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A Methodology For Cost/Benefit Safety Analyses For Fusion Reactors

by

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Abstract

A methodology is presented which can be used to determine if a proposed fusion power plant design directed at improving plant safety is cost effective. Economic risks related to both normal plant operation and accident situations can be evaluated. The incremental costs involved with a dose reduction measure for normal plant operation or an accident situation are identified and models for their assessment are developed.

An approach for evaluating the maximum justified spending on safety is outlined. By comparing the actual spending on the design modification to the expenditure ceiling, the appropriate decision can be made.

The utility of this approach for assessing cost effectiveness was illustrated through two examples. In the first application, the cost effectiveness of the change from the steel alloy PCA to low activation silicon carbide in the STARFIRE design was assessed. A range of possible costs of high purity silicon carbide was investigated. It was determined that if the installed cost of silicon carbide components is less than 116 $/kg, then the low activation design is cost effective.

A second example served to illustrate how the methodology can be applied to an accident situation. Four emergency detritiation options for INTOR,with zero, one, two or three clean up units, were compared to determine which was most cost effective. The evaluation was based on a release of 25 g of tritium into the reactor building. The analysis indicated that if the probability of the accident occurring over the plant lifetime exceeds 3.59 x 10^{-2}, the most cost effective option would be the option using one detritiation unit. For lower probabilities, the use of an emergency detritiation system is not cost effective.

PUBLICATIONS UNDER CONTRACT #K-1702 ON FUSION SAFETY

A. General Safety and Risk Assessment

1. M. S. Kazimi et al., "Aspects of Environmental Safety Analysis of Fusion Reactors," MITNE-212, Dept. of Nuclear Engineering, M.I.T. October 1977.

2. R. W. Sawdye, J. A. Sefcik, M. S. Kazimi, "Reliability Requirements for Admissible Radiological Hazards from Fusion Reactors," Trans. Am. Nucl. Soc. 27, 65-66, November 1977.

3. R. W. Sawdye and M. S. Kazimi, "Application of Probabilistic Consequence Analysis to the Assessment of Potential Radiological Hazards of Fusion Reactors," MITNE-220, Dept. of Nuclear Engineering, M.I.T., July 1978.

4. R. W. Sawdye and M. S. Kazimi, "Fusion Reactor Reliability Requirements Determined by Consideration of Radiological Hazards," Trans. Am. Nucl. Soc. 32, 66, June 1979.

5. M. S. Kazimi and R. W. Sawdye, "Radiological Aspects of Fusion Reactor Safety: Risk Constraints in Severe Accidents," J. of Fusion Energy, Vol. 1, No. 1, pp. 87-101, January 1981.

6. S. J. Piet, M. S. Kazimi and L. M. Lidsky, "Potential Consequences of Tokamak Fusion Reactor Accidents: The Materials Impact," PFC/RR-82-19, Plasma Fusion Center, M.I.T., June 1982.

7. S. J. Piet, V. J. Gilberti, "FUSECRAC: Modifications of CRAC for Fusion Application," Nuclear Eng. Dept. and Plasma Fusion Center, M.I.T., PFC/RR-82-20, June 1982.

8. M. S. Kazimi, "Safety and Risk Targets for Fusion Energy," Societe Francaise de Radioprotection 10th Annual Congres, Avignon, France, Oct. 18-22, 1982.

9. M. S. Kazimi, "Safety Methodology and Risk Targets," in Proc. of 1982 IAEA Workshop on Fusion Safety, IAEA-TECDOC-277, 1983.

10. M. S. Kazimi, "Risk Considerations for Fusion Energy," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 527-532, Sept. 1983.

11. S. J. Piet, M. S. Kazimi and L. M. Lidsky, "Relative Public Health Effects from Accidental Release of Fusion Structural Radioactivity," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 533-538, Sept. 1983.

12. S. J. Piet, M. S. Kazimi and L. M. Lidsky, "Modeling of Fusion Activation Product Release and Reactor Damage from Rapid Structural Oxidation," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 3, pp. 1115-1120, Sept. 1983.

13. S. Piet, M. S. Kazimi and L. M. Lidsky, "The Materials Impact on Fusion Reactor Safety," Nucl. Tech./Fusion 5 (3), 382-392, May 1984.

14. M. S. Kazimi, "Safety Aspects of Fusion," A Critical Review paper to appear in the IAEA Journal Nuclear Fusion, 1985.

15. S. J. Brereton and M. S. Kazimi, "A Methodology for Cost/Benefit Safety Analyses for Fusion Reactors," PFC/RR-85-3, Plasma Fusion Center, M.I.T., February 1985.

B. Lithium Reactions

1. D. A. Dube, M. S. Kazimi and L. M. Lidsky, "Thermal Response of Fusion Reactor Containment to Lithium Fire," 3rd Top. Meeting on Fusion Reactor Technology, May 1978.

2. D. A. Dube and M. S. Kazimi, "Analysis of Design Strategies for Mitigating the Consequences of Lithium Fire within Containment of Controlled Thermonuclear Reactors, MITNE-219, Dept. of Nuclear Engineering, M.I.T., July 1978.

3. M. S. Tillack and M. S. Kazimi, "Development and Verification of the LITFIRE Code for Predicting the Effects of Lithium Spills in Fusion Reactor Containments," PFC/RR-80-11, Plasma Fusion Center, M.I.T., July 1980.

4. P. J. Krane and M. S. Kazimi, "An Evaluation of Accidental Water-Reactions with Lithium Compounds in Fusion Reactor Blankets," PFC/RR-81-26,, Plasma Fusion Center, M.I.T., July 1981.

5. M. S. Tillack and M. S. Kazimi, "Modelling of Lithium Fires," Nuclear Technology/Fusion, Vol. 2, No. 2, pp. 233-245, April 1982.

6. V. J. Gilberti and M. S. Kazimi, "Modeling of Lithium and Lithium-Lead Reactions in Air Using LITFIRE," PFC/RR-82-08, Plasma Fusion Center, M.I.T., January 1983.

7. E. Yachimiak, V. Gilberti, and M. S. Tillack, "LITFIRE User's Guide," Nuclear Eng. Dept. and Plasma Fusion Center, M.I.T., PFC/RR-82-11, June 1983.

8. M. S. Kazimi, V. Gilberti and G. Florentine, "A Comparison of Lithium Pool Fire Consequences to that of Sodium and Lithium Lead Components," Trans. Am. Nucl. Soc. 46, 291, 1984.

9. E. Yachimiak and M. S. Kazimi, "Safety Analysis of Liquid Lithium-Lead Breeders in Fusion Reactors Geometries," PFC/RR-84-10, Plasma Fusion Center, M.I.T., June 1984.

10. W. J. Ijams and M. S. Kazimi, "Temperature Effects on Lithium-Nitrogen Reaction Rates," PFC/RR-85-7, Plasma Fusion Center, M.I.T., January 1985.

C. Tritium

1. S. J. Piet and M. S. Kazimi, "Uncertainties in Modeling of Consequences of Tritium Release from Fusion Reactors," PFC/TR-79-5, Plasma Fusion Center and Nucl. Eng. Dept., M.I.T., July 1979.
2. M. J. Young and S. J. Piet, "Revisions to AIRDOS-II," PFC/TR-79-8, Plasma Fusion Center and Nucl. Eng. Dept., M.I.T., August 1979.
3. S. J. Piet and M. S. Kazimi, "Implications of Uncertainties in Modeling of Tritium Releases from Fusion Reactors," Proc. Tritium Technology in Fission, Fusion and Isotopic Applications, April 1980.
4. D. R. Hanchar and M. S. Kazimi, "Tritium Permeation Modelling of a Conceptual Fusion Reactor Design," PFC/RR-81-27, Plasma Fusion Center, M.I.T., July 1981.
5. D. R. Hanchar and M. S. Kazimi, "Transient Tritium Transport in a Solid Breeder Blanket," Nuclear Technology/Fusion, Vol. 4, No. 2, Part 2, pp. 395-400, Sept. 1983.
6. D. R. Hanchar and M. S. Kazimi, "A Tritium Permeation Model for Conceptual Fusion Reactor Designs," J. Fusion Energy 3 (1), 4-61, 1983.

D. Electromagnetic Considerations

1. R. W. Green and M. S. Kazimi, "Safety Considerations in the Design of Tokamak Toroidal Magnet Systems," Trans. ANS 32, 69, June 1979.
2. R. W. Green and M. S. Kazimi, "Aspects of Tokamak Toroidal Magnet Protection," PFC/TR-79-6, Plasma Fusion Center, M.I.T., July 1979.
3. M. S. Tillack, "A Study of Structural Responses to Plasma Disruptions in Toroidal Shells," Dept. of Nucl. Eng. and Plasma Fusion Center, M.I.T., PFC/RR-83-16, June 1983.
4. M. S. Tillack, M. S. Kazimi and L. M. Lidsky, "Aspects of the Structural Effects of Plasma Disruptions on Tokamaks," Dept. of Nuclear Eng. and Plasma Fusion Center, M.I.T., PFC/RR-83-30, 1983.

E. Others

1. M. S. Kazimi, "IAEA Workshop on Fusion Safety March 23-27, 1981, Vienna, Austria," J. of Fusion Energy, Vol. 1, No. 3, pp. 241-243, 1981.

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Chapter One

Introduction

As progress is made towards solving the physics and engineering problems of creating usable energy from fusion reactions, it becomes increasingly important to consider potential safety and environmental concerns. An effort to address these issues and incorporate safety features into fusion reactor designs is needed at the conceptual stage. However, another major factor in fusion reactor research, development and design decisions is that of economics. Balancing the benefits and costs resulting from the safety and economic factors is playing an increasing role in design evolution. The purpose of this study was to develop an analytical tool which will aid in achieving the balance between these opposing constraints.

The approach taken to determine whether a design modification to reduce potential doses is justified involves defining a maximum justifiable value for spending on safety. This can be evaluated from consideration of relevant socio-economic factors, exposure limits and the actual magnitude of the risk. The expenditure ceiling then provides a measure of the permissible additional cost of risk reduction.

The methodology requires a base case design. This could be a reactor design which just meets minimum safety standards, or any other design which already has some safety features but has some particular safety issue requiring attention. The costs associated with a proposed design improvement must be evaluated relative to the base case. The expenditure ceiling, sensitive to the actual level of risk associated with the base case, can be employed to determine if the spending for the design change is warranted. Such a tool will prove invaluable to the design decision maker.

Risk studies to date have generally concentrated on potential health impacts of fusion reactor operation. Another aspect of risk involves economic impacts or costs associated with fusion reactor operation or reactor accidents. Economic risks include costs incurred due to the occurrence of an event, or benefits foregone. For example, under normal plant conditions, all costs associated with plant operation can be considered economic risks. An objective of the design team would be to minimize the economic risks associated with plant operation. If two design alternatives are being considered, and the more cost effective option is not implemented, then a benefit has been foregone and an economic risk has resulted. Subsequent to an accident, all costs associated with decontamination and repair are considered economic risks.

In Chapter 2, a procedure is outlined for determining the maximum justified spending on design changes which would reduce doses incurred during normal plant operation. Models are presented for assessing costs incurred during plant operation, plant maintenance and waste handling activities. The change in these costs due to the implementation of a proposed design change can be evaluated. changes in equipment costs, materials costs, labor costs, health detriment costs, overhead costs, replacement power costs and waste disposal costs are included. Knowing the change in costs and the resulting dose reduction, it can be determined if the design option is cost effective.

Economic risks of fusion reactor accidents are dealt with in Chapter 3. A methodology is given for estimating the maximum justified spending on accident consequence mitigation measures. Models are given for evaluating both onsite and offsite costs resulting from a particular accident. Onsite costs include replacement power costs, capital costs, decontamination costs, repair costs, early decommissioning costs and health detriment costs. Offsite costs include health effects costs, decontamination costs, agricultural product disposal costs, evacuation costs, relocation costs and land interdiction costs. These economic risks can be evaluated, for the particular accident, with and without the use of the accident consequence mitigation measure being examined. The change in costs due to the implementation of the proposed accident consequence mitigation action can then be determined. Knowing this change in costs, the resulting dose reduction and the probability of the accident occurring, it can be determined if the accident consequence reduction option is cost effective.

The methodology of Chapter 2, for normal plant conditions, is applied to the low activation STARFIRE design in Chapter 4. The procedure is used to determine whether or not the dose reduction associated with the change from the reference STARFIRE design to the low activation design justifies the costs involved.

An application of the methodology of Chapter 3, for accident conditions, is given in Chapter 5. Four emergency detritiation options for INTOR, each having different clean up capabilities are evaluated. The assessment is carried out for a particular accident consisting of a release of 25 g of tritium into the reactor building. It is determined if the increased costs associated with a shorter clean up time are warranted.

Finally, conclusions and recommendations concerning the use of the methodology in design decision making are outlined in Chapter 6. Results from the applications of the methodology in this study are summarized. Areas where possible improvements to this methodology could be made are identified and discussed.

Chapter 2

Cost/Benefit Safety Analysis For Normal Plant Conditions

Normal conditions at a fusion plant are those associated with operation, maintenance and waste handling procedures which occur in the absence of unexpected mishaps. In other words, normal conditions are planned or expected modes of carrying out operation, maintenance and waste handling tasks. In this section, a method is presented for analyzing the economic risks associated with suggested changes to fusion reactor designs which would improve the safety of normal operation, maintenance, or waste management procedures. It can be determined if the proposed design change will be cost effective and enhance the overall acceptability of fusion power.

2.1 Sources Of Radiation Risk In A Fusion Power Plant

Although detailed fusion power plant designs are not yet available, the conceptual designs allow potential health and safety problems that may arise during normal operation, maintenance and waste handling procedures to be identified.

First generation fusion reactors will utilize the deuterium-tritium (D-T) reaction, yielding alpha particles and 14 MeV neutrons as reaction products. Most of the radiological health and safety concerns associated with fusion reactors arise from the tritium and the high energy neutrons. These species must be dealt with regardless of the plasma confinement scheme used. For a given net electrical energy capacity, the quantity of tritium consumed and the number of neutrons produced will be essentially independent of the reactor design to within a factor of two [2.1]. Differences in recirculating power fraction (10 to 40 %) and thermal-to-electric efficiency (30 to 40 %) are primarily responsible for this variation. It has also been determined that for magnetic fusion devices, the induced radioactivity from the high energy neutrons does not vary between confinement schemes by more than a factor of two, for a fixed structural material-breeder blanket combination [2.1, 2.2]. Consequently, any procedures will likely be more closely affected by cost/benefit analyses dealing with occupational exposures than by the confinement concept.

It is expected that the major hazard within a fusion power plant will be that of ionizing radiation, since it is associated with all parts of the onsite fuel cycle. Major components and support equipment will contain radioactive materials, and work areas will be in proximity to ionizing radiation hazards. Such sources include tritium, neutrons and beta-gamma radiation arising from the decay of activation products.

