited within facility boundary and could be ruptured dispersing the contents off site (via ground and surface waters) in the event of an uncontrolled explosion of 20 kg or more of HE. This scenario is considered to be a potential MATTE based on consequence.

Fault Ref: F1 to F5 **Explosion of a round during transport due to lightning, electrostatic discharge or vehicle impact scenarios**

The frequency of lightning striking the HE during a round movement is 1.17×10^{-8}/yr. Lines of Defence arguments are presented for other initiating events. The typical mass of HE round is 6kg. The consequence of this scenario will depend on the location of the van. However. 6kg is not considered to be large enough to cause an off-site impact. These scenarios are not considered to be a MATTE based on the quantity of HE being transported and the existing controls to prevent initiation given in the Safety Case.

Fault Ref: F6 to F10 **Explosion of unassembled HE during transportation due to lightning, electrostatic discharge or vehicle impact scenarios**

These faults are bounded by F1 to F5 above.

Fault Ref: F11 to F16 **Explosion of HE during preparation or storage owing to: electrostatic discharge; electro-magnetic radiation; lightning; friction or chemical reaction; missile or impact.**

A frequency has not been calculated for these scenarios. The quantities held are in excess of the 20 kg amount in fault L24. The explosion of this quantity is considered to cause an off site impact. The large storage tanks of insulating oil (30,000 litres) in the tanks in H Area could be dispersed off site (via ground and surface waters) in the event of an uncontrolled explosion of greater than 6kg or more of HE. These scenarios are considered to be potential MATTE.

Fault Ref: F26 **Flammable gas explosion caused by leak in chamber**

The frequency of various fires has been calculated as follows: precursor/initial fires - ~0.1 y^{-1} per building; medium fires - ~10^{-4} y^{-1} per building; large fires ~10^{-5} y^{-1} per building. It is considered that only a large (engulfing) fire will result in a potential MATTE. Owing to the design and procedures that minimise the potential for fire in an explosive facility like H Area, it is considered reasonable to reduce the expected fire frequency by a factor of 10 compared with the average building on site. This scenario is therefore considered to be ~10^{-6} y^{-1} per building and improbable. and is not considered to be MATTE based on frequency.

Fault Ref: F27 **Fire involving HE – vehicle fire from accident**

This scenario is not considered to be a MATTE based on the absence of any other hazardous material that could be released in a fire/explosion.

Fault Ref: F28 **Fire involving HE – building fire**

This fault is bounded by the arguments given in Fault F26.

Fault Ref: F29 **Petrol ignited following a road accident leading to a fire**

This is not considered to be a MATTE based on the absence of HE or any other hazardous material that could lead to a MATTE consequence.

Fault Ref: F30 **Fire: Hydrogen leak - flammable gas ignited**

This fault is associated with hydrogen leak that is judged in the Safety Case to lead to significant building damage but not cause catastrophic structural failure. This is not considered to be a MATTE scenario based on consequence.

Fault Ref: F31 **Fire: Propane leak - flammable gas ignited**

The tolerability of this fault is based on the risk of a person being present and hence a fatality. It is not possible to screen this scenario on the information currently available. A number of solvents and asbestos fibres, used in building construction, could be released in the event of an explosion. This is considered a potential MATTE based on consequence.

Fault Ref: F32 **Fire: vehicle impact on gas bottles – flammable gas ignited**

The inventory for this fault is 3 flammable gas bottles (2 hydrogen and 1 deuterium) stored on the side of the chamber. The consequences of this scenario would be severe damage to the chamber but would not result in an off site release and is therefore not considered to be a potential MATTE.

Fault Ref: F33 **Fire: leak from high pressure gas system - flammable gas ignited**

This fault (F33) is a high pressure gas leak. It is not possible to screen this scenario out on information currently available and is considered to be a MATTE based on potential consequence (explosion).

Fault Ref: F34 **Fire: acetylene gas leak**

This is an acetylene gas fire for which the Safety Case calculated a frequency of $1.4 \times 10^{-5}\ y^{-1}$. The return frequency of this scenario is not low enough to screen out on probability. The consequence of this type of fire is pessimistically judged to be MATTE in the absence of any information to prove otherwise.

Fault Ref: F35 **Fire: combustible material – ignition of wood in chamber**

A number of solvents, gases and oils could be released in the event of a major fire. The Safety Case assessed acceptability of this fault based on human health (fatality) only. If a fire did occur before firing while the firing chamber was unoccupied, the chamber would provide an effective containment, especially if the door was closed upon detection of the fire. If the chamber was occupied the operators present would detect the fire rapidly allowing it to be extinguished, or allowing the staff to evacuate the chamber before the fire became too large. This is not considered to be a MATTE based on consequence.

Fault Ref: F36 **Fire: combustible material – excessive heating of hot rounds**

The consequence was assessed as critical due to potential fatalities. The frequency was determined as improbable (10^{-5}-10^{-7} yr^{-1}). The Safety Case concluded that if a fire did occur, as a result of the excessive heating of the round, the firing chamber would provide an effective containment i.e. the chamber is fully sealed with the doors and dampers fully closed. This is not considered to be a MATTE based on consequence and frequency.