Table 2.1 summarizes where potentially hazardous radioactive materials may be encountered in a fusion power plant. The following sections discuss the particular hazards associated with each of plant operation, plant maintenance and waste

Table 2.1: Principal Sources of Radioactivity Encountered at a Fusion Power Plant

Type	Operation	Maintenance	Waste Handling
Tritium	Tritium recovery operations Coolant loops	Reactor Hall Blanket processing Fuel recycle	Blanket and component processing Tritium traps Air filters Spent resin beds
Activation Products	Penetrations of coolant loops	Reactor Hall Steam generator maintenance Blanket processing	Blanket and component processing Spent resin beds
Neutrons	Leakage through penetrations of the reactor building	Not present	Not present

handling in more detail.

2.1.1 Radiation Risk During Plant Operation

During plant operation, all three sources of radiation hazard (tritium, neutrons and activation products) will be present. Special design considerations and careful planning of procedures will minimize exposure of plant workers to these radiation risks.

Tritium causes concern for protection of the occupational work force since it is associated with many procedures carried out during plant operation. These procedures include fueling, breeding and fuel reprocessing. In addition, because of its high mobility, tritium will be found in coolant streams, on the surfaces of components which require frequent contact by workers and in other undesirable areas as a result of permeation. It is probable that all areas which encounter tritium will possess some form of atmospheric clean up system capable of maintaining acceptable levels during normal plant operation. Thus, high level exposures may result only from accidental occurrences or special maintenance procedures.

Neutrons, being a reaction product, become a potential hazard only during reactor operation. As a result of possible neutron leakage through penetrations of the reactor structure and the high levels of radioactivity resulting from neutron activation of structural materials, entry of personnel to the reactor building during operation will be prohibited. It is unlikely that personnel exposure to neutrons will occur at locations external to the reactor building due to the shielding effect of reactor parts and the building walls.

During plant operation, the neutrons released from the reaction will induce activity in reactor components. The induced activity will increase over time until a saturation level is achieved for each isotope. Neutron activation products will be found in highest concentration in the first wall/breeding blanket assembly. Direct personnel access to areas containing such highly activated components will be precluded. Exposures of plant workers in other areas will be minimized by the provision of adequate shielding. Since most of this activity is fixed within solid structural materials, it should not present a significant radioactive hazard to personnel during operation.

2.1.2 Radiation Risk During Maintenance Outages

Tritium exposures and radiation from activated components will be of concern during maintenance outages. Since the fusion reaction is no longer occurring when the reactor is shutdown, neutrons will not be a hazard.

Although the fuel cycle will not be operative during shutdown, the potential for exposure to tritium still exists. As a consequence of its high mobility, tritium will be present on surfaces requiring contact maintenance, in coolant streams and in other areas where component replacement must be carried out manually. Exposure to tritium must be maintained at an acceptable level during routine maintenance and during repair of reactor components and tritium systems. This may be accomplished through atmospheric cleanup systems and the use of protective clothing for workers.

Activation products present a potential source of exposure during maintenance operations. The highest activity levels will be found in the first wall/breeding blanket assembly. Periodic replacement of breeding blanket sectors and components related to fueling, heating, pumping and instrumentation will be necessary. These operations could result in the exposure of personnel to high levels of radiation. There exists, also, the possiblilty for the activation of the coolant/breeder itself (e.g. LiPb) or the transport of activated corrosion products by the coolant to other areas of the power plant. These areas include other components of the power cycle, such as the steam generator, pumps, valves and piping. Other sources of radiation risk include activation of the reactor cover gas and localized hot spots of activated material resulting from neutron streaming through penetrations. As a consequence of this, certain procedures which might otherwise allow contact maintenance may require increased shielding or remote operations. Suspect areas for neutron streaming include wave guides, pumping lines, helium lines and other locations containing material with a poor capacity for attenuation. Proper procedures and protective measures must be implemented in order to avoid unnecessary exposures of workers in these areas.

2.1.3 Radiation Risk During Waste Management Procedures

During the lifetime of a fusion power plant, it will be necessary to handle and dispose of radioactive wastes. The major hazard will arise from activation products in reactor components. However, tritium permeation into the components will provide an additional cause for concern.

In a fusion reactor, the majority of the radioactivity generated will be in the form of activation products which will be retained in the first wall/blanket structure of the reactor. Blanket sectors must be periodically replaced. Processing of blanket materials will be necessary in order to reduce the volume of waste for recycle or disposal. Recycle of breeder materials will be possible in certain cases [2.3]. It is unlikely that complete onsite recycle of blanket modules or first walls will be carried out. Thus, these materials must be prepared for offsite shipment. Preparatory measures prior to offsite shipment will include decontamination and volume reduction. Decontamination measures may involve baking out tritium, surface cleansing and possibly slagging radioactive impurities in molten metal. This last operation would also serve as a volume reduction measure. It is essential that proper procedures and protective measures be instituted during these actions.

A much smaller amount of activity is associated with: (1) processing systems designed to minimize the activity in plant effluent streams; (2) items used in maintenance operations, such as mops, swabs and clothing; and (3) wastes generated from tritium handling. These low activity wastes may be contaminated with either tritium and/or activated corrosion products from the coolant systems. Potential for exposure exists while handling and packaging these wastes for disposal. Attention must be given to these procedures to ensure minimizing personnel exposure.

2.1.4 Risk Reduction

The preceeding discussion highlights those areas of a fusion plant where risk of exposure to radiation exists. In order to maximize the overall acceptance of fusion power, some effort should be devoted to reducing the radiation hazard. In order to reduce wasting finite societal resources, spending on safety measures should be directed towards those areas where risk is highest. A cost effective approach to risk management is required which is in line with relevant socio-economic considerations and which would allow for increased expenditures in areas of higher levels of risk. Such a method is presented in the next section.

2.2 Cost Effective Radiation Risk Management Methodology

The demonstration of an appropriate level of worker protection which is also economically attractive will influence the commercial acceptance of fusion power. Hence, it is essential to assess the effectiveness of dose reduction measures in a given design to determine if the maximum safety benefit is being obtained. To ascertain whether further dose reduction measures are justified, a suitable method for cost effective radiation risk management is needed. Such a method, based on radiation detriment optimization measures which were formulated in the modified (1977) ALARA (As Low As Reasonably Achievable) concept, has been developed at AECL †. The methodology allows for the determination of maximum justifiable expenditures for additional reduction in the radiological detriment (both occupational and public). Factors including economic and social climate, administrative/legal limits and the actual magnitude of the risk are taken into consideration. Having determined the monetary ceiling on expenditures, a decision can be made as to whether or not a proposed design modification is necessary and/or cost effective. If a cost effective dose reduction measure is not implemented, then a risk is taken in forgoing the expected benefit (dose reduction). Using this approach, obtaining the maximum benefit per safety dollar invested will be assured.

In order to satisfy the revised ALARA requirements, a method of Cost Effective Radiation Risk Management (CERRM) has been developed [2.4]. This method is based on experience with the generic CANDU-PHWR* where an extensive radiation exposure control program has been implemented at the design level since 1969. This approach provides the means for comparing risks and assessing the cost effectiveness of safety expenditures. In this way, the reasonableness of a proposed level of risk can be ascertained.

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† AECL - Atomic Energy of Canada Limited

* CANDU-PHWR - CANada Deuterium Uranium Pressurized Heavy Water Reactor

2.2.1 Factors Affecting The Expenditure Ceiling

To determine an acceptable upper bound on safety spending, socio-economic considerations and exposure limits must be regarded. Further, the upper bound on expenditures can be assessed by decomposing it into two parts: the occupational and public components.

The socio-economic factor which plays a role in the occupational component of the expenditure ceiling is that of the cost of replacement manpower (L_c). This cost will vary from country to country, and regionally within each country. The regulatory occupational exposure limit per individual (E_{LIM})[‡] is 5 rem/year. This poses a restriction on the utilization of a worker. Replacement manpower cost is an appropriate means of evaluating an upper bound on dose reduction expenditures because at, or near, the limiting level of risk, it will be necessary to replace the current manpower. As part of the evaluation process, the cost of replacing the labor is compared to that of the dose reduction measure (which, if implemented, would avoid incurring the replacement manpower cost). Depending on the actual level of radiation (R) to which workers are exposed, an appropriate decision can be made.

The degree to which any society can afford to spend on safety measures is dependent to some extent on the lifetime earning potential of the individuals at risk [2.5]. Wealthier countries, having higher per capita incomes, can spend more on safety than poorer third world countries, which are more concerned about sustaining their population. The current performance of existing nuclear plants has kept public exposures to less than a fraction of the regulatory limits (E^{*}_{LIM}). It is hoped and anticipated that this record will be carried over to fusion power plants. Hence, a parameter indicating the willingness of the society to further reduce the exposure

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[‡] Note that 1 sievert equals 100 rems. Hence, the occupational exposure limit, E_{LIM}, is 5 x 10^{-2} Sv/yr.

detriment would be per capita income (L_c^*). Appropriate values for this parameter can be obtained from compilations of statistical information (e.g. Statistical Abstract of the United States [2.6]).

To establish a relationship between the "value" of a person-sievert and the risk level, the costing process should consider the human response to the exposure. Studies have been conducted to assess functional forms of dose-response data [2.7]. It has been found that the dose response curve for harm induced by radiation follows a linear, no threshold relationship at low dose rates, and a quadratic relationship at higher dose rates (i.e. response is proportional to the square of the dose) in the normally encountered range [2.4, 2.7, 2.8]. The conservative approach to incorporating the effect of dose response would be to use the quadratic relation over the entire range. Since spending is proportional to the dose incurred, and the dose is proportional to the square root of the harm induced (i.e. response is proportional to the square of the dose), an exponent (N) of 0.5 should be incorporated to express the human response to radiation risk.

2.2.2 Formulae For Evaluating The Ceiling On Expenditures

Having discussed the factors influencing justified expenditures, the formulae for deriving the ceiling on spending for safety measures will be presented. These have been adopted from the AECL approach to cost effective radiation risk management developed for CANDU reactors [2.4].

The ceiling on occupational safety expenditures is given by:

$$\alpha = \left(\frac{L_c}{E_{LIM}}\right)\left(\frac{R}{E_{LIM}}\right)^N \qquad (2.1)$$

where

$\alpha =$ ceiling on occupational safety expenditures (\$/person Sv)

$L_c =$ labor cost (\$/person yr)

$E_{LIM} =$ occupational exposure limit (Sv/yr)

$R =$ actual exposure rate (Sv/yr)

$N =$ exponent chosen to express dose response for harm induced by radiation (0.5)

The ceiling on public safety expenditures is given by:

$$\alpha^* = \left(\frac{L_c^*}{E_{LIM}^*}\right)\left(\frac{R^*}{E_{LIM}^*}\right)^N \tag{2.2}$$

where

$\alpha^* =$ public ceiling on safety expenditure (\$/person Sv)

$L_c^* =$ per capita income (\$/person yr)

$E_{LIM}^* =$ public exposure limit (Sv/yr)

$R^* =$ actual public exposure rate (Sv/yr)

Once the expenditure ceiling has been defined, it can be employed as a measure of the permissible cost of a proposed design improvement.

2.2.3 The Design Decision Process

To determine if a proposed design change, aimed at improving plant safety, is economically justified, analyses must be carried out to determine the resulting dose savings. If the dose reduction measure is aimed at only one group (workers or public), the appropriate costing formula (for α or α^*) should be used. If both groups are affected, an overall expenditure ceiling (α'), which considers both occupational and public components, can be evaluated:

$$\alpha' = U\alpha + V\alpha^* \tag{2.3}$$

where

α'= overall ceiling on safety expenditures which results in the dose savings of D_o and D_p (\$/person Sv)

$U = \frac{D_o}{D_T}$

= fraction of the total dose savings affecting plant workers

$V = \frac{D_p}{D_T}$

= fraction of the total dose savings affecting the public

D_o= occupational dose savings (person Sv/yr)

D_p= public dose savings (person Sv/yr)

D_T= total dose savings (person Sv/yr)

Before a proposed design change can be deemed acceptable, the actual cost of implementation must be evaluated. Since dose savings are expressed on an annual basis, the cost of the dose reduction measure should also be assessed on an annual basis. Knowing this cost, and the resulting total dose savings, a value for the cost of the exposure reduction can be determined:

$$\beta = \left(\frac{C_T}{D_T}\right) \tag{2.4}$$

where

β = additional spending for the dose reduction measure (\$/person Sv)

C_T = annualized cost of the dose reduction measure over the plant lifetime (\$/yr)

D_T = total dose savings (person Sv/yr)

If the additional cost for the benefits obtained (i.e. dose reduction) is less than the maximum acceptable expenditure for these benefits (α, α^* or α' depending on which group(s) is(are) affected), then the dose reduction measure is justified.

Utilizing this approach to decision making for radiation protection will satisfy the intent of the ALARA concept and will provide the necessary justification for spending or not spending on additional methods of dose reduction.

2.3 Assessing The Total Cost Of A Particular Protective Action

The implementation of a dose reduction measure will result often in increased costs. Using the methodology outlined in the last section, it can be determined if the benefit provided by the action (i.e. decreased exposure to radiation), justifies the increased expenses. In order to assess this, a value for C_T, the total cost of the dose reduction measure, is required. The total cost is comprised of four major components:

$$C_T = C_C + C_{TO} + C_{TM} + C_{TW} \tag{2.5}$$

where

$C_T =$ total annualized cost of the dose reduction action (\$/yr)

$C_C =$ annualized capital cost of the dose reduction action (\$/yr)

$$C_C = C_{Ci} \cdot e^{rt_l} \left(\frac{e^r - 1}{e^{rt_l} - 1} \right) \tag{2.6}$$

$C_{Ci} =$ initial capital cost of the dose reduction action (\$)

$t_l =$ expected plant lifetime remaining after the dose reduction measure is implemented (yrs)

$r =$ real discount rate

$C_{TO} =$ increase in the total annual operation cost (\$/yr)

$C_{TM} =$ increase in the total annual maintenance cost (\$/yr)

$C_{TW} =$ increase in the total annual waste handling cost (\$/yr)

The capital cost of the dose reduction measure represents the cost of materials and installation for those items directly responsible for the dose reduction. For example, if the dose reduction measure is to install increased shielding over that employed in a base case design (e.g. a design which just meets regulatory limits for exposure), then the capital cost would include the additional materials cost for the shield plus any additional costs for installing a greater amount of shielding. If the dose reduction measure is to replace a component by another which will reduce the doses incurred, then the capital cost would be the increase in the initial cost of the component plus any additional installation costs.

The other contributors to the total cost of the dose reduction measure are composed of several elements. These elements include the cost of additional materials and equipment required for carrying out tasks, the change in labor costs for all affected jobs, the change in health effects costs due to radiation exposure, the change in overhead costs, the change in replacement power costs and the change in waste disposal costs. It should be noted that the change in cost can be either positive or negative. Since several tasks may be affected by the design modification, the total change in the cost will include contributions from all tasks which are affected. As well, it may be necessary to carry out certain tasks several times during the year. Hence, in determining the change in labor costs and doses incurred (for health detriment costs), job frequency, in addition to job time and crew size, must be considered. In some cases, there may be little or no savings in terms of labor, materials or overhead. The motivation for the design change in these cases would solely be the avoidance of health detriment. Table 2.2 summarizes the data required to evaluate a particular dose reduction action.