Fault Ref: F37 **Fire: combustible material – sparks from welding**

The consequence of this fault was assessed in the Safety Case as critical due to potential fatalities. The frequency was determined as improbable (10^{-5}-10^{-7} yr^{-1}). Welding sparks may cause a small fire, however the risk of this leading to an engulfing fire and hence a potential MATTE is minimised by the presence of operators who can tackle the fire. The chamber will also provide an effective containment barrier preventing the fire escalating. This is not considered to be a MATTE based on frequency and consequence.

Fault Ref: F38 **Fire electrical – Burnt out damper motor**

This fault is a fire from faulty wiring. The consequence was assessed as critical due to potential fatalities. The frequency was determined as remote (10^{-3}-10^{-5} yr^{-1}). If a fire occurred while the chamber was unoccupied, the chamber would provide an effective containment. In the event of a fire within an occupied chamber, the operators present would detect the fire rapidly allowing it to be extinguished, or allowing the staff to evacuate the chamber before the fire became too large. This is not considered to be a MATTE based on consequence.

Fault Ref: F39 **Fire electrical – Burnt out damper motor**

This fault is a burnt out damper motor fire. The consequence was assessed as critical due to potential fatalities. The frequency was determined as remote (10^{-3}-10^{-5} yr^{-1}). If a fire occurred while the chamber was unoccupied, the chamber would provide an effective containment. This is not considered to be a MATTE based on consequence.

Fault Ref: F40 **Fire: electrical – faulty electrical equipment or wiring fault**

This is a fire from faulty wiring as per F38. The consequence was assessed as critical due to potential fatalities. The frequency was determined as remote (10^{-3}-10^{-5} yr^{-1}). If a fire occurred while the chamber was unoccupied, the chamber would provide an effective containment. In the event of a fire within an occupied chamber, the operators present would detect the fire rapidly allowing it to be extinguished. or allowing the staff to evacuate the chamber before the fire became too large. This is not considered to be a MATTE based on consequence.

Fault Ref: F41 **Loss of Containment DU and Beryllium detonation of round during a move**

Beryllium and DU is used as a component in rounds fired in certain chambers. Typically rounds contain between 100 g and 2000 g of beryllium, which will be pulverised after detonation. The release fraction is assumed to be 2 x 10^{-1} [AWE Company Safety Procedure 865 Section 9. 2 x 10^{-1} is the fraction released for Plutonium in a high explosion detonation. Plutonium is assumed to behave the same as Beryllium]. Frequency assessment in the Safety Case is limited to risk of fatality to humans. All H Area facility buildings are at least 125 m from the site fence. A consequence assessment has been carried out for the inadvertent detonation of a 15 kg explosive (2 kg of Be) charge during transport. This is considered to be a worst-case analysis for airborne releases. Using a 2 kg release of Beryllium (from the Safety Case) gives 0.0076 g s m^{-3} at 125 m (time integrated concentration).

The concentration of Beryllium has been assessed using a unit release programme. The result is a maximum ground level concentration (at 125m) of approximately 5.1 E-6 g/m^3, this is 4000% of the EAL and therefore considered to be a MATTE.

Fault Ref: F42 **Loss of Containment DU and Beryllium – Road Accident**

There is the potential for the loss of containment of Beryllium as a result of a round exploding during transportation, as a result of a road accident. If a round was engulfed in a fire following a road accident, but without the HE exploding, then only a small fraction (~3%,) of the Beryllium will become a respirable aerosol, because so much less material is dispersed. For a fire the release fraction is 3% (3E-2) of the inventory. The explosion is bounded by F41. A fire will result in 3% release fraction which gives an off site ground level concentration using the Aermod programme of 7.6 E-7 g/m^3 which is less than 10 times the EAL for Beryllium and therefore not considered to be a MATTE.

Fault Ref: F43 **Loss of Containment DU and Beryllium – Contaminated firing chamber**

This scenario is a routine condition rather than an accident and results in a small health risk to workers who work in the chambers. This is not a MATTE scenario

Fault Ref: F44 **Loss of Containment – Contaminated film cassette removed from chamber**

This is a routine condition. There is the potential for personnel to ingest, inhale or inject DU and Beryllium during the removal of the contaminated film cassette. This is not a MATTE scenario.

Fault Ref: F45 **Loss of Containment DU and Beryllium – toxic seal breached by explosive fragments**

There is the potential for fragments from an explosion within a firing chamber that could breach the toxic seal, which prevents the spread of DU, and Beryllium into the adjacent laboratory. A release of DU and Beryllium into the laboratory could result in a severe occupational illness, to any personnel inside the laboratory. The consequence of this fault is contained inside the laboratory and not an environmental release. This is therefore not a MATTE scenario.

Fault Ref: F46 **Loss of Containment DU and Beryllium – release of water from scrubbers**

The consequence from this fault is a potential release of Beryllium contaminated waters from the scrubbers. The system is fully bunded, and provides protection against the release of contaminated water to the environment. This is not a MATTE scenario.

Fault Ref: F47 **Loss of Containment DU and Beryllium – dampers not sealed properly after maintenance**

This fault is bounded by F48. See analysis below.