All cost elements can be incorporated into a general formula which can be used to assess the total change in operation, maintenance or waste handling costs. It should be noted that not all cost elements will be required in all cases. Also, the manner of calculating certain cost elements may be different depending on whether operation, maintenance or waste handling costs are being considered. These differ-

Table 2.2: Data Required for Evaluating Radiation Protection Measures in a Fusion Power Plant

Dose Parameters:	Occupational:	dose rate job time job frequency crew size working conditions
	Public (if applicable):	size of affected population
Protection and Production Costs:		Investment Costs Labor Costs Overhead Costs

ences are discussed in the sections to follow. The general formula for estimating the change in normal operating, maintenance or waste handling costs is:

$$C_{Tx} = C_{Mx} + C_{Lx} + C_{Hx} + C_{OHx} + C_{Px} + C_{Dx} \tag{2.7}$$

where

x= subscript indicating either operating (O), maintenance (M) or waste handling (W) costs

C_{Tx}= increase in the total annual operating, maintenance or waste handling costs resulting from the dose reduction measure (\$/yr)

C_{Mx}= annualized additional materials and equipment costs for carrying out all affected tasks (\$/yr)

$$C_{Mx} = C_{Mix} \cdot e^{rt_l} \left(\frac{e^r - 1}{e^{rt_l} - 1} \right) \tag{2.8}$$

C_{Mix}= initial addtional materials and equipment costs (\$)

t_l= expected remaining plant lifetime (yrs)

r= real discount rate

C_{Lx}= increase in annual labor costs for all jobs affected due to the implementation of the dose reduction measure (\$/yr)

$$C_{Lx} = \sum_j (C_{nj} t_{nj} f_{nj} m_{nj} - C_{oj} t_{oj} f_{oj} m_{oj}) \tag{2.9}$$

C_{oj}, C_{nj}= old and new crew sizes required to complete task j (persons)

t_{oj}, t_{nj}= old and new times required to complete task j (hrs)

f_{oj}, f_{nj}= old and new frequencies of carrying out task j (yr^{-1})

m_{oj}, m_{nj}= old and new rates of worker remuneration for task j ($/person hr)

C_{Hx}= change in annual health detriment due to radiation exposure ($/yr)

$$C_{Hx} = H \cdot D_{Tx} \tag{2.10}$$

H= estimate of the total (somatic plus genetic) societal detriment attributable to radiation exposure

= 3,800 $/person Sv (from [2.9], see appendix B)

D_{Tx}= total dose savings (person Sv/yr)

$$D_{Tx} = D_{xo} + D_{xp} \tag{2.11}$$

D_{xo}= total occupational dose savings (person Sv/yr)

$$D_{xo} = \int_0^{t_{oj}} R_{oj}(t) C_{oj} f_{oj} dt - \int_0^{t_{nj}} R_{nj}(t) C_{nj} f_{nj} dt \tag{2.12}$$

$R_{oj}(t), R_{nj}(t)$= old and new functions describing how the dose rate varies with time while carying out task j (Sv/hr)

D_{xp}= total public dose savings (person Sv/yr)

$$D_{xp} = \left[\frac{\int_0^{t_x} (R_{op}(t) - R_{np}(t))\, P \cdot dt}{t_x} \right] \qquad (2.13)$$

$R_{op}(t), R_{np}(t)$= old and new functions describing how the public dose rate varies with time (Sv/hr)

P= size of affected population (persons)

t_x= duration of public exposure resulting from normal operation, maintenance or waste handling activities (yrs)

C_{OHx}= increase in annual overhead costs resulting from the dose reduction measure (\$/yr)

C_{Px}= change in the annual replacement power cost resulting from the dose reduction measure (\$/yr) (This can be calculated using a simple model described in appendix C. Note that this cost component is only included when assessing the total change in maintenance costs since maintenance tasks are carried out during downtime, when replacement power must be purchased.)

C_{Dx}= change in the annual waste disposal cost resulting from the dose reduction measure (\$/yr) (This cost component is only relevant in evaluating the total change in waste handling costs.)

The normal operation, maintenance and waste handling cost contributions are discussed in more detail in the following sections. Any specific differences for calculating cost elements (e.g. those related to doses incurred) are outlined. The general formula presented above can then be applied to assess the total cost.

2.3.1 Normal Operation Costs

The smooth operation of a fusion power plant will involve many tasks which are carried out on a regular basis. While performing these tasks, workers may be exposed to some level of radiation. A particular protective action which would reduce the exposure to these workers may alter the manner in which specific tasks are carried out. Such alterations may include a change in job completion time or the need to use additional or different equipment to accomplish the task. As a consequence, the dose reduction action may lead to increased operation costs. These effects are discussed further in the next section. Section 2.3.1.2 then summarizes all operational cost elements in a simple cost equation.

2.3.1.1 Influence Of A Protective Action On Normal Operation Procedures And Costs

The exposure received by plant workers is directly dependent on the dose rate in the area where the required tasks must be carried out and on the time spent in this area. Any design change which would lead to a decreased dose rate or job duration would decrease the exposure. To evaluate the cost effectiveness of a particular protective measure, its effect on plant operations must be outlined. Any increased expenditures can then be identified.

Two types of situations can be identified when assessing how protective actions interfere with plant operations. The first type (A) involves jobs in areas where the dose rate is sufficiently low as to allow the crew (one or more individuals, depending on task complexity) to work under average productivity conditions, and without time limits. Such tasks contribute to the collective dose, but do not result in increased operating costs when compared to a non-nuclear installation (the rate of carrying out work is unhampered by the radiation hazard). Dose reduction measures for "category A" jobs may entail extra expenses including capital costs of any new equipment or materials needed to complete the tasks, increased labor and health effects costs if the job must be carried out in a different manner resulting in a different time for completion, or increased overhead costs (e.g. fuel or electric power required to perform the task, insurance costs, etc.).

The second type of job (B) concerns areas where the dose rate is sufficiently high that individual limits force a less productive form of working to be adopted. Task preparation, the use of multiple crews and reinforced protection of workers (e.g. protective clothing) all conspire to reduce productivity. The time required to accomplish a particular job under these conditions is greater than the time required to complete a similar task in the absence of radiation. Thus labor and health effects costs are somewhat greater for this second type or "category B" jobs, since the rate at which work proceeds is somewhat slower. If protective actions are aimed at substantially reducing either the dose rate or the job time, the operating costs may be reduced. If the dose rate is decreased by such an amount that the tasks affected now fall into category A, then a substantial decrease in the job time will likely result. As with category A jobs, category B jobs may also lead to increased equipment, materials or overhead costs.

2.3.1.2 Evaluation Of The Change In Normal Operation Costs

The methodology for assessing design changes affecting plant operation requires obtaining a value for C_{TO}, the increase in the total annual normal operation costs resulting from the dose reduction measure. This can be assessed using the general formula (2.7). Included in this cost estimate are the annualized capital cost over the plant lifetime of any new materials or equipment required to carry out tasks plus the change in labor costs, annual overhead costs and annual health effects costs.

The increase in the annual normal operation costs resulting from the implemention of a dose reduction measure is given by:

$$C_{TO} = C_{MO} + C_{LO} + C_{HO} + C_{OHO} \tag{2.14}$$

The cost components have all been previously defined. In assessing the change in health effects costs, the dose rates can be assumed constant at all times after the initial start up of the reactor. Any doses incurred by workers while they are not performing operations tasks are assumed negligible compared to the doses incurred while carrying out the job. The duration of public exposure due to normal plant proceedings is the total time in one year during which the plant is operating (i.e. availability).

2.3.2 Maintenance Costs

Maintenance procedures are carried out on a regular basis during scheduled outages. While carrying out these functions, the potential exists for the exposure of occupational personnel to radiation hazards. Principal reactor parts which must be replaced regularly will become activated as a consequence of neutron bombardment. Many of the major reactor and auxiliary components will also become hazardous due to the presence of activated corrosion products. A proposed design change may decrease dose rates in areas where maintenance jobs must be carried out and may also require a modification in the procedure to be followed. Additionally, the decreased dose rates may allow certain jobs which were originally carried out remotely to be carried out manually. Hence, the dose reduction measure may lead to a change in the total cost incurred during a scheduled maintenance outage. These effects are described in more detail in subsequent sections and are summarized in a cost equation in section 2.3.2.3. However, a discussion of expected doses incurred during maintenance at a fusion power plant is presented first.

2.3.2.1 Discussion Of Expected Doses During Maintenance At A Fusion Power Plant

Maintenance operations at a fusion power station will encompass maintenance of the coolant/steam generator system, tritium handling and replacement of the first wall/blanket structure. Much attention has been given to water cooled fusion reactor designs. It is expected that the power cycle for a water cooled fusion plant will be similar to that of a conventional steam plant. Hence, a rough picture of what to expect from the power conversion components of a fusion power station can be obtained from the operating experience of fission reactors. Similar occupational exposure conditions will exist for the steam generator. Handling of the first wall/blanket structures is somewhat analagous to fuel replacement in fission power plants, as both operations involve remote handling of large, radioactive objects. However, significantly larger components will be involved at a fusion plant. Nevertheless, a rough idea of expected doses at a fusion power plant can be obtained.

2.3.2.1.1 Exposures During Maintenance Of The Coolant/Steam Generator System

The coolant/generation systems for fusion reactors will be similar to fission reactors in that each must transfer heat, released in a nuclear reaction, to an electrical generation system. Three primary potential candidates for fusion reactor coolants include water, helium and liquid lithium. Thermal conversion efficiencies for fusion and fission systems are expected to be similar. Hence, for a given coolant, the steam generators will be roughly the same size for the same output power. Based on the STARFIRE design [2.10], the surface area of the steam generator dominates the total area available for heat transfer, as in fission plants. Thus, the fact that the fusion reactor has a larger in-reactor surface will result only in small differences in the levels of activated corrosion products between the two reactors, for a given set of structural materials and coolant chemistry. Furthermore, small differences in activation product levels will result from the different neutron spectra found in fusion and fission reactors.

Current experience with coolant system maintenance in PWRs has been investigated. Murphy and Kreger [2.11], as reported by Easterly [2.1], have found that over 75 % of the exposures at a typical PWR occur as a consequence of maintenance activities during outages. The primary source of exposure has been identified as the radiation fields associated with the activated corrosion products. About 50 % of the annual collective dose at a PWR (in the range of 5 person Sv/yr for a work force of 600 to 700 [2.11]) is estimated to result from procedures performed in the auxiliary building rather than at the reactor [2.12]. Recent studies have indicated that radiation fields in a PWR increase with power plant life [2.13, 2.14]. Early in plant life, Co^{58} is the main contributor to the radiation hazard. Later in plant life, the dominance shifts to Co^{60} [2.13]. This isotope is expected to dominate the dose contribution from the steam generator [2.12].

Detailed plant designs and maintenance scenarios are not currently available for fusion coolant systems. However, for water cooled plants, they will probably be quite similar to current LWR systems. Analyses performed for STARFIRE have indicated similar coolant radiation levels to those in fission reactors (see table 2.3). In addition, deposited activities in the steam generator tubes (see table 2.4) are similar [2.15]. Hence, if similar work procedures are employed in fusion coolant/generator systems for water cooled plants, radiation doses at fusion reactors are expected to be essentially the same as doses incurred at fission plants.

The need for periodic inspection and maintenance of the steam generator tubes at fission power plants has arisen as a result of corrosion problems leading to tube

Table 2.3: Coolant Activity Levels for Water Cooled Power Reactors (mCi/m^3) [2.15]

	Co^{60}	Mn^{54}	Co^{58}	Fe^{59}	Cr^{51}
STARFIRE (fusion)	0.96	2.02	2.64	0.06	3.87
Oconee-1 (fission)	1.2	0.66	10	5.5	3.7
Maine Yankee (fission)			10		
Conneticut Yankee (fission)			20		

Table 2.4: Deposited Activity Levels for Water Cooled Power Reactors (mCi/m^2) [2.15]

	Co^{58}	Co^{60}	Mn^{54}	Fe^{59}
STARFIRE (fusion)	118	86	152	2
CHOOZ (fission)	97	84	44	4
Beznow (fission)	300-400	170-180	34-39	7
Oconee-1 (fission)	625	34	6.7	
Douglas Point (fission)		28		
Maine Yankee (fission)	2-500	0.5-75		
Conneticut Yankee (fission)		0.45-113		

failure. High exposure activities generally include those in the vicinity of reactor coolant piping or in the channel head area of the steam generator. Other activities in relatively low radiation zones (such as removal of shields, supports, walls and floors) result in high exposures since a large number of person-hours is involved. In many instances, retubing is a viable option. In other cases, as a result of the large amount of downtime and occupational dose problems, some utilities have chosen to replace the entire steam generator. It is expected that a fusion power plant will require either retubing or replacement of steam generators as in fission power plants. Consequently, increased exposure of workers at the station will occur during these activities. Replacement of the entire steam generator system is postulated to be necessary near the midpoint of the operational life of the plant. Changeout operations would be carried out during the same time interval as a blanket replacement operation.

For a fixed structural material, the radionuclide concentrations due to structrual activation will be unaffected by the choice of coolant. However, release mechanisms of these radionuclides, modes of transport, deposition patterns and the degree of corrosion will be strongly dependent on the particular coolant used. For a helium cooled system, postulated mechanisms of radionuclide release from the piping walls include direct daughter recoil and bulk neutron sputtering of activated material [2.16]. It has also been found that the deposition pattern of released radionuclides is highly dependent on helium flow velocity and pipe diameter [2.16]. Deposition patterns in the steam generator are predicted to be similar to the water cooled system, although the actual deposited activities are predicted to be less [2.17]. For a stainless steel structure, the use of liquid lithium as a coolant will result in the removal and transport of substantially more corroded material than water. The corrosion rate of stainless steel in lithium may be 50 to 100 times greater than in water at operating temperatures. Increased shielding would be required for coolant system components to avoid higher occupational exposures during maintenance activities. However, if the structural material used is vanadium, the corrosion rate by lithium is low. This would relax the shielding requirements.

2.3.2.1.2 Exposures Due To Tritium

Because tritium must be bred to fuel a D-T fusion reactor, tritium handling systems are an integral part of all D-T fusion reactors. The physical characteristics of tritium dictate that the occupational work force be protected from prolonged contact with the isotope. The tritium processing building presents the highest potential for exposure. Wherever it is conveyed by pumping, or wherever diffusional processes result in significant concentrations (e.g. at vacuum pump and coolant line locations), tritium may be encountered. Reactor designs include ventilation cleanup systems which will be utilized to maintain ambient conditions acceptable for worker occupancy. Not incorporated into design details are possible radiation exposures occurring from maintenance procedures and small accidental leaks. Much of the necessary information will become available after experience is gained at the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. This facility will provide information on normal leak rates, effects of barriers, maintenance requirements and accident frequencies which can be utilized to improve existing designs. In addition, operation of TSTA will provide valuable information on surface contamination. This is an important contribution to the occupational dose from reactor components subject to a high level of contact maintenance.