Fault Ref: F48 **Loss of Containment DU and Beryllium – damage to filter**

This fault is associated with a filter failure releasing Beryllium and DU to atmosphere. The Beryllium content is assumed to be 2g of Beryllium in a filter (150g of DU). For a filter failure the entire loading is assumed to escape (2 g). Failure frequency for a heavily contaminated filter set is assumed to be 0.01 y^{-1}. Using the Unit Release Programme based on Aermod for a release of 2g gives a maximum ground level concentration (at 125m) of approximately 2.5 E-7 g/m^3, this is less than 25% of the EAL and not considered to be a MATTE.

Fault Ref: F49 **Loss of Containment DU and Beryllium – dampers incorrectly re-fitted**

Fault Ref: F50 **Loss of Containment DU and Beryllium – open damper during firing**

These faults are bounded by F48.

Fault Ref: F51 **Loss of Containment DU and Beryllium – exposure of contaminated surfaces during maintenance**

This fault results in exposure of maintenance staff to contaminated surfaces and is therefore not an environmental release.

Fault Ref: F52 **Loss of Containment DU and Beryllium – failure of door seal**

This fault results in failure of the firing chamber door seal resulting in release of Be/DU to the local environment and not the external environment.

Fault Ref: F53 **Loss of Containment DU and Beryllium – failure of RA sump tank**

This fault is a loss of containment from the R/A sump tank. The toxic firing chamber R/A tanks have bunds preventing an environmental release.

Fault Ref: F54 **Loss of Containment DU and Beryllium – airborne activity during tank de-sludging**

This fault refers to tank de-sludging and the risks to operators. There is a negligible environmental release risk, as the sludge is kept wet at all times.

Fault Ref: F55 **Loss of Containment DU and Beryllium – airborne activity during HE trap cleaning**

This fault refers to HE trap cleaning. There is a negligible environmental release risk as the work is carried out inside the firing chamber.

Fault Ref: F56 **Loss of Containment DU and Beryllium – Beryllium mirror in camera breaks creating dust**

This refers to breaking a Beryllium camera mirror and the consequence of this is not an environmental release.

Fault Ref: F58 **Loss of containment release of lead contamination after firing**

Lead is fired in the open chambers and the ventilation dampers are closed during firing. Once the pressure has dropped the vent dampers are opened and the chamber purged to atmosphere. Monitoring is carried out for lead from the vent system and nothing has been detected – the assumption is that the lead condenses out on the chamber walls. This is therefore not an environmental release and not considered to be a potential MATTE.

Fault Ref: F59 **Loss of containment release of fluorine from explosives**

Fluorine is present in some, but not all of the explosives used in H Area. These are fired from the controlled area chambers where the action of the scrubbers will remove the fluorine gas by dissolution in water. This is therefore not an environmental release and not considered to be a potential MATTE

Fault Ref: F60 and F61 **Contaminated Wound DU and Beryllium – Pre-firing and Post-firing operations**

This refers to contaminated wounds and is not an environmental release.

Fault Ref: NH8 to NH9 **Inadvertent explosion of HE in firing chamber – operation of shredder and lightning strike**

These faults are bounded by faults F17 to F22.

Fault Ref: NH10 **Failure of gas system pipework leading to hydrogen explosion into an occupied area outside the firing chamber**

The frequency of a hydrogen fire/explosion due to leakage into an occupied area is estimated to be $1.1 \times 10^{-3}\ y^{-1} \times 3 \times 10^{-3} \times 0.1 = 3.3 \times 10^{-7}\ y^{-1}$. The location of the hydrogen bottles to other chemicals substances is currently unknown. This is currently considered to be a potential MATTE.

Fault Ref: NH11 **Methane leak leading to a fire**

The frequency of various fires has been calculated as follows: precursor/initial fires - ~0.1 y^{-1} per building; medium fires - ~$10^{-4}\ y^{-1}$ per building; large fires ~$10^{-5}\ y^{-1}$ per building. It is considered that only a large (engulfing) fire will result in a potential MATTE. Because of the design and procedures that minimise the potential for fire in an explosive facility, it is considered reasonable to reduce the expected fire frequency by a factor of 10 compared with the average building on site. This scenario is therefore considered to be ~$10^{-6}\ y^{-1}$ per building and improbable, and is not considered to be MATTE based on frequency.

Fault Ref: NH19 **Ignition of hydrogen gas during LiH reaction with water leading to a fire within the firing chamber**

The frequency of various fires has been calculated as follows: precursor/initial fires - ~0.1 y^{-1} per building; medium fires - ~$10^{-4}\ y^{-1}$ per building; large fires ~$10^{-5}\ y^{-1}$ per building. It is considered that only a large (engulfing) fire will result in a potential MATTE. Because of the design and procedures that minimise the potential for fire in an explosive facility, it is considered reasonable to reduce the expected fire frequency by a factor of 10 compared with the average building on site. This scenario is therefore considered to be ~$10^{-6}\ y^{-1}$ per building and improbable, and is not considered to be MATTE based on frequency.