2.3.2.1.3 Exposures During First Wall/Blanket Changeouts

A major maintenance procedure for fusion reactors will be that of first wall/ blanket replacement. This procedure, to a first approximation, will resemble activities required in the decommissioning of a fission reactor. Such activities include breaking of coolant lines and segmenting of large radioactive vessels. It is anticipated that extensive use will be made of temporary shielding and remote handling. It is expected, however, that some non-remote work will be required for fusion reactors. Such operations will take place in varying levels of radiation arising from equipment contaminated with tritium, activation products or activated corrosion products. Table 2.5 presents a brief summary of the parameters and activities involved in PWR and fusion reactor dismantling.

2.3.2.2 Influence Of A Protective Action On Maintenance Procedures And Costs

During maintenance procedures, the potential exists for workers to be exposed to high levels of radiation. These procedures include replacement of the first wall/blanket structure as well as maintenance of heating and fueling devices, pumping and coolant systems and diagnostic instruments. Since the first wall/blanket structure will consist of highly activated components, the concept of fully remote maintenance has been postulated. However, remote maintenance is inherently slow, and the economic viability of such a plan is questionable. The eventual commercial acceptance of fusion will depend to a large degree on the anticipated amount of downtime, since outages of significant duration will require the purchase of replacement power. Recent studies [2.18, 2.19, 2.20] have indicated that downtime can be reduced by allowing some contact and/or semi-remote maintenance in areas where radiation levels and shielding allow. It has been calculated that a total downtime reduction of 3.6 to 27.4 % can be achieved by maximizing the use of contact maintenance [2.19].

A particular dose reduction measure may decrease the dose rates in areas where maintenance is carried out. If the maintenance plan is unaltered, and all tasks

Table 2.5: Parameters Related to PWR and Fusion Reactor Dismantling [2.15]

	Weight (kg)	Specific Activity (Ci/kg)	Dose (person Sv)
PWR			
Segmenting pressure vessel and internals	3×10^5	15	1.7
Removal of pumps and other support equipment			2.6 to 6.0
STARFIRE			
Disconnecting of coolant lines and support equipment			2.6 to 6.0
Disconnecting first and second walls	4×10^5	150	2.0
Reconnecting coolant and support equipment and preparation for new blanket assemblies			1.3 to 3.0

are carried out in the original mode (i.e. fully remote, semi- remote or contact), then the total dose incurred by maintenance workers will be reduced. However, replacing some remote maintenance tasks with contact maintenance will decrease the downtime and the replacement power costs. Implementation of this option will increase the dose to workers above that of the original maintenance plan. However, the cost of replacement power and hence, the cost of the dose reduction measure, will be reduced. The decrease in cost may offset the increase in the dose incurred, improving the cost effectiveness of the dose reduction measure.

In addition to the above effect, a dose reduction measure may result in changes in other costs incurred during maintenance outages. Task durations may be affected, causing changes in labor and health effects costs. Additional equipment and materials may also be needed if the dose reduction measure requires alterations in procedures. Overhead costs may also change.

2.3.2.3 Evaluation Of The Change In Maintenance Costs

Assessment of the cost effectiveness of a design change affecting plant maintenance requires obtaining a value for C_{TM}, the increase in the total annual maintenance costs resulting from the change. The general formula (2.7) is applicable. This will include the annualized capital cost, over the plant lifetime, of any newly required materials or equipment, plus the change in annual labor costs, annual overhead costs, annual health effects costs and replacement power costs.

The increase in total maintenance costs resulting from the implementation of a dose reduction measure is given by:

$$C_{TM} = C_{MM} + C_{LM} + C_{HM} + C_{OHM} + C_{PM} \tag{2.15}$$

The definitions of these cost components are given following the general cost equation (2.7). In estimating the annual health detriment cost, consideration of time varying dose rates must be given since the reactor has been shutdown.

2.3.3 Waste Handling Costs

Waste disposal operations will have some influence on the radiation dose received by station workers. Complete onsite recycle of any reactor components, such as blanket modules, first walls, etc., is considered to be too costly to be carried out at each reactor facility. However, materials must be prepared to meet acceptance criteria set forth by the waste management company or agency. Expected doses incurred during waste handling tasks are discussed in the next section. Following this, the influence of dose reduction measures on waste handling costs are described.

2.3.3.1 Discussion Of Expected Doses During Waste Handling At A Fusion Power Plant

Day to day waste management at a power station will consist of replacement of spent resin beds, air filters and tritium traps. For a water cooled plant, these operations are basically similar to fission plants, except for the additional requirements due to the tritium systems. Relatively small occupational exposures result from waste management operations at fission plants, giving rise to only 5 to 7 % of the total occupational dose [2.11].

A major operation at a fusion power station will be the replacement, processing and storage of the first wall/blanket structures. At a fission power station, the analagous operation would be fuel replacement, since it also involves remote handling of large, radioactive objects. However, larger components requiring a greater degree of onsite processing will be involved at a fusion plant. This would imply that waste handling at fusion plants will present a larger contribution to the total onsite dose than at fission plants. However, the fact that blanket components are much colder than spent fuel pins may result in the total dose during waste handling being nearly the same for both types of plants.

2.3.3.2 Influence Of A Protective Action On Waste Handling Procedures And Costs

Some degree of worker exposure will occur during waste management operations. However, the doses received may be reduced as the result of a particular protective action. The reduction may be due to either handling lower level waste or modifications in waste handling procedures. Handling of lower level waste represents an indirect effect of a protective action since the actual dose reduction measure would involve reactor components (e.g. the use of increased shielding around the reactor, a slightly different design for components, or different materials could lead to lower induced activity and hence lower level waste). Increased shielding or a change in equipment or procedures for waste handling may affect both doses and costs incurred during these operations. It may be necessary to carry out tasks in a different manner or using different tools or equipment, leading to a change in materials and/or labor costs for waste handling. It should be noted that a protective action involving waste handling procedures or equipment may not be directly linked to reactor operation or maintenance. Hence, the action may have little or no effect on operation or maintenance costs. This would be reflected in the operation and maintenance cost contributions to the total cost of the dose reduction measure being either very small or non-existant.

2.3.3.3 Evaluation Of The Change In Waste Handling Costs

In order to assess the total cost of a dose reduction measure, the effect of the design change on waste handling costs must be determined. A value for C_{TW}, the increase in total annual waste handling costs resulting from the dose reduction measure can be obtained from the general formula (equation 2.7). Changes in labor costs, health detriment costs, overhead costs and equipment and materials costs are to be included.

The increase in the total waste handling costs resulting from the implementation of a dose reduction measure can be evaluated using:

$$C_{TW} = C_{MW} + C_{LW} + C_{HW} + C_{OHW} + C_{DW} \tag{2.16}$$

All cost elements are defined following the general formula (equation 2.7). For estimating health effects costs, D_{W_o} and D_{W_p}, the total occupational and public dose savings during waste handling, are required. Since the reactor components being handled are no longer being exposed to a constant neutron flux, doses incurred by plant workers will be time dependent. Since waste handling occurs continuously, the dose rates to which the public is exposed during these procedures (expected to be low) can be assumed approximately constant at an average value.

2.4 Assessing The Cost Effectiveness Of A Particular Protective Action

Now that all cost components have been defined, the total cost of implementing a dose reduction measure can be evaluated. Before the cost effectiveness of the protective action can be assessed, the resulting dose reduction must be known. The total dose reduction (collective dose to workers and/or public) resulting from the proposed design change is given by:

$$D_T = D_{TO} + D_{TM} + D_{TW} \tag{2.17}$$

where

D_T= total dose reduction resulting from a protective action (person Sv/yr)

D_{TO}= total dose reduction during normal plant operation resulting from the protective action (person Sv/yr)

D_{TM}= total dose reduction during maintenance outages resulting from the protective action (person Sv/yr)

D_{TW}= total dose reduction for waste handling activities resulting from the protective action (person Sv/yr)

The total occupational dose savings is equal to the sum of the occupational dose savings during normal operation, maintenance and waste handling procedures. The total public dose savings can be found in a similar manner. These are then given by:

$$D_o = D_{O_o} + D_{M_o} + D_{W_o} \tag{2.18}$$

$$D_p = D_{Op} + D_{Mp} + D_{Wp} \tag{2.19}$$

where

D_o, D_p = total occupational and public dose savings resulting from the protective action (person Sv/yr)

D_{Oo}, D_{Mo}, D_{Wo} = total occupational dose savings during normal operation, maintenance and waste handling activities resulting from the protective action (person Sv/yr)

D_{Op}, D_{Mp}, D_{Wp} = total public dose savings during normal operation, maintenance and waste handling activities resulting from the protective action (person Sv/yr)

Knowing this, a value for β can then be computed (see equation 2.4). This value can then be compared to α' , the maximum justifiable expenditure for the dose reduction. An acceptable dose reduction measure would have a value of β less than α'. If several alternatives for reducing the radiation exposure exist:

(1) Obtain a value of β for each alternative.

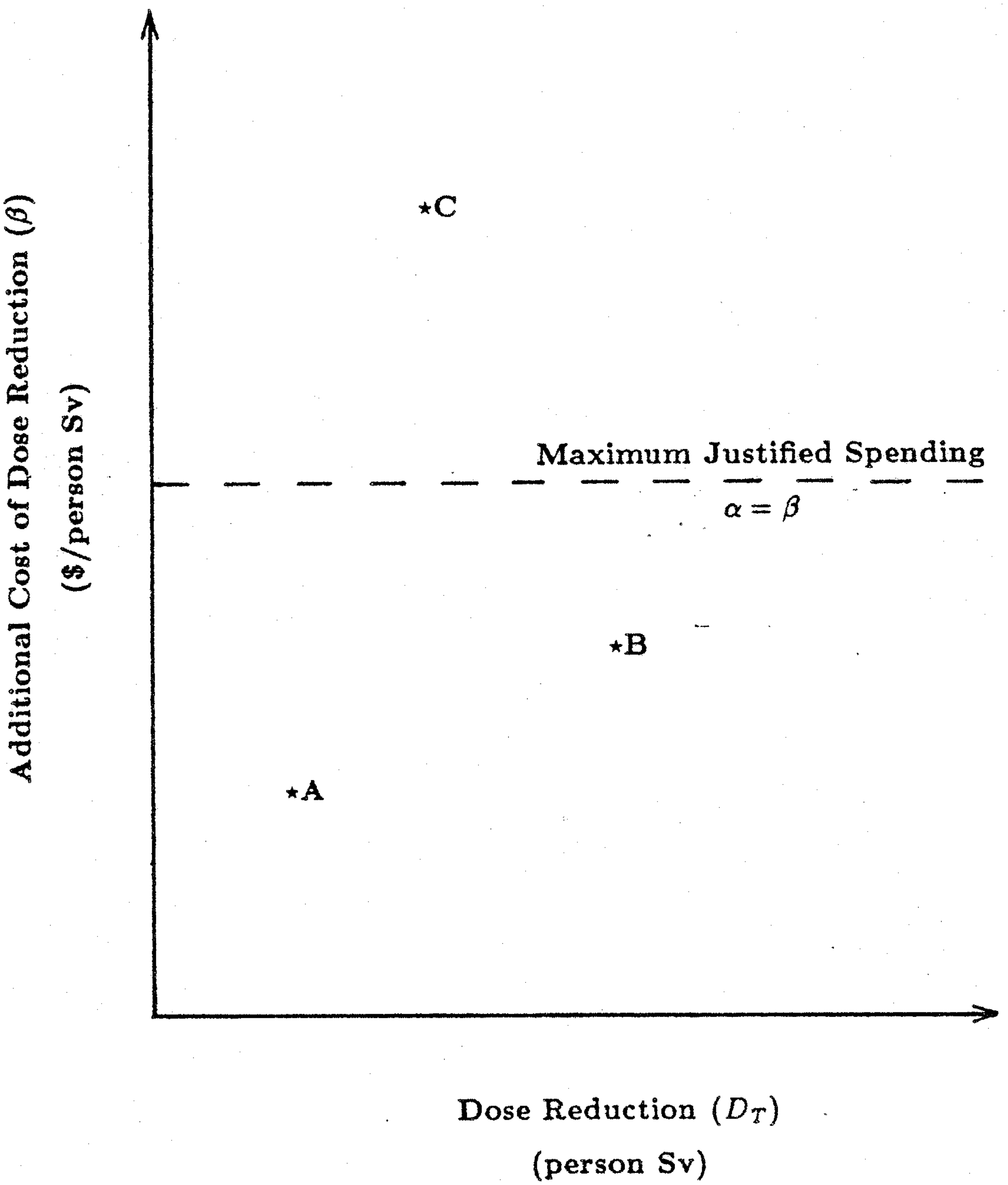
(2) Obtain a value of α' for each alternative. (Note : α and α^* will be the same for each since all alternatives are being assessed for the same initial dose rates to workers and the public. However, D_o and D_p, and therefore α', may differ.)

(3) If β exceeds α', the dose reduction measure is unjustified.

(4) If several alternatives result in a value of β less than α', the best alternative has the lowest value of β and therefore will result in the minumum cost per sievert averted (or the maximum safety benefit per dollar invested).

The design decision process can be illustrated through figure 2.1. The additional spending for a given dose savings (β) is plotted against the dose savings achieved (D_T). The ceiling on expenditures is shown by the dotted line. In this example, three alternatives for improving plant safety are to be assessed. Although alternative C results in the greatest dose reduction, it is unacceptable since the additional expenditures for this dose reduction exceed the expenditure ceiling. Alternatives A and B are both economically justified; it must be determined which of these should be chosen. Again, it may appear that since alternative B results in a larger dose savings, it should be chosen. However, alternative A should be selected, since it would result in the minimum cost per sievert averted or the maximum benefit per safety dollar invested. Alternative A is the most cost effective option.

Figure 2.1: Cost Effectiveness of Design Alternatives



2.5 An Issue Of Concern: Shielding Versus Downtime

A question often posed is whether there is a net benefit from designing a reactor with increased shielding so that human access into the reactor floor within a short time after shutdown is possible, allowing for some maintenance procedures to be carried out manually or in semi-remote mode. Primarily, the benefit from personnel access is a reduction in the total downtime, which results in lower replacement power costs. The penalty incurred is an increase in the capital cost for the additional shielding. It is desired to minimize both the economic and health risks during maintenance of a given design. Having this as an objective will ensure that an optimum maintenance plan is found.

A maintenance plan consists of groupings of specific tasks which must be accomplished in a given order within a given time frame. Tasks vary from simple standard duties (e.g. periodic inspections and replacement of items such as valves) to extremely complex and time consuming functions (e.g. removing and replacing a section of the vacuum vessel). The prescribed tasks should include a certain amount of preventive maintenance, depending on expected failure frequencies and the importance of the equipment to continued reactor operation. Unscheduled maintenance will also occur, but it cannot be incorporated into a maintenance plan due to the uncertainty in occurrence. Unfortunately, only a limited number of maintenance operations (e.g. replacement of first wall/blanket and shield, maintenance of reactor cooling, vacuum pumping and fueling systems) are generic to fusion power systems. Hence, it is not possible to develop a general maintenance plan. However, once the maintenance operations for a particular design have been defined, a method for each particular operation must be selected from a hierarchy of available techniques. These would typically be arranged in order of increasing completion time, equipment cost and the effectiveness of protection from adverse radiation environments.

A broad range of partially-remote operations can exist between the extremes of contact and fully-remote. Contact maintenance is described as the use of direct hands-on or conventional techniques using hand-held and guided tools to repair or maintain components. Fully-remote operations are those which can be accomplished without any human assistance within the immediate area of operation. Semi remote or contact/partially-remote maintenance may be implemented in order to minimize lost time with fully remote operations.

Varying amounts of contact maintenance may be performed on different components depending on the equipment design and task involved. If detailed maintenance information is available, a series of plausible maintenance schemes, varying between the extremes of maximum remote/minimum contact maintenance to minimum remote/maximum contact maintenance, and the corresponding critical paths, can be identified. Limited contact maintenance can begin at a suggested maximum dose rate of 0.1 Sv/hr [2.21]. Calculations can be carried out to determine the amount of shielding required to reduce the dose rate to this level in time for contact maintenance to begin (the time after shutdown at which contact maintenance begins depends on the particular maintenance scenario). The degree of hands-on maintenance possible and the amount of shielding required is strongly dependent on the technology employed (e.g. neutral beams versus rf heating) and the actual reactor design.

To determine the most cost effective maintenance scheme, all plausible schemes, ranging from minimum remote (certain tasks must be carried out remotely) to completely remote, must be identified. (Note that contact and remote activities can be carried out in parallel. Generally, t_r, the time required to complete all remote operations, will be greater than t_c, the time required to complete all contact operations.) The dose rate at which limited contact maintenance can begin must be set (0.1 Sv/hr). For a given scheme in which specific tasks have been defined as either contact or remote, the time after shutdown at which contact maintenance begins should be varied, providing several sub-schemes. These different situations are illustrated in figure 2.2.

Once the schemes and subschemes have been identified, the total change in maintenance, operation and waste handling costs, as well as the increase in the cost of shielding can be assessed. Each scheme and subscheme will result in a different total annualized cost for the dose reduction measure and a different dose incurred to plant workers. A value of β for each scheme can be calculated and compared to α', the ceiling on dose reduction expenditures. Any scheme having β exceeding α' is not cost effective in terms of dose reduction. For schemes having β less than α' , the most cost effective one is that corresponding to the minumum value of β.

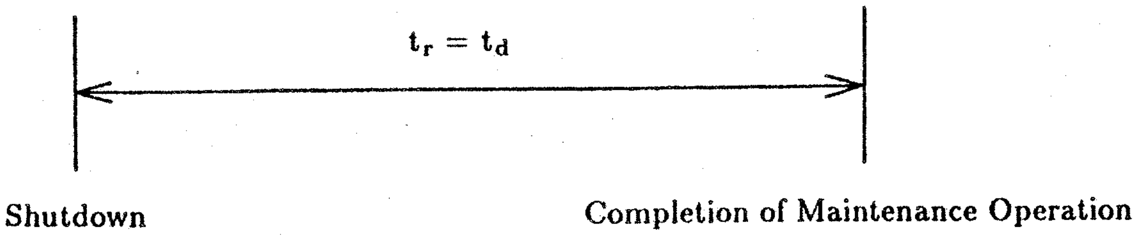
Figure 2.2: Plausible Maintenance Scenarios

t_d = downtime

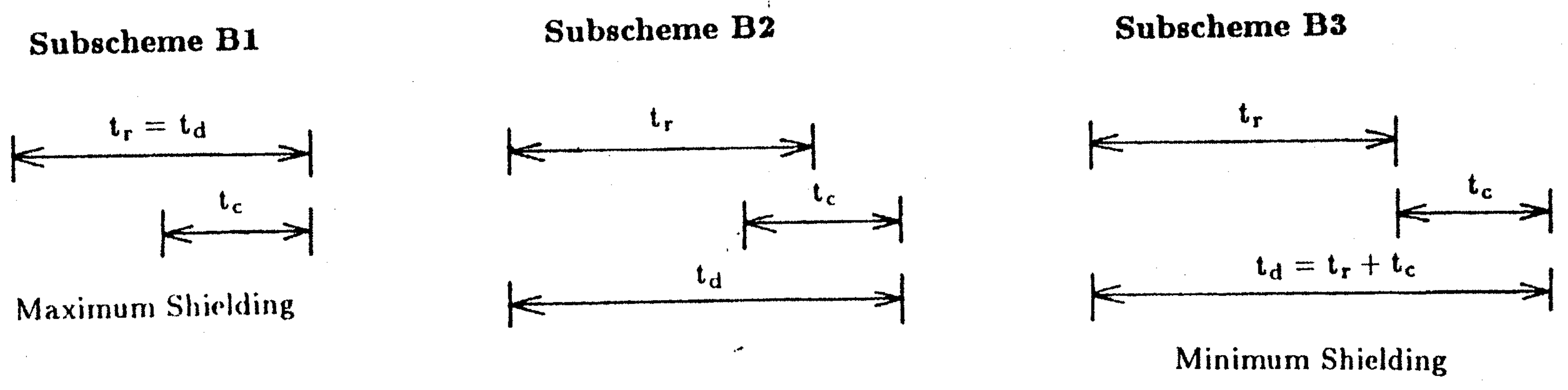
t_r = time required to complete all remote maintenance

t_c = time required to complete all contact maintenance

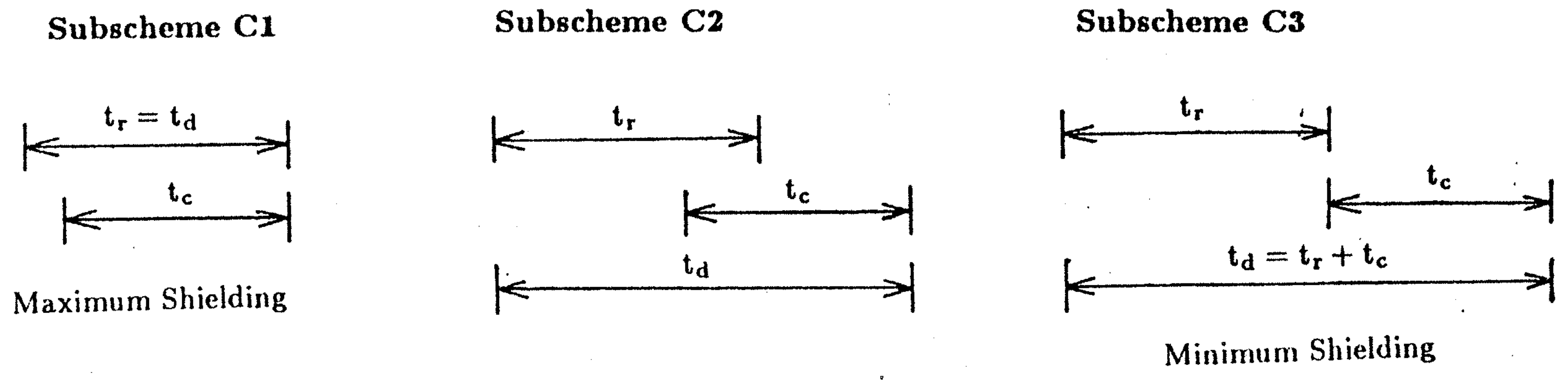
Scheme A: Fully Remote



Scheme B: Semi-Remote



Scheme C: Semi-Remote (with increased contact maintenance)



2.6 References

(2.1) C.E. Easterly, Occupational Exposures at a Fusion Power Station, Nuclear Technology/Fusion, 2, p. 723, October 1982.

(2.2) J.P. Holdren and S. Fetter, Contribution of Activation Products to Fusion Accident Risk: Part II. Effects of Alternative Materials and Designs, Nuclear Technology/Fusion, 4, p. 599, November 1983.

(2.3) H.J. Willenberg et al., Materials Flow, Recycle and Disposal for Deuterium-Tritium Fusion, Pacific Northwest Laboratories, PNL-2830, 1978.

(2.4) M.A. Maan, Cost Effective Radiation Risk Management in a Generic Nuclear Plant Design, Atomic Energy of Canada Limited, AECL-7536, November 1982.

(2.5) E.J. Henley and H. Kumamoto, Reliability Engineering and Risk Assessment, Prentice-Hall Incorporated, Englewood Cliffs, New Jersey, 1981.

(2.6) United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States: 1984, 104th edition, Washington D.C., 1984.

(2.7) Committee on the Biological Effects of Ionizing Radiations, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980, National Academy Press, 1980.

(2.8) National Council on Radiation Protection and Measurements, Influence of Dose and Its Distribution in Time On Dose-Response Relationships for Low-LET Radiations, NCRP Report No. 64, 1980.

(2.9) P.G. Voilleque and P.A. Pavlick, Societal Cost of Radiation Exposure, Health Physics, 43, No. 3, p. 405, 1982.

(2.10) C.C. Baker et al., STARFIRE - A Commercial Fusion Tokamak Power Plant Study, Argonne National Laboratory, ANL/FPP-80-1, 1980.

(2.11) T.D. Murphy and W.E. Kreger, Regulatory Considerations for Reducing Occupational Radiation Exposures at United States Nuclear Power Plants, Proceedings of Occupational Radiation Exposures in Nuclear Fuel Cycle Facilitiles, Los Angeles, California, June 18-22, 1979, p. 541, 1980.

(2.12) P. Beslu et al., Prediction of Primary Circuit Contamination in Power Reactors, Proceedings of the Fifth International Conference on Reactor Shielding, Knoxville, Tennessee, April 18-23, 1977, CONF-770401, p. 374, 1977.

(2.13) R.A. Shaw, Getting at the Source: Reducing Radiation Fields, Nuclear Technology, 44, p. 97, 1979.

(2.14) C.A. Bergmann, E.I. Landeman, D.R. Lorentz and D.D. Whyte, Evaluation of Cobalt Sources in Westinghouse Designed Three- and Four-Loop Plants, Electric Power Research Institute, EPRI NP-2681, 1982.

(2.15) J.B. Cannon, Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy, Oak Ridge National Laboratory, DOE/ER-0170, August 1983.

(2.16) W.E. Bickford, Coolant Channel Sputtering Source Terms in a Compact Tokamak Fusion Power Plant, Pacific Northwest Laboratories, PNL-2942, 1979.

(2.17) W.E. Bickford, Transport and Deposition of Activation Products in a Helium Cooled Fusion Power Plant, Pacific Northwest Laboratories, PNL-3487, 1980.

(2.18) M. Sniderman, Fusion Reactor Maintenance Study, Electric Power Research Institute, EPRI-1046, 1979.

(2.19) G.M. Fuller et al., Developing Maintainability for Tokamak Fusion Power Systems, Vols I, II and III, McDonnell Douglas Astronautics Company, COO-4184-6, 1978.

(2.20) H.S. Zahn, Developing Maintainability for Fusion Power Systems, McDonnell Douglas Astronautics Company, COO-4184-8, 1979.

(2.21) M.A. Abdou, G. Fuller, E.R. Hager and W.F. Vogelsang, Shielding and Maintainability in an Experimental Tokamak, Argonne National Laboratory ANL/FPP/TM-127, p. 54, November 1979.

(2.22) E. Siddall, Risk, Fear and Public Safety, Atomic Energy of Canada Limited, AECL-7404, April 1981.

(2.23) F.J.G. Derkinderen and R.L. Crum, eds, Risk, Capital Costs and Project Financing Decisions, Martinus Nyhoff Publishing, 1981.

(2.24) J.L. Riggs, Essentials of Engineering Economics, McGraw Hill, 1982.

(2.25) J.A. White, M.H. Agee and K.E. Case, Principles of Engineering Economic Analysis, John Wiley and Sons, 1977.

(2.26) N.J. McCormick, Reliability Risk Analysis, Academic Press, New York, 1981.

(2.27) J.A. Hasson, The Economics of Nuclear Power, Longmans, Green and Company Limited, 1965.

(2.28) Report of a Colloquium Conducted by the Committee on Public Engineering Policy, Perspectives on Benefit Risk Decision Making, National Academy of Engineering, April 1971.

(2.29) K.J. Boudreaux and H.W. Long, The Basic Theory of Corporate Finance, Prentice-Hall Incorporated, 1977.

(2.30) E. Mansfield, Economics: Principles, Problems, Decisions, Fourth Edition, W.W. Norton and Company, 1983.

(2.31) D.W. Rasmussen and C.T. Haworth, Economics: Principles and Applications, Science Research Associates Incorporated, Chicago, 1979.

(2.32) R. Sugden and A. Williams, the Principles of Practical Cost-Benefit Analysis, Oxford University Press, New York, 1978.

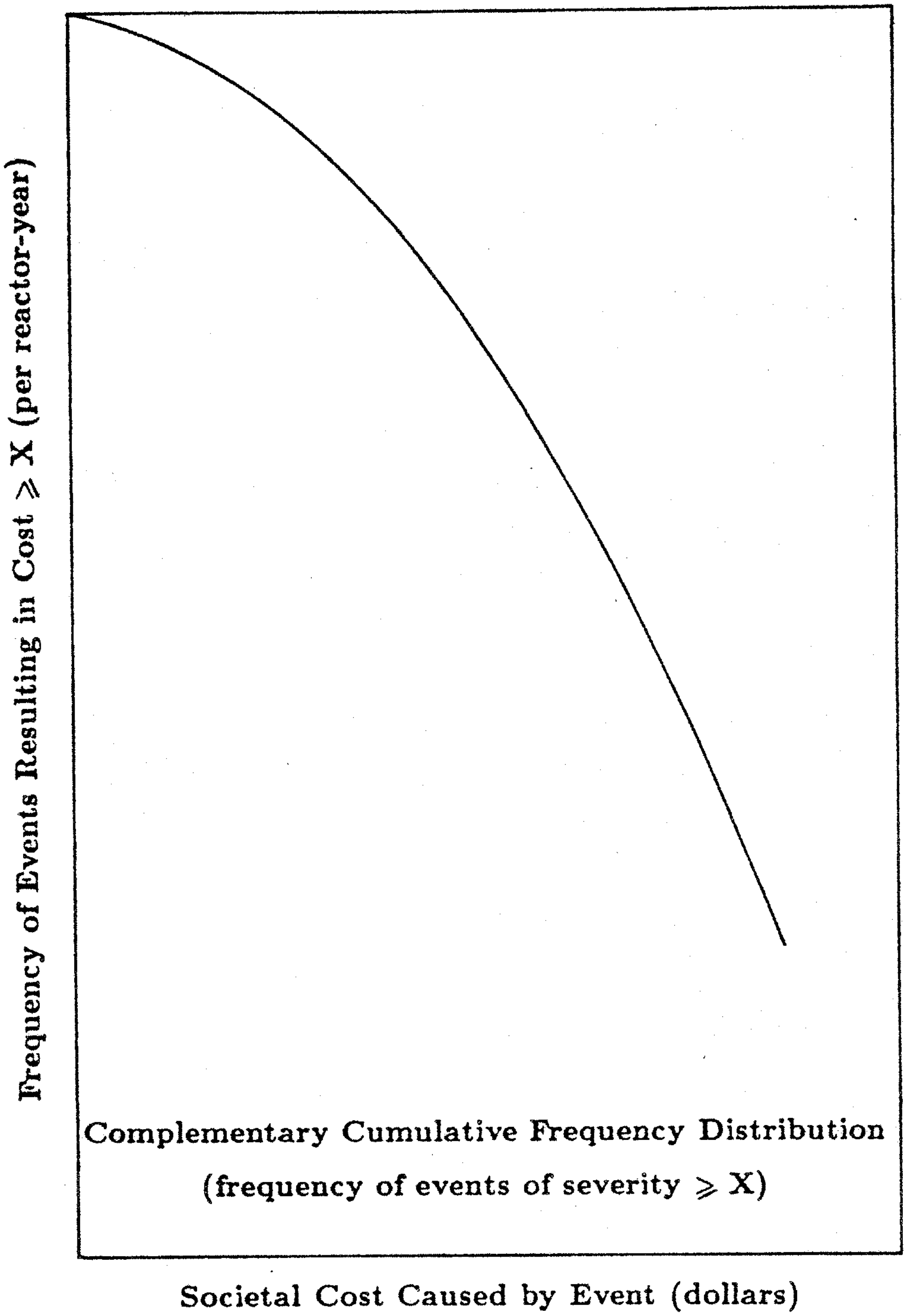
(2.33) W.A. Baumol, On the Appropriate Discount Rate for the Evaluation of Public Projects in H.H. Hinricks and G.M. Taylor eds, Program Budgeting and Benefit-Cost Analysis, Goodyear Publishing Company, Pacific Palisades, California, 1969.