Fault Ref: A3 **Major fire inside toxic chemical store**

The frequency of this fire for the auxiliary building toxic chemical store has been calculated as 6 x 10^{-4} y^{-1}. The consequence of the fault would be the dispersal of toxic substances to the off site environment. This fault is considered to be a potential MATTE based on frequency and consequence.

Fault Ref: D2 **Failure of transfer pipe from the LINX oil tank pipework**

If this is an un-revealed fault it could involve the entire oil inventory on transfer. The frequency of this fault has been fully assessed under P7 to P14 above and is considered to be approximately 10^{-3} y^{-1}, which is remote. This scenario is considered to be a potential MATTE owing to a previous failure of the LINX system, which led to an off-site release of oil killing fish.

Fault Ref: H **Failure of transfer pipe from the LINX oil tank pipework**

This fault has been fully assessed under P7 to P14 above and the frequency is considered to be not greater than improbable $10^{-7} > y^{-1}$. This scenario is not considered to be MATTE based on an incredible frequency of coincident failure of both Mogul storage tanks.

Fault Ref: WT1 **Underground oil pipeline leak. Pipeline runs underground for approximately 7m from building to storage tank**

No maintenance regime and given the age of the pipework (approximately 30 years), a fairly high failure rate should be assumed. During a pumping or transfer operation it is possible that a previously unidentified leak or breach will go unnoticed. Therefore a major volume of oil could be lost to the ground. This scenario is considered to be a potential MATTE.

Fault Ref: WT2 **Above ground oil leak during transfers from tank to machine**

This fault was already identified (as D2) see above.

Fault Ref: WT5 **Fire in H8 Beryllium store**

The frequency of various fires has been calculated as follows: precursor/initial fires - ~0.1 y^{-1} per building; medium fires - ~10^{-4} y^{-1} per building; large fires ~10^{-5} y^{-1} per building. It is considered that only a large (engulfing) fire will result in a potential MATTE. Owing to the nature of the material stored, this is considered to be a potential MATTE.

Fault Ref: WT6 Rupture of PCB insulation tank (capacitors)

A total 25 litres of material is stored. Potential accident scenarios include impact damage and leaks due to corrosion. At this stage external storage of un-bunded capacitor insulation is considered to be a potential MATTE. If all of the PCB present was released (25 litres) this may be sufficient to cause a MATTE.

CONCLUSIONS

A total of 18 scenarios were identified from the assessment as potential MATTE as follows:

Fault ID	Identified from	Fault Description
L24	Fault Schedule	Initiation of HE (explosion)
F11 to F16	Bounding faults from Fault Schedule	Explosion of HE during preparation or storage
F31	Fault Schedule	Fire: propane leak – flammable gas ignited
F33	Fault Schedule	Fire: leak from high-pressure gas system - flammable gas ignited.
F34	Fault Schedule	Fire: acetylene gas
F41	Fault Schedule	Loss of Containment DU and Be - detonation of round during move
NH10	Fault Schedule	Failure of gas system pipework leading to hydrogen explosion into an occupied area outside the firing chamber.
A3	Fault Schedule	Major fire inside toxic chemical store.
D2	Environmental Addenda	Failure of transfer pipe from the LINX pipework.
WT1	Walkthrough	Underground oil pipeline leak. Pipeline runs underground for approximately 7m from H1 to storage tank.
WT2	Walkthrough	Above ground oil leak during transfers from tank to machine.
WT5	Walkthrough	Fire in H8 Beryllium store
WT6	Walkthrough	Rupture of potential PCB bearing capacitor tanks.

The results of this MATTE identification exercise can now be used to assess the adequacy of the H Area Facility's emergency response arrangements. The focus of the emergency response assessment will be the identification of procedures and equipment to mitigate the consequences of any major environmental accident. The DETR guidance gives detailed information on what is considered to be best practice for emergency response as part of Risk Management strategies for environmental accidents.

Appendix O
Significance Testing (Application of the Risk Matrix)

CONTENTS

The following table repeats the faults from **Appendix N** giving frequency and consequence information for all faults. It is important to note that the fault must have both a consequence and a frequency to enable a judgement of significance to be made. This is distinct from step 5 of the MATTE analysis, which in some cases only needed to assess frequency or consequence. The author, for environmental risk assessment purposes, has designed the table to give a transparent record of the analyses undertaken.