Chapter 3

Cost/Benefit Safety Analysis For Accident Conditions

Accidents can potentially occur during fusion reactor operation. Associated with these possible events is a range of economic consequences and a certain level of economic risk. In a recent study, a spectrum of LWR economic risks was presented [3.1], given by a distribution of event frequency versus cost or severity. A spectrum of economic risk due to accidents is also expected for fusion reactors and is depicted in figure 3.1. The distribution is a complementary cumulative frequency distribution of event costs. It gives the frequency of events which result in costs greater than a specific magnitude. As can be seen, the expectation of low cost - low severity events is relatively high, while high cost - severe events are relatively infrequent.

Figure 3.1: Example of Fusion Reactor Economic Risk Spectrum



In this section, a methodology for assessing the economic risks of fusion reactor accidents is presented. It has largely been adopted from previous work done for LWRs by Burke [3.1], with some minor modifications. Having the capability of estimating the total economic risk associated with a particular accident scenario, it is then possible to evaluate the cost effectiveness of suggested accident consequence mitigation proposals. A proposed methodology for an analysis such as this is outlined in this chapter.

3.1 Fusion Reactor Accidents

In the following section, fusion reactor accidents are categorized in a fashion appropriate for analyzing the economic consequences. A brief discussion of potential fusion reactor accidents is also given.

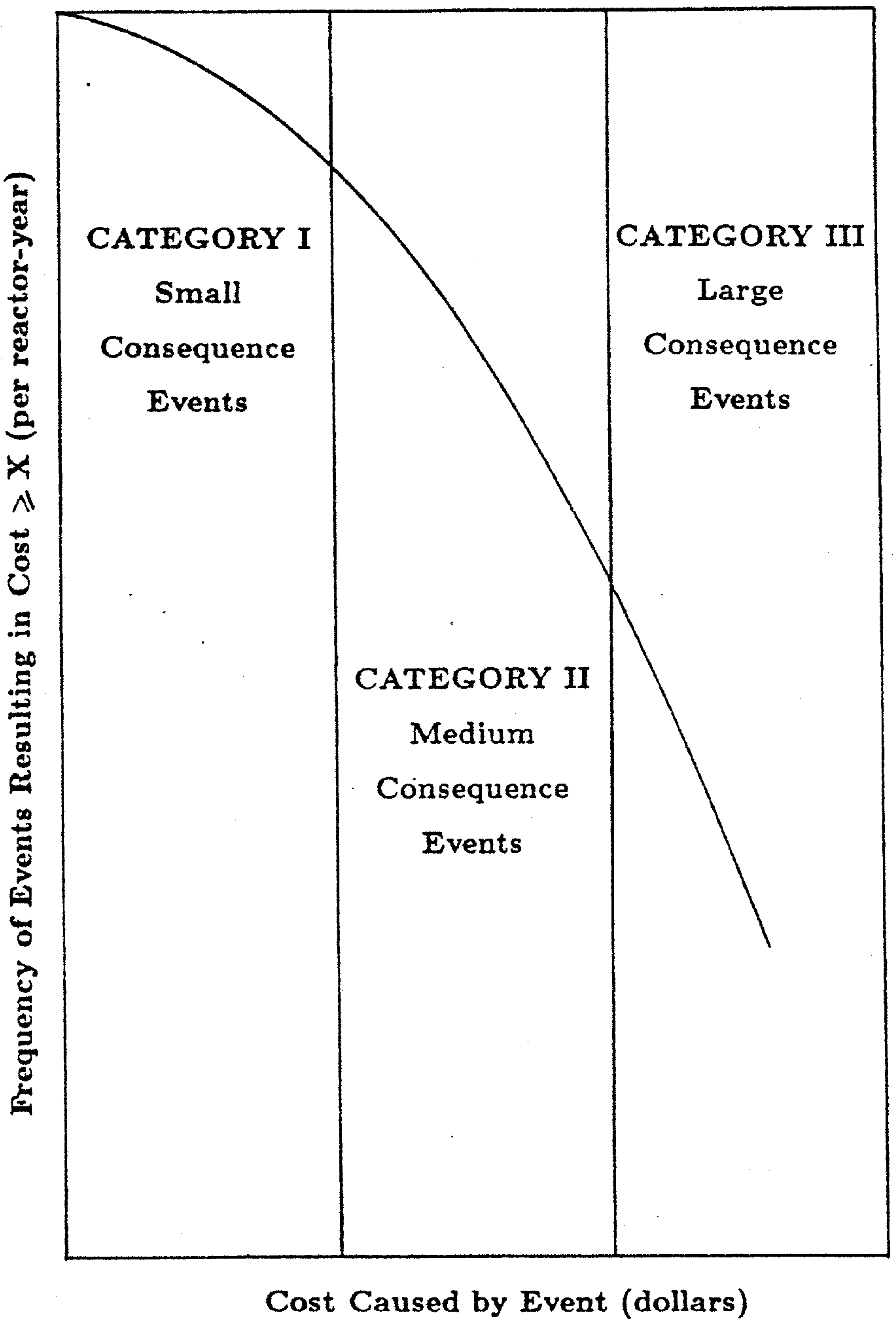
3.1.1 Categorization Of Fusion Reactor Accidents

The events comprising the LWR risk spectrum have been divided into three event categories, based on severity or cost [3.1]. This approach has also been taken in this study. The category divisions are shown in figure 3.2. It should be noted that no events during plant construction or decommissioning are considered. The category divisions are based on the costs resulting from an event. An exact dollar value for the division between categories cannot be provided at this time. However, the flexibility of the methodology allows this shortcoming to be overcome.

Category I accidents are small consequence events which include all forced outages not resulting in first wall damage or significant plant contamination. No offsite health impacts or property damage result. Events in this category may be due to operator errors, plant system failures, component failures, external events or maintenance requirements. These events are unscheduled, in contrast to scheduled maintenance outages. They result in an unplanned period of zero power production from the plant. Hence, a significant cost incurred will be that of replacement power.

Medium consequence events are placed in category II. This category is defined to include auxiliary system failures, divertor failures, hydrogen fires and accidents which result in first wall damage without breach of the vacuum vessel (possibly due to plasma instabilities and disturbances, minor plasma disruptions, loss of coolant or coolant flow, cryogenic failures, or magnet failures). The outcome of these oc-

Figure 3.2: Event Categories for Estimation of Economic Risk



currences may be substantial equipment damage, and there may be some release of radioactive material to the environment. There is a need for a plant decontamination effort subsequent to the event, followed by either repair or decommissioning of the plant. Some offsite health impacts or property damage costs may result from these events. Plant outages could last many years if the plant is repaired, or may be permanent if decommissioning is undertaken.

Large consequence accidents are very low probability occurrences. These are placed in category III. Included are rupture of coolant or tritium processing lines, lithium fires, hydrogen explosions and all events resulting in severe first wall damage where the vacuum vessel is breached (e.g. vessel melt-through, possibly due to major plasma disruptions, magnet malfunctions, loss of coolant or coolant flow, or auxiliary system failures). Such events are costly in that significant damage to the plant results. Hence, there will be a large capital investment loss. A significant quantity of radioactive material may be released to the environment. Offsite public health impacts and property damage may occur. Plant decontamination and cleanup is required before plant repair or decommissioning can take place.

3.1.2 Discussion Of Potential Fusion Reactor Accidents

Section 2.1 outlined sources of radiation risk in a fusion power plant. In this section, potential release mechanisms are briefly described. Further details can be found in references 3.2 to 3.7.

Many major components of fusion reactor systems will handle significant quantities of tritium. Components vulnerable to tritium release under accident or failure events include: blanket and blanket processing systems, recycled fuel processing system, fuel storage system, coolant and atmospheric cleanup systems, vacuum pumps and fuel injectors. In addition to tritium, it will be necessary to deal with activated materials. The level of activation will depend on proximity to the plasma, material composition, neutron flux and spectrum at the component's location and the total operation time.

Potential mechanisms by which a portion of the radioactive inventory of a fusion reactor can be released have been postulated. These include magnet system accidents, plasma disruptions, coolant system failures, auxiliary system failures, fires and explosions.

To achieve the necessary magnetic fields, without excessive power consumption, fusion reactor designs have generally employed large superconducting magnet systems. Magnet accidents may occur as a result of arcing across current leads or conductor rupture. Arcing could lead to conductor vaporization and the need to replace the entire magnet. The most severe damage would ensue the simultaneous ruptures of the entire winding and casing at two different locations, after which missile generation might occur. Coolant lines or tritium processing lines could be disturbed or broken, resulting in the release of radioactive material.

Plasma disturbances which are of concern include the sudden loss of plasma and thermal excursions. The first of these involves gross MHD movement of the plasma towards the reactor walls. If a major disruption should occur in a tokamak, a large fraction of the plasma thermal energy may be deposited over a small area of the first wall. Local ablation and melting could result, with the release of activation products. Thermal excursions are possible since the fusion reaction cross section increases more rapidly with temperature than energy loss mechanisms. A rapid increase in plasma temperature, and therefore fusion power output, would occur. Thermal excursions could develop as the result of a failure in the system controlling the fusion power level. Since the fusion cross section increases rapidly with temperature, power output could increase severalfold within a short period. This could lead to ablation and melting of the first wall, with subsequent release of radioactivity. Additionally, magnetic consequences of plasma disruptions may lead to significant structural damage (e.g. warping of the vacuum vessel).

Heat from the first wall/blanket region is removed by the primary coolant system. Loss of coolant or loss of coolant flow accidents may result in large temperature increases due to the decay heat from the activated structure. This can cause first wall/blanket mechanical failure and possible release of radioactive material. Other coolant/power disturbances resulting from overpower transients or plasma disruptions could also lead to thermal mechanical failures and subsequent release of activated material.

Liquid helium will be used in the vacuum and fuel handling cryopumps and to maintain the superconducting coils below the critical temperature. In the event of a coil or helium pipe break, the liquid helium will escape and flash into a two phase mixture, extracting heat from the reactor structures. This will induce thermal strains in the structures and represents a potential cause for failure of the reactor. In addition, loss of helium will drive the superconductor into the normal state, possibly melting the coils, further aggravating the previously described effect.

Hydrogen explosions can occur under certain conditions. This is of concern since large quantities of hydrogen isotopes will be present onsite. The actual outcome of a hydrogen explosion will be a strong function of the total amount of hydrogen present (hence, the materials used in the design), the building geometry and volume and the atmosphere within the building.

Auxiliary systems store hazardous quantities of energy which could serve to initiate radioactive releases. Chief areas of concern are plasma heating systems, fueling equipment, the vacuum chamber and pumps, divertors, direct convertors, high voltages and eddy currents. Neutral beams may be used for plasma heating and end-plug maintenance. Concern arises in cases where beams are energized in the absence of a plasma. This would result in damage to the first wall and possible release of activation products. Radiofrequency heating of the plasma requires a large amount of power, thus requiring special precautions. Fueling equipment may allow explosive concentrations of hydrogen to exist and must therefore be regarded as a potential hazard. Vacuum chamber failure could allow for infiltration of air and perhaps the creation of explosive mixtures within the reactor. In addition, vacuum chamber failure could heat the cryopumps, causing them to release their inventories of deuterium, tritium and helium.

Divertors are intentionally designed to intercept magnetic flux lines. Hence, the divertor is intimately connected to part of the plasma volume. An increase in the neutral and impurity content of the "scrape-off" region of the plasma would occur in a divertor failure, and an MHD plasma disruption could be initiated.

The chemical energy released from chemical reactions involving lithium is the greatest potential source of energy in a reactor utilizing lithium as the breeder/coolant. This presents a mechanism for release of large quantities of activation products. Liquid lithium is capable of generating large quantities of heat upon reaction with air, concrete or water. This could lead to volatilization and release of activated materials. In addition, an inventory of tritium will exist in the liquid metal, which would be released as the lithium was reacting. Lithium is required, in some form, for breeding tritium, but a less reactive form than the liquid metal could greatly alleviate chemical safety concerns.

3.2 Categorization Of Economic Consequences

It is appropriate to discuss the accident economic consequences on the basis of location and the organization impacted by the occurrence. Accident costs can be classified as either onsite or offsite costs. Onsite costs occur at onsite locations or are those losses directly affecting the plant licensee, the fusion power industry, or the electric utility industry. Offsite costs include those losses occurring at offsite locations. These two classes of economic consequences are not completely independent, for some costs may first affect the plant licensee who subsequently transfers the cost to consumers at offsite locations. Present worth discounting should be used to express these costs since using present dollars when discussing future cash flows is less subject to misinterpretation.

Onsite and offsite cost elements are discussed further below. Those elements contributing to the total economic risk of each reactor accident category are summarized in table 3.1.

3.2.1 Onsite Economic Consequences

This category encompasses cost elements which directly affect the plant licensee, the fusion power industry, or the electric utility, or occur at onsite locations. Onsite consequences include replacement power costs, plant decontamination costs, plant repair costs, plant capital costs, early decommissioning costs, plant worker health impact costs, fusion power industry costs, electric utility business impacts, and litigation costs.

3.2.2 Offsite Economic Consequences

Costs directly affecting the public or which occur at offsite locations are considered as offsite costs. Cost components associated with countermeasures taken to reduce radiation exposure to the public, costs of radiation induced health effects and health care costs incurred by the population living in the affected offsite area, offsite property damage or losses occurring as an outcome of an event, and indirect secondary costs which may occur outside the contaminated area at offsite locations are included in the offsite economic risk. More specifically, offsite costs encompass population evacuation and temporary relocation costs, property decontamination costs, land area interdiction and permanent relocation costs, agricultural product disposal costs, population health effect and health care costs, secondary economic effects costs and offsite litigation costs.

3.2.3 Accident Risk Reduction

In fusion reactor design, attention must be given to those areas where the potential for accident occurrence exists. Some degree of accident consequence mitigation must be incorporated into the design. To avoid wasting resources, a cost effective approach to accident risk reduction is needed. A method for accomplishing this, similar to that presented in Chapter 2 is given in the next section.

Table 3.1: Important Cost Contributions for Fusion Reactor Accidents

		Accident Category	
Cost Component	Type I	Type II	Type III
Onsite Costs:			
Replacement Power, C_P	+	+	+
Plant Decontamination, C_D	-	+	+
Plant Repair, C_R	+	+	+/-
Plant Decommissioning, C_{AD}	-	-	-/+
Capital Investment, C_{CI}	-	-	+
Health Effects, C_{Hi}	*	*	*
Fusion Power Industry Costs	-	⋆	⋆
Electric Utility Business Costs	-	⋆	⋆
Litigation Costs	⋆	⋆	⋆
Offsite Costs:			
Health Effects, C_{Ho}	-	+	+
Land and Property Decontamination, C_d		++	++
Population Relocation, C_r	-	++	++
Agricultural Product Disposal, C_{cd}, C_{dd}	-	**	**
Population Evacuation, C_E	-	+	+
Emergency Phase Relocation, C_{EP}	-	++	++
Intermediate Phase Relocation, C_{IP}	-	+	+
Land Interdiction, C_I	-	++	++
Secondary Effects Costs	-	⋆	⋆
Litigation Costs	-	⋆	⋆

+	may contribute to total economic risk of reactor accident
-	does not contribute to total economic risk of accident
+/-	an option exists between including this component (if the situation dictates that it should be included) and another alternative (indicated by -/+)
*	contribution to total economic risk is negligible
⋆	estimate is not included in this study
++	may contribute to total economic risk if the dose rate exceeds a certain level
**	may contribute to total economic risk if the accident occurs during the growing season

3.3 Cost Effective Accident Risk Management Methodology

When assessing proposals for reducing accident consequences, a similar approach to that for reducing risk during normal plant operation can be taken. The ceiling on occupational expenditures for accident consequence reduction is given by:

$$\alpha_a = \left(\frac{L_c}{E_{LIM}}\right)\left(\frac{R_a}{E_{LIM}}\right)^N \tag{3.1}$$

where

α_a= ceiling on occupational expenditures for the reduction of accident consequences (\$/person Sv)

L_c= labor cost (\$/person yr)

E_{LIM}= occupational exposure limit (Sv/yr)

R_a= maximum occupational exposure rate after the accident occurrence (Sv/yr)

N= exponent indicating the dose response for harm induced by radiation (0.5)

A ceiling on public safety expenditures can similarly be defined:

$$\alpha_a^* = \left(\frac{L_c^*}{E_{LIM}^*}\right)\left(\frac{R_a^*}{E_{LIM}^*}\right)^N \tag{3.2}$$

where

α_a^*= ceiling on public expenditures for the reduction of accident consequences (\$/person Sv)

L_c^* = per capita income (\$/person yr)

E_{LIM}^* = public exposure limit (Sv/yr)

R_a^* = maximum public exposure rate after the accident occurrence (Sv/yr)

A question may rise as to what should be the correct limiting exposure rate in an accident situation. On a routine basis, the limiting rate for occupational exposure is known to be 0.05 Sv/yr (5 rem/yr). Assuming an individual to work 40 hours per week, 50 weeks per year, this would allow continuous exposure to a dose rate of 2.5 x 10^{-5} Sv/h, without exceeding the annual limit. If it is thought to be unacceptable to exceed the exposure limits for normal conditions, even in the event of an accident, then the above exposure limit should be used. However, it is permitted for an individual to incur a dose of 0.25 Sv (25 rem) in an off-normal situation, provided this does not cause the individual to exceed his total accumulated lifetime dose† [3.8, 3.9]. The time during which this dose is incurred is not of concern; it is the total dose which is important. If the duration of exposure during potential accidents can be postulated, then dividing 0.25 Sv by the exposure time would give a more appropriate limit for the exposure rate. Since the duration of exposure would likely not be large, the limiting exposure rate would tend to be higher than for normal situations. This would have the effect of lowering the expenditure ceiling.

The ceiling on expenditures represents the permissible cost of a proposed accident consequence mitigation scheme. To determine if the proposed scheme is justified, analyses must be carried out to assess the expected dose reductions in the event of a postulated accident (compared to the dose which would be incurred if no attempt was made to decrease the accident consequences). If the dose reduction

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† The total accumlated lifetime dose is given by (N-18) x 0.05 Sv, N = individual's age.

measure is aimed at only one group (workers or public), the appropriate costing formula (for α_a or $\alpha_a^{\times}$) should be used. If both groups are affected, an overall expenditure ceiling (α'_a), which considers both occupational and public components, can be evaluated:

$$\alpha'_a = U_a \alpha_a + V_a \alpha_a^{\times} \tag{3.3}$$

where

α'_a= overall ceiling on expenditures for the reduction of accident consequences which will result in the dose savings of D_{ao} and D_{ap} (\$/person Sv)

U_a= $\frac{D_{ao}}{D_{aT}}$

= fraction of the total dose savings for a given accident scenario due to worker exposure

V_a= $\frac{D_{ap}}{D_{aT}}$

= fraction of the total dose savings for a given accident scenario due to worker exposure

D_{ao}= occupational dose savings during a given accident scenario when an accident consequence reduction measure has been used (person Sv)

D_{ap}= public dose savings during a given accident scenario when an accident consequence reduction measure has been used (person Sv)

D_{aT}= total dose savings during a given accident scenario when an accident consequence reduction measure has been used (person Sv)

Before a given accident consequence reduction proposal can be evaluated in terms of cost effectiveness, the actual increase in costs associated with the proposal must be evaluated. These costs can be evaluated in one of two ways: (1) relative to the case where no mitigation actions are taken, or (2) relative to a base case, if several alternatives are being compared. The base case would be that alternative having the minimum capital cost. The assessment must be performed from the perspective of a particular accident scenario, which may only occur with a certain probability. In determining the total costs for a dose reduction scheme, this probability must be somehow incorporated. A proposed method for accomplishing this is presented in the next section. Since the dose will only be incurred if the accident does in fact occur, the dose must be multiplied by the probability of the accident occurring to determine the health risk. Knowing the economic risk for the proposal and the savings in health risk resulting from the use of a particular consequence reduction measure, a value for the total cost of an accident consequence reduction proposal can be evaluated:

$$\beta_a = \left(\frac{C_{aT}}{D_{aT} \cdot p} \right) \tag{3.4}$$

where

$\beta_a =$ actual additional spending for the accident consequence reduction proposal for a particular accidental occurrence (\$/person Sv)

$C_{aT} =$ increase in costs for an accident consequence reduction proposal over the costs which would be incurred if no consequence reduction scheme was used or over the costs which would be incurred for the base case (see section 3.4) (\$)

D_{aT}= total dose reduction resulting from the use of the accident consequence reduction proposal from that which would be incurred if no consequence reduction scheme was used or from that which would be incurred for the base case (person Sv)

p= probability, over the plant lifetime, of the given accident occurring

As with normal plant operation, if the additional cost for the benefits obtained is less than what is justified (α_a, α_a^* or α_a'), then the proposal is cost effective.

3.4 Assessing The Total Cost Of An Accident Consequence Mitigation Action

The implementation of an accident consequence reduction measure will result in increased costs. Using the methodology presented in section 3.3, it can be determined if the resulting decrease in the expected exposure justifies the expenditure. In order for this to be assessed, a value for C_{aT}, the total cost of the accident consequence reduction measure is required. This cost is comprised of two components: the capital cost and the costs incurred subsequent to the accident. Since the accident related costs will only result if the accident does actually occur, they should be multiplied by the probability of occurrence of the accident to determine the appropriate economic risk. Hence, the total cost is given by:

$$C_{aT} = C_{aC} + p \cdot C_a \tag{3.5}$$

where

C_{aT}= total increase in costs resulting from the use of the accident consequence reduction measure over the costs which would be incurred if no reduction scheme was used (or over the base case costs) (\$)

C_{aC}= capital cost of the accident consequence reduction measure (\$)

C_a= change in the accident related costs compared to the case where no accident consequence reduction measure has been used (or compared to the base case) (\$)

p= probability, over the plant lifetime, of the given accident occurring

The capital cost of an accident consequence mitigation action represents the cost of materials and installation for those items directly responsible for reducing the accident consequences. If it has already been determined that a consequence reduction scheme of some sort is definitely required, then the capital cost component would represent the increase in capital cost for a particular alternative over the minimum cost alternative being assessed (base case). (Similarly, the value for D_{aT}, would be the expected reduction in dose, for a postulated accident, for a particular alternative, from the case where the minimum cost alternative (base case) was employed.)

Several cost elements may contribute to the accident related costs, depending on the severity of the accident. These cost components were previously summarized in table 3.1 and are discussed further in the next section.

3.5 Economic Risks From Small Consequence Fusion Reactor Accidents

In this section, models are presented for estimating the economic consequences of cateogory I fusion reactor accidents. The models are based on those developed in a recent study for LWR events [3.1] and have been adapted for fusion applications.

3.5.1 Onsite Economic Risks From Small Consequence Fusion Reactor Accidents

Onsite cost components for category I events include power production cost increases, plant repair costs and worker health effect and health care costs. Only unscheduled outages are dealt with so that an estimate of the economic risk associated with abnormal occurrences can be obtained.

3.5.1.1 Replacement Power Costs

The most significant contribution to onsite costs of category I events probably arises from the cost of replacement power due to plant outage time. Events not resulting in outage time contribute minimally to the total economic risk associated with the plant. It is assumed that the option to purchase replacement power during the outage is chosen and that no other methods for compensating for the lost generating capacity are implemented. This may result in an overestimate of the cost associated with the event, especially for shorter duration outages as often may be the case for category I events.

The simplified model presented in appendix C can be employed to estimate the replacement power cost during the outage. Assuming that no significant escalation in real power production cost increases occurs over the short time duration of each outage, the replacement power cost is given by:

$$\begin{aligned} C_P &= \left(\frac{GC}{C'}\right)\int_0^{t_d} F\cdot e^{-rt}dt \\ &= \left(\frac{GCF}{C'r}\right)\left[1 - e^{-rt_o}\right] \end{aligned} \tag{3.6}$$

where

C_P= present value of the production cost increase over the outage period ($)

G= electrical generation rating of the reactor (MWe)

C= actual capacity factor of the plant had the outage not occurred

C'= average capacity factor of the plant, obtained from operating data

t_d= outage duration (yrs)

F= unit production cost increase of outage ($/MWe yr)

r= real societal discount rate

As was discussed in section 2.5, a major issue to be resolved regarding scheduled maintenance was whether there is a net benefit from designing the reactor for human access into the reactor floor within a short time after shutdown so that some maintenance operations can be carried out manually or semi-remotely. The additional cost of shielding to allow earlier access leads to a decrease in reactor downtime and therefore replacement power costs. If causes of unscheduled outages and the required operations to return the plant to working order can be postulated, then the procedure outlined in section 2.5 can be employed to determine the optimal scheme to follow subsequent to an event. This will not be possible for all unscheduled outages since it is highly unlikely that all possible events can be accounted for. However, this procedure would be quite useful for those events which can be identified, since a plan would be ready if the event occurred. Knowing the costs involved for a particular scheme, the expected probability of occurrence of the event and the dose incurred, a value for β_a can be obtained. The alternatives can be compared and the most cost effective plan to follow during the unscheduled outage can be selected. Such unscheduled outages can be kept to a minimum by incorporating preventive actions into maintenance plans.

3.5.1.2 Plant Repair Costs

Certain plant components may be damaged during an accident and require repair before the plant can return to operation. Since it is desired to assess the economic consequences of a particular event, only marginal repair costs should be included in the analysis. This excludes any repair costs which would have been borne if the accident had not occurred.

The cost for plant repair will depend on the particular accident and the components damaged. Often, replacement parts for repairs have relatively small costs. It maybe difficult to quantify the magnitude of the plant repair costs since the distinction between normal plant maintenance and repairs resulting from the accident may not be clear. The normal plant operation crew may be able to complete the repairs in many instances, so that outside contractors are not required.

Analyses of plant repair costs for LWR outages have shown these costs to be small compared to the replacement power cost incurred during the outage [3.1]. As a lower bound, plant repair costs were considered negligible in comparison with replacement power. Based on historical plant operational data and insurance property damage data, the upper bound on plant repair costs was found to be 20 % of replacement power cost. A value of $1,000 per hour of outage was used as the best estimate for repair costs in analyses of small consequence accidents [3.1]. Since the capital cost associated with fusion reactors is expected to be larger than that associated with LWRs, repair costs may be higher. (Note that higher modularity may make repair/replacement costs less. However, due to lack of information at this time, this consideration was not incorporated and the estimate for plant repair costs was based solely on capital costs.) In Chapter 4, it will be shown that the capital cost of the STARFIRE plant can be estimated at 3.85 billion 1984 dollars [3.10]. Burke assumes a value of 3.08 billion 1984 dollars (updated from reference 3.1) as the capital cost of a new fission plant. Applying the ratio of capital costs directly, a value of \$1,250 per hour of outage was obtained as the best estimate for repair costs in small consequence fusion reactor accidents. The present value of the cost to society due to plant repairs from a category I accident (taken from Burke's work [3.1]) is:

$$C_R = \int_0^{t_d} R_P \cdot e^{-rt} dt \tag{3.7}$$

where

C_R= present value of the plant repair cost (\$)

t_d= outage duration (days)

R_P= plant repair cost per day of outage (30,000 \$/day or 1,250 \$/hr)

r= real societal discount rate

3.5.1.3 Worker Health Effects And Health Care Costs

Worker health impacts may occur as a consequence of any accident at a fusion plant. However, since category I events result in no significant plant contamination, plant worker health effects are expected to be extremely rare. Any effects would be from exposure to very low levels of radiation for a short period of time. The cost of any effects (C_{Hi}), then, would be small. It is expected that other costs related to the outage would dominate the total cost. Hence, worker health effects for category I events can be considered negligible.

3.5.1.4 Summary Of Onsite Impacts Of Small Consequence Fusion Reactor Accidents

Estimates for onsite costs of small consequence events can be obtained using the simple replacement power cost and plant repair cost models. Plant repair costs are expected to make only a small contribution to the total outage costs. Hence, the uncertainty in repair cost estimates are relatively unimportant. Since during short outages other options exist for compensating for the lost generation capacity, the replacement power model may lead to an overestimate of the total cost of the outage (i.e. it may not be necessary to purchase replacement power). In addition, projecting costs to future years creates more uncertainty especially regarding the availability of excess generating capacity to produce replacement power and the costs of fuels. More detailed plant-specific analyses could greatly reduce the uncertainties associated with replacement power cost estimates. This would result from consideration of utility replacement power agreements, load variations and excess generating capacities which might exist.

Category I events and any event leading to a period over which no power is produced, can result in significant societal costs. Priority should be given to preventing these outages and reducing the ensuing losses. Substantial savings maybe realized from a well organized plant maintenance program. Furthermore, a reduction in occurrence of these events will reduce plant transients, which place demands on systems. A reduction in transient induced accidents, and therefore the total public health risk and economic risk posed by the operation of the plant will result.