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
P1	Explosion of HE in firing chamber	No frequency information available.	The maximum amount of explosive involved in this fault is 6kg. The chamber will contain the by-products generated in the explosion. There is therefore no environmental release.	N/A
P7 to P14 inclusive	Loss of Containment Oil from: Pipe leaks Marx tank breach Overfilling	The Safety Case calculates a return frequency of less than 1 x 10^{-6}. This is an **improbable** frequency classification.	Mineral oil leaking onto the ground will result in potential contamination of surface water systems. This is a **marginal** consequence classification.	C
P15	Failure to empty the oil sump of rainwater.	This fault is dominated by human error. Based on past experiences this is considered to be an **improbable** frequency classification.	Could result in environmental contamination as a result of release of oily water from the sump. This is a **marginal** consequence classification.	C
P16	Leak of SF_6	Failure of this type of plant falls into the **remote** frequency classification.	Release of a cylinder of SF_6 to atmosphere. Greenhouse gas with a high Global Warming Potential (24900). This is a **marginal** consequence classification.	B
P33	Fire due to flammable solvents or electrical fault	The Safety Case calculates a return frequency of <1 x 10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification.	Toxic chemicals released to atmosphere. This is a **marginal** consequence classification.	C
L1	Fire ignition of ethanol in solvent fire (during preparation of BMI Dye)	No frequency information available.	The volume of solvent is limited to 1 litre and this is not considered enough to cause a fire large enough to sustain a building fire. There is therefore no environmental release.	N/A
L2	Fire – over heating laser	The Safety Case calculates a return frequency of < 1 x 10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification.	Toxic chemicals released to atmosphere. This is a **marginal** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
L3	Fire – laser beam ignition	The Safety Case calculates a return frequency of < 1 x 10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification.	Toxic chemicals released to atmosphere. This is a **marginal** consequence classification.	C
L4	Fire – faulty electrical equipment	The Safety Case calculates a return frequency of <1 x 10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification.	Toxic chemicals released to atmosphere. This is a **marginal** consequence classification.	C
L9	Spillage of BMI laser dye	The frequency of spillages owing to human error is 1 x 10^{-3}.	Carcinogenic material released into lab. There is therefore no environmental release.	N/A
L24	Initiation of HE (explosion)	Frequency not calculated but based on the strong Lines of Defence (LOD) this is considered to be < 1 x 10^{-6}. This is an **improbable** frequency classification	Potential for toxic explosive by products to be released into the atmosphere. The nearby oil tanks could be ruptured releasing oil into surface water systems. This is a **marginal** consequence classification.	C
F1 to F5	Explosion of Round during transportation due to: Lightening Electrostatic discharge Vehicle impact	The return frequency for lightning initiating an explosion is 1.17 x 10^{-8}. This is an **incredible** frequency classification. The electrostatic discharge and vehicle impact is considered to be <1 x 10^{-6}. This is an **improbable** frequency classification	Potential for toxic explosive by products to be released into the atmosphere. These faults are all classed as **marginal** consequence classification.	C
F6 to F10	Explosion of unassembled HE during transportation due to: Lightening Electrostatic discharge Vehicle impact	The return frequency for lightning initiating an explosion is 1.17 x 10^{-8}. This is an **incredible** frequency classification. The electrostatic discharge and vehicle impact is considered to be <1 x 10^{-6}. This is an **improbable** frequency classification	Potential for toxic explosive by products to be released into the atmosphere. These faults are all classed as **marginal** consequence classification.	C
F11 to F16	Explosion of HE during preparation or storage Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact	A bounding frequency of between 10^{-4} and 10^{-6} (**remote**) is considered to be the worse case frequency for these scenarios.	Potential for toxic explosive by products to be released into the atmosphere. These faults are all classed as **marginal** consequence classification.	B

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
F17 to F22	Inadvertent explosion of HE in firing chamber Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact Premature firing Human error	The frequency for these faults varies depending on the actual fault sequence. There is no need to quantify the frequency as the consequence does not involve the external environment.	The maximum amount of explosive involved in this fault is 6kg. The chamber will contain the by-products generated in the explosion. There is therefore no environmental release.	N/A
F23 to F24	Pressure vessel explosion	No frequency information available.	The maximum amount of explosive involved in this fault is 6kg. The chamber will contain the by-products generated in the explosion. There is therefore no environmental release.	N/A
F26	Flammable gas explosion caused by leak in chamber	The Safety Case calculates a return frequency of < 1×10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification	Toxic chemicals released to atmosphere. This is a **marginal** consequence classification.	C
F27	Fire involving HE - vehicle fire from an accident.	Based on the controls in place for this area of site the frequency is considered to be < 1×10^{-6}. This is an **improbable** frequency classification.	Potential for toxic explosive by products to be released into the atmosphere. This is a **marginal** consequence classification.	C
F28	Fire involving HE – building fire.	The Safety Case calculates a return frequency of < 1×10^{-6} for large fires. Large fires are required to result in a release to the environment. This is an **improbable** frequency classification	Potential for toxic explosive by products to be released into the atmosphere. This is a **marginal** consequence classification.	C
F29	Petrol ignited following a road accident leading to a fire.	Based on the controls in place for this area of site the frequency is considered to be < 1×10^{-6}. This is an **improbable** frequency classification.	Potential for combustion by products to be released into the environment. This is a **marginal** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
F30	Fire: Hydrogen leak – flammable gas ignited.	No frequency information is available for this fault.	This fault is associated with hydrogen leak that is judged in the Safety Case to lead to significant building damage but not cause catastrophic structural failure. There is no environmental release.	N/A
F31	Fire: Propane leak – flammable gas ignited.	The Safety Case calculates a return frequency of < 1.4 x 10^{-5} for this fault. This is a **remote** frequency classification.	A number of solvents and asbestos fibres, used in building construction, could be released in the event of an explosion. This is a **marginal** consequence classification.	B
F32	Fire: vehicle impact on gas bottles – flammable gas ignited.	No frequency information is available for this fault.	Severe structural damage to the chamber but no release to the environment.	N/A
F33	Fire: leak from high pressure gas system – flammable gas ignited.	The Safety Case calculates a return frequency of < 1.4 x 10^{-5} for this fault. This is a **remote** frequency classification.	This could lead to a fire, which in a worse case would result in solvents and asbestos fibres, used in building construction, being released to the environment. This is a **marginal** consequence classification.	B
F34	Fire: acetylene gas leak	The Safety Case calculates a return frequency of < 1.4 x 10^{-5} for this fault. This is a **remote** frequency classification.	A worse case consequence would be an engulfing fire that leads to a loss of combustion by products to the external environment. This is a **marginal** consequence classification.	B
F35	Fire: combustible material – ignition of wood in chamber.	The return frequency for this type of fire is calculated to be 1 x 10^{-5}. This is a **remote** frequency classification.	The consequence of a fire is judged, in a worse case scenario, to be limited to the confines of the chamber and the building. There is therefore no environmental release.	N/A
F36	Fire: combustible material – excessive heating of hot rounds.	The frequency was determined as **improbable**.	Firing chamber provides an effective containment preventing any release o the external environment.	N/A
F37	Fire: combustible material – sparks from welding	The frequency was determined as **improbable**.	Firing chamber provides an effective containment preventing any release o the external environment.	N/A
F38	Fire electrical – Burnt out damper motor (faulty wiring).	The frequency was determined as **remote**.	Firing chamber provides an effective containment preventing any release o the external environment.	N/A
F39	Fire electrical – Burnt out damper motor (burnt out motor).	The frequency was determined as **remote**.	Firing chamber provides an effective containment preventing any release o the external environment.	N/A
F40	Fire electrical – faulty electrical equipment or wiring fault.	The frequency was determined as **remote**.	Firing chamber provides an effective containment preventing any release o the external environment.	N/A
F41	Loss of containment DU and beryllium detonation of round during a move.	The frequency is pessimistically considered to be **remote.**	Ground level concentration of Beryllium at the site fence of 5.1 E-6g/m^3. There will also be a small quantity of DU released. This is a **minor** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
F42	Loss of containment DU and beryllium – Road Accident.	The frequency is pessimistically considered to be **remote.**	Ground level concentration of Beryllium at the site fence of 7.6 E-7g/m^3. There will also be a small quantity of DU released. This is a minor consequence classification for the beryllium but as DU is also involved the classification rises to **critical**.	B
F43	Loss of containment of DU and beryllium – contaminated firing chamber	This is not a fault condition but a routine hazard.	Limited to health effects of workers and not an environmental release.	N/A
F44	Loss of containment – contaminated film cassette removed from chamber.	This is not a fault condition but a routine hazard.	Limited to health effects of workers and not an environmental release.	N/A
F45	Loss of containment of DU and beryllium – toxic seal breached by explosive fragments.	No frequency information available.	Consequence limited to the confines of the laboratory – not an environmental release.	N/A
F46	Loss of containment of DU and beryllium – release of water from scrubbers.	No frequency information available.	System is fully bunded protecting the environment.	N/A
F47	Loss of containment of DU and beryllium – dampers not sealed properly after maintenance.	The frequency was determined as **occasional**.	Release of Beryllium or DU to the environment. Consequence will not be worse than that for F48. This is a **critical** consequence based on the DU.	A
F48	Loss of containment of DU and Beryllium – damage to filter.	The frequency was determined as **occasional**.	Maximum ground level concentration at site fence of 2.5 E-7 g/m3 of Beryllium. Also potential for a release of DU to the environment. This is a **critical** consequence based on the DU.	A
F49	Loss of containment DU and Beryllium – dampers incorrectly re-fitted.	As per F48	As per F48	A
F50	Loss of containment of DU and beryllium – open damper during firing.	As per F48	As per F48	A
F51	Loss of containment of DU and beryllium – exposure of contaminated surfaces during maintenance.	No frequency information available.	The consequence of this fault is limited to health effects and is not an environmental release.	N/A
F52	Loss of containment of DU and beryllium – failure of door seal.	No frequency information available.	Release limited to the local environment only.	N/A
F53	Loss of containment of DU and beryllium – failure of RA sump tank.	No frequency information available.	The toxic firing chamber R/A tanks have bunds preventing an environmental release.	N/A
F54	Loss of containment of DU and beryllium – airborne activity during tank de-sludging.	No frequency information available.	There is negligible environmental release as the sludge is kept wet.	N/A
F55	Loss of containment DU and beryllium – airborne activity during HE trap cleaning.	No frequency information available.	Work is carried out inside the firing chamber and there is therefore no environmental release.	N/A
F56	Loss of containment DU and beryllium – beryllium mirror in camera breaks creating dust.	No frequency information available.	No environmental consequence.	N/A

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
F57	Lithium Hydride reaction due to water (used for cleaning) reaction with lithium.	No frequency information available.	Evolution of hydrogen – no environmental release contained within the building.	N/A
F58	Loss of containment release of lead contamination after firing	No frequency information available – depends on number of lead firings.	The lead condenses on the chamber walls. There is therefore no environmental release.	N/A
F59	Loss of containment release of fluorine from explosives	No frequency information available.	Fluorine is removed by the action of the scrubbers. There is therefore no environmental release.	N/A
F60	Loss of containment of DU and beryllium.	No frequency information available.	This fault refers to contaminated wounds and is not an environmental release.	N/A
F61	Loss of containment of DU and beryllium.	No frequency information available.	This fault refers to contaminated wounds and is not an environmental release.	N/A
NH1	Release of K10 (coagulant used to bind explosive) during handling of HE (Normal Operations).	N/A	No environmental release as it is normal operations and not a fault scenario.	N/A
NH2 to NH6	Explosion of detonators during transport Electrostatic discharge Electro-magnetic radiation Lightning Friction Chemical reaction Missile or impact Premature firing Human error	Based on operating practices and experiences over the past 40 years the frequency of all of these faults is pessimistically considered to be **improbable**.	Potential for toxic explosive by products to be released into the atmosphere. This is a **marginal** consequence classification.	C
NH8	Inadvertent explosion of HE in firing chamber – operation of shredder.	The frequency of this fault is considered to be **remote**.	The maximum amount of explosive involved in this fault is 6kg. The chamber will contain the by-products generated in the explosion. There is therefore no environmental release.	N/A
NH9	Inadvertent explosion of HE in firing chamber – lightening strike.	The frequency of this fault is considered to be $< 1 \times 10^{-7}$ i.e. **Incredible**.	The maximum amount of explosive involved in this fault is 6kg. The chamber will contain the by-products generated in the explosion. There is therefore no environmental release.	N/A
NH10	Failure of gas system pipework leading to hydrogen explosion into an occupied area outside the firing chamber.	The frequency was determined as 3.3×10^{-7} i.e. **Improbable**.	Evolution of hydrogen and rupture of gas bottles containing hydrogen. A secondary fault could be the release of building fabric material (asbestos) to atmosphere. This is a **marginal** consequence classification.	C
NH11	Methane leak leading to a fire	The frequency of this fire is calculated as $<1 \times 10^{-6}$. This is an **improbable** frequency.	Large engulfing fire could result in the release of toxic materials to the atmosphere. This is a **marginal** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
NH15 to 17	Inadvertent initiation of the proof test charge /detonator during assembly	Based on operating practices and experiences over the past 40 years the frequency of all of these faults is pessimistically considered to be **improbable**.	Potential for toxic explosive by products to be released into the atmosphere. However, as only gram quantities are involved the consequence will be limited to internal building damage and injury. There is therefore no environmental release.	N/A
NH19	Ignition of hydrogen gas release during LiH reaction with water leading to a fire within firing chamber	The frequency of this fire is calculated as <1 x 10^{-6}. This is an **improbable** frequency.	The amount of LiH in the chamber is trivial. The consequences of an engulfing fire will result in the release of inert materials to the environment only.	N/A
		AUXILIARY BUILDINGS FAULTS		
A1	HEPA filter failure could result in a release of R/A (DU) material to air. This accident condition could result in contaminated land and/or groundwater pollution.	In order for a release to the environment to be released two stages of HEPA filter are required to fail. The frequency for this is 1 x 10^{-4}/yr. This is a **remote** frequency classification.	The consequence of two stages (in series) failure of HEPA filtration will result in the accidental loss of R/A material to air. This is a **critical** fault classification.	B
A2	HEPA filter changes in the "red filter" room are carried out in a temporary containment structure. A dropped filter may lead to an airborne release that could challenge the unfiltered extract system.	This fault is a result of human error which has a return frequency of 1x 10^{-3}/yr [Human Error Probability for a simple procedure. Taken from AWE Company Safety Procedure 865 Section 7 Issue 1 February 1996. In addition the local containment system (tented enclosure) will also need to fail (1 x 10^{-2}/yr). This is a combined frequency of ~ 1 x 10^{-5}/yr. This is a **remote** frequency classification.	A fully loaded filter is estimated to hold up to 150 g of DU. The release fraction for a dropped filter is calculated to be 1 x 10^{-4}. Assuming a specific activity of 18.5 x 10^{3} Bq/g gives a total release of: 150 x 1E-4 x 18.5E3 = 2.78 E2 Bq of DU. This is a **catastrophic** fault classification.	A
A3	Major fire inside toxic chemical store.	The Safety Case calculated the toxic store fire frequency of 6 x 10^{-4}/yr. This is a **remote** frequency classification.	This will result in the evolution of combustion by products. This is therefore a **marginal** fault classification.	B
A4	Major fire that breeches the existing containment systems for waste oil and MnO.	The Safety Case calculated the toxic store fire frequency of 2 x 10^{-6}/yr. This is an **improbable** frequency classification.	This will result in the evolution of combustion by products. This is therefore a **marginal** fault classification.	C
A	Overfilling Marx tank	This fault is dominated by human error and based on the very infrequent filling operations is pessimistically assumed to be **improbable**.	Leak within building – creation of clean-up waste. This is a **minor** consequence classification.	C
B	Leaking Marx tank	Undetected leaks based on equipment of this type failing are considered to fall into the **remote** frequency classification.	Leak within building and generation of clean up waste. This is a **minor** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
C	Leaking storage tank	Undetected leaks based on equipment of this type failing are considered to fall into the **remote** frequency classification.	Leak into bund & generation of clean up waste. Potential water contamination during rainwater pump out. This contaminated water and the clean up waste will both result in the generation of extra trade waste and is therefore a **minor** consequence classification.	C
D1	Failure of transfer pipe- isolated.	Undetected leaks based on equipment of this type failing are considered to fall into the **remote** frequency classification.	Leakage into pipe trench and generation of clean up waste. This is a **minor** consequence classification.	C
D2	Failure of transfer pipe from the LINX pipework.	The frequency of this fault is considered to be **remote**.	This runs above ground and failure would result in oil leaking onto the ground. This fault has occurred in the past whereby the consequence was a loss of oil killing fish. This is a **marginal** consequence classification.	B
D3	Failure of transfer pipe from the MOGUL D & E pipework.	The frequency of this fault is considered to be **remote**.	The MOGUL D & E pipe trench is connected to the machine bunding and oil leaking into the trench will flow into the bund. These machines are therefore fully bunded. Some clean up waste will be generated giving a **minor** consequence classification.	C
E	Dropped Drum	This fault is dominated by human error. The drum would have to be dropped and fail and the resulting oil would have to leak into a surface water drain. This combination of faults is pessimistically assumed to be **improbable**.	Contamination of land and water systems. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	C
F	Leaking drum	These drums are sited on shallow drip trays. The drum would have to leak and remain undetected until the tray overflowed. This is pessimistically assumed to be **improbable**.	Contamination of land or water system. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	C
G	Impact damage to tank or pipework	This fault is dominated by human error and is considered to be in the **remote** frequency classification range.	Leak into a bund or leak into the ground causing contamination of land and water systems. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	B
H	Failure of both MOGUL storage tanks would exceed the capacity of the MOGUL sump. This would only happen if the two MOGUL tanks were drained of oil and there was coincident failure of the storage tank.	The frequency of this fault is considered to be not greater than 1 x 10^{-7}, which is **improbable**.	Contamination of land or water systems with mineral oil. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	C

Appendix O Table O1

ID	Fault Description	Frequency Analysis (f) (y^{-1})	Consequence Analysis – Environmental Impact	Risk Class
WT1	Underground oil pipeline leak. Pipeline runs underground for approximately 7m from H1 to storage tank.	In the absence of any known frequency information this fault is pessimistically assumed be **remote**.	Contamination of land or water systems with mineral oil. This is an accidental release of water contaminated with trade effluent (oil) and therefore a **marginal** consequence classification.	B
WT2	Above ground oil leak during transfers from tank to machine.	This is the same fault as D2.	See Fault D2.	Already assessed as fault D2
WT3	Spillage during emptying trade effluent tanks (R/A effluent)	This fault is dominated by human error probability and based on only 2 transfers per year this i s pessimistically assumed to be **improbable**.	The amount of R/A contamination is trivial and not above background. The consequence of this fault is a release of trade effluent to the environment. This is a **marginal** consequence classification.	C
WT4	Spillage during pumping of trade effluent from tanks (non R/A contaminated washings)	This fault is dominated by human error probability and based on only 2 transfers per year this i s pessimistically assumed to be **improbable**.	The consequence of this fault is a release of trade effluent to the environment. This is a **marginal** consequence classification.	C
WT5	Fire in H8 Beryllium store	The frequency of this fire is calculated as <1 x 10^{-6}. This is an **improbable** frequency.	Toxic chemicals (beryllium) and combustion by products released to atmosphere. This is a **marginal** consequence classification.	C
WT6	Rupture of potential PCB bearing capacitor tanks. As a result of a recent Abnormal Event, the contents and storage arrangements are under review. The potential risk from the un-bunded storage of this substance represents an environmental hazard.	This fault is dominated by human error faults (vehicle impact) and is pessimistically assumed to be **improbable**.	Toxic chemicals released to water systems. This is a **marginal** consequence classification.	C

The Development of Life-Cycle and Risk Assessment Methodology Using Data From AWE Aldermaston

SUPPORTING CD-ROM

The enclosed CD-ROM contains the full Appendices H, I, J and K

Appendix H	Environmental Burdens - Life Cycle Inventory (Excel Spreadsheet ***ASPECT*** (368 kB));
Appendix I	Normalisation Factors for Life-Cycle Impact Assessment (Excel Spreadsheet ***normalisation2*** (140 kB));
Appendix J	Results of Characterisation, Normalisation and Valuation (Life-Cycle Impact Assessment) (Excel Spreadsheet ***ASPECT-IMPACT*** (2434 kB));
Appendix K	Results of Characterisation, Normalisation and Valuation for Transport Activities (Life-Cycle Impact Assessment) (Excel Spreadsheet ***Translca*** (182 kB)).

All four of these spreadsheet files contain cells with pasted links.


COMPACT
disc
Recordable
DIGITAL PERFECTION
SILVER DISK
80
MIN.
RECORDABLE
MULTISPEED