3.5.2 Offsite Economic Risks From Small Consequence Fusion Reactor Accidents

Since small consequence fusion reactor accidents do not result in significant releases of radioactivity, there are no resulting offsite health impacts or property effects. Hence, there is no offsite cost component contributing to the total cost of the outage.

3.6 Economic Risks From Medium Consequence Fusion Reactor Accidents

Models for estimating the economic consequences of category II fusion reactor accidents are described in this section. As for category I events, they are based on models developed for LWR accidents [3.1].

In view of recent fusion reactor accident studies [3.5, 3.11, 3.12, 3.13], plausible events appear to result in no significant releases of radioactive materials to the environment. Consequently, no offsite health or property damage costs are likely to be incurred. If this is so, economic risks of fusion reactor events can then be assessed using the onsite models.

3.6.1 Onsite Economic Risks From Medium Consequence Fusion Reactor Accidents

Onsite cost components for category II events include replacement power costs, plant repair costs and decontamination/clean up costs. In addition, fusion power industry costs, electric utility business costs and onsite litigation costs may be important for this category of event.

3.6.1.1 Replacement Power Costs

The cost of replacement power due to plant outage time will likely be a major contributor to the total outage cost. The simple replacement power cost model can be employed. For these events, however, outage durations may be such that allowance for real power production cost increases must be made. The replacement power cost is given by (see appendix C):

$$
\begin{aligned}
C_P &= \left(\frac{GC}{C'}\right) \int_0^{t_d} F_0 \cdot e^{-(r-g)t} dt \\
&= \left(\frac{GCF_0}{C'}\right) \left[\frac{1 - e^{-(r-g)t_d}}{r - g}\right]
\end{aligned}
\tag{3.8}
$$

where

C_P= present value of the power production cost increase over the outage duration ($)

G= electrical generation rating of the reactor (MWe)

C= actual capacity factor of the plant had the outage not occurred

C'= average capacity factor of the plant, obtained from operating data

F_0= power production cost increase at time zero ($/MWe)

t_d= outage duration (yrs)

r= real societal discount rate

g= real escalation rate of replacement power costs (yr^{-1})

3.6.1.2 Plant Decontamination Costs

Subsequent to a type II event, it may be necessary to decontaminate areas of the fusion plant which have become contaminated. Decontamination costs will include the cost of removal and disposal of any radioactive wastes, labor costs, decontamination equipment operating costs and the health detriment costs due to radiation exposure. These cost components are not individually considered in Burke's model, but are specifically accounted for here.

There are definite economic advantages to completing the cleanup program in a minimal time period. However, this may not always be possible due to problems encountered in financing cleanup operations and from regulatory concerns. In addition, there will be the cost of bringing the plant to, and maintaining the plant in, a stabilized condition throughtout the decontamination period. It is anticipated that this will result in only small additional costs.

Before decontamination can be carried out, an actual cleanup program must be defined. The specific tasks, their duration, the required crew size and the point in time at which the tasks should be carried out must be specified. The decontamination program can be subdivided into phases or periods during which similar tasks are carried out. The cost incurred for decontamination during any particular phase is given by:

$$C_{dn} = \int_0^{t_n} (C_{Wn} + C_{Ln} + C_{On} + C_{Hn})\, e^{-(r-g)t} dt \tag{3.9}$$

where

C_{dn}= decontamination cost during phase n of the decontamination program (\$)

t_n= duration of phase n of the decontamination program (yrs)

C_{Wn}= cost of radioactive waste removal and disposal during phase n of the decontamination program (\$/yr)

C_{Ln}= cost of labor to carry out tasks during phase n of the decontamination program (\$/yr)

C_{On}= cost to operate any equipment required during phase n of the decontamination program (\$/yr)

C_{Hn}= health detriment cost due to radiation exposure during phase n of the decontamination program (\$/yr)

$$C_{Hn} = H \cdot D_{Dn} \tag{3.10}$$

H= estimate of the total societal detriment attributable to radiation exposure

= 3,800 \$/person Sv

D_{Dn}= dose incurred during phase n of the decontamination operations (person Sv/yr)

$$D_{Dn} = \sum_j \int_{t_{sj}}^{t_{fj}} R_{jn}(t) C_{jn} f_{jn} dt \tag{3.11}$$

t_{sj}= time after event occurrence at which task j begins (hr)

t_{fj}= time after event occurrence at which task j is completed (hr)

R_{jn}(t)= function describing how the dose rate varies with time while carrying out task j (Sv/hr)

C_{jn}= crew size for task j (persons)

f_{jn}= frequency of carrying out task j (yr^{-1})

r= real societal discount rate

g= real escalation rate of costs (yr^{-1})

The costs for each phase of the decontamination program must be added to obtain a total cost for decontamination:

$$C_D = \sum_{n=1}^{m} C_{dn} \cdot e^{-rt_{pn}} + C_{st} \tag{3.12}$$

where

C_D= present value of the total cost of the decontamination program ($)

m= total number of phases required to complete the clean up program

C_{dn}= decontamination cost during phase n of the program ($)

t_{pn}= time after occurrence of the event at which phase n of the decontamination program begins (yrs)

C_{st}= present value of plant stabilization costs ($)

$$C_{st} = \int_0^{t_d} C_{sa} \cdot e^{-(r-g)t} dt \tag{3.13}$$

t_d= outage duration (including the repair period) (yrs)

C_{sa}= annual cost to maintain the plant in a stable condition ($/yr)

r= real societal discount rate

g= real escalation rate of costs (yr^{-1})

3.6.1.3 Plant Repair Costs

It is expected that plant repair costs will be significant in relation to replacement power costs. Plant repair costs will only be incurred if the option of decommissioning is not selected. Repair costs will be dependent on the actual extent of the damage. In this study, Burke's model [3.1] has been modified to include the replacement cost of any damaged components, the labor to replace these components and the cost of health detriment due to any worker exposure during the repair job. Labor and health detriment costs will be incurred continuously over the repair period, while materials costs occur only once (assumed at the beginning of the repair period). Since repair cannot begin until decontamination is completed, an additional factor to include the effect of discounting must be applied to obtain the present value of the plant repair costs (i.e. at the beginning of the outage). Hence, for category II events, repair costs are given by:

$$C_R = C_{MR} + \int_0^{t_R} (C_{LR} + C_{HR})\, e^{-rt} dt \cdot e^{-rt_d} \tag{3.14}$$

where

C_R= present value of repair costs (\$)

C_{MR}= cost of replacement materials or components (\$)

t_R= time to complete repair job (days)

C_{LR}= labor cost to perform repair job (\$/day)

$$C_{LR} = \sum_j C_j m_j \tag{3.15}$$

C_j= crew size for task j of the repair job (persons)

m_j= rate of worker remuneration for task j of the job (\$/person day)

C_{HR}= health detriment due to radiation exposure while performing repair job (\$/day)

$$C_{HR} = H \cdot D_R \tag{3.16}$$

H= estimate of the total societal detriment attributable to radiation exposure

= 3,800 \$/person Sv

D_R= dose incurred during plant repair (person Sv/day)

$$D_R = \sum_j \int_0^{t_j} R_j(t) C_j f_j dt \tag{3.17}$$

t_j= time required to complete task j of the repair job (hr)

R_j(t)= function describing how the dose rate varies with time while carrying out task j (Sv/hr)

C_j= crew size for task j of the repair job (persons)

f_j= frequency of task j (days^{-1})

t_d= time to perform the repair operations (yrs)

r= real societal discount rate

3.6.1.4 Worker Health Effects And Health Care Costs

As a consequence of a category II accident, there is an increased potential for worker health effects because of the radioactive material released within the plant. Accidents in this category do not result in large releases of radioactive material to the environment. Hence, any health effect costs will likely not be large. In areas of the plant where serious system failures have occurred, plant workers may also sustain injuries from causes other than radiation. However, the impact of this cost would be small in comparison to other accident costs.

Health detriment costs due to exposure of workers to radiation in post-accident operations have been included in the costs of the various activities. (If an overall value for onsite health effects costs (C_{Hi}) is required, it can be obtained by summing the health detriment costs incurred during the various activities subsequent to the accident.) Estimations of the costs of radiation exposure are based on the average cost of one case of cancer and the expected costs resulting from genetic effects in the offspring (first generation) of exposed individuals. A cautious estimate, taken from Voilleque and Pavlick [3.15], updated to current dollars is 3,800 \$/person Sv (see appendix B).

3.6.1.5 Fusion Power Industry Costs

Burke [3.1] discusses the influence of reactor accidents on the fission power industry. It is expected that similar effects may be observed in the fusion power industry subsequent to a fusion reactor accident. These costs are not included in this study, but a condensed version of Burke's discussion is given below.

Fusion reactor accidents could potentially impact policy decisions or risk perceptions, leading to the rapid shutdown, phasing out or slowed growth of the fusion power industry. Forced shutdown of all or many operating plants may possibly result from society overreacting to the event. This would effectively eliminate fusion power as an alternative for electricity generation.

The exclusion of fusion power would considerably reduce the reserve margin (total installed capacity minus the peak load), and some areas might not be able to meet load requirements. Forced shutdown would markedly decrease the reliability of electrical power supply. Furthermore, the need to replace the lost power generation capacity with power generated from non-economy sources would result in much higher cost electric power. In order to supply this replacement power, it would also be necessary for sufficient replacement capacity and interconnections to exist.

Reduced growth of the fusion industry subsequent to an accident could result from increasing opposition from society or from regulatory bodies. If consumption of electricity was on the rise at the time of the accident, and the fusion industry was not permitted to grow at a rate commensurate with this, it would then be necessary to rely on more expensive sources. This represents a real cost to society.

In addition, the value of stocks and bonds issued by a particular utility may show some devaluation after an accident. This is likely due to the uncertainty of future actions related to the industry.

3.6.1.6 Electric Utility Business Costs

Burke [3.1] also describes electric utility business costs arising from reactor accidents. Again, a similar effect subsequent to fusion reactor accidents is anticipated. These costs are not included in the present economic model, but, a brief outline of Burke's discussion follows.

Increased "business costs" to a plant licensee or electric utility include increased costs for borrowing capital and for continuing to provide adequate electricity to service areas. These costs may be a consequence of altered risk perceptions in financial markets in combination with the need for the plant licensee to replace the income once generated by the operating plant. Business costs occur in direct response to an increase in the cost of borrowing or as a result of limited access to financial markets. The increased borrowing costs orginate from altered perceptions of risk in investing in a specific utility, leading to a higher demanded return on capital. Limited access to financial markets may be a consequence of the plant licensee's loss of income. This, in turn, results in insufficient coverage of current financial commitments. The increased borrowing costs may be due to correct information provided by an accident or by mis information or falsely perceived risks. The correct or improved information regarding the accident will lead to a redistribution of benefits within society, causing the value of an investment in fusion power utilities to be altered. Misconceived information regarding fusion power risks results in true societal losses in that existing and future construction and maintenance programs may be significantly altered due to cash flow limitations.

It is difficult to assess the exact effect of the business costs resulting after an accident. The actual distribution, magnitude and specific characteristics which influence the ultimate cost need further investigation. Obviously, the electric utility industry and fusion plant licensees will be quite concerned with these potential costs since the stature of companies in financial markets may be greatly influenced. Business costs are important and should be considered in estimating the financial risk associated with a particular accident.

3.6.1.7 Onsite Litigation Costs

As discussed by Burke [3.1], severe accidents at a fission power plant may involve issues of liability and compensation. This will likely be true for fusion power plants as well. Most legal awards for damages directly resulting from the accident are transfer payments within society and do not lead to additional net societal costs. Compensation payments for "pain and suffering" do represent societal costs, but are not expected to be large.

Individuals carrying out litigation procedures must be paid a fee for their time and efforts. This does represent a cost to society. Fees demanded by lawyers are high. However, litigation costs are unlikely to be significant in comparison with other costs associated with accident.

3.6.1.8 Summary Of Onsite Economic Impacts Of Medium Consequence Fusion Reactor Accidents

The onsite consequences of medium consequence events can be estimated using the models presented in this section. The option of decommissioning after cleanup instead of plant repair is also included. Estimates can be obtained for replacement power costs, decontamination costs, plant repair or decommissioning costs and plant capital investment losses. The cost of worker health effects incurred during the accident are assumed small and are neglected, but effects incurred during subsequent operations are accounted for. Fusion power industry costs, electric utility and plant licensee business costs and onsite litigation costs are anticipated to be small from the societal perspective, but may be important to these specific groups.

3.6.2 Offsite Economic Risks From Medium Consequence Fusion Reactor Accidents

Category II events may result in releases of radioactivity to areas external to the site. It may be necessary to consider health effects costs or property damage costs. These costs may include evacuation (highly unlikely), relocation, decontamination, land interdiction, agricultural product disposal, health effects, secondary effects and litigation costs. Since it may also be necessary to include these costs when determining offsite economic risks associated with a type III event, proposed models for their evaluation are presented and discussed in section 3.7.2, which deals with category III occurrences.

3.7 Economic Risks From Large Consequence Fusion Reactor Accidents

This section presents models for assessing the economic consequences of category III fusion reactor accidents. These models have been built upon models developed for LWR accidents in previous studies [3.1, 3.16].

3.7.1 Onsite Economic Risks From Large Consequence Fusion Reactor Accidents

Onsite costs include replacement power costs, decontamination costs and health effects costs. Category III events may not allow for the option of plant repair. Early decommissioning may be the most cost effective action to undertake. A large capital investment loss may result. In addition, fusion power industry costs, electric utility costs and litigation costs will contribute to the onsite economic risk.

If permanent reactor shutdown follows a category III accident, replacement power costs will be incurred until the plant's productive capacity can be replaced (estimated at 6 years [3.10]). This cost can be calculated using equation 3.8 from section 3.6.1.1.

Decontamination costs can be calculated in the same manner as described in section 3.6.1.2. A possibly large contribution to the cleanup cost will result from working in highly radioactive environments. As well as affecting the dose incurred by workers, it is expected that task durations, and hence labor costs, will be augmented as a consequence of working in such environments. Light water fission reactor experience has revealed that each person-hour spent in a high radiation environment requires an additional 10 to 100 person-hours in preparation and in carrying out regulatory activities. It is probable, then, that decontamination costs for category III events will be somewhat greater than for category II events. The actual cleanup costs will depend, to a large degree, on the state of the facility after the accident.

Significant injuries or fatalities among workers may result from a severe accident at a power plant. Failure of the vacuum vessel and the release of activated material to the environment could significantly contaminate equipment and expose workers in many plant areas. Although the effects are potentially serious, the cost arising from health impacts will be relatively small.

Electric utitity and plant licensee business costs after severe events are important and should be included in decision making. Fusion power industry costs and onsite litigation costs to society are expected to be small. They may, however, be of importance to particular groups, especially in the case of societal overreaction.

3.7.1.1 Plant Decommissioning Costs

In severe accidents, damage may be so extensive that decommissioning is the only alternative. This results in real costs because the money for decommissioning must be outlayed earlier than anticipated. The magnitude of this cost will depend on the time during the life of the reactor at which decommissioning occurs.

Decommissioning of fusion reactors is not forseen as being too difficult an operation. Disassembly and removal of the reactor will be facilitated by the built-in maintenance capabilities of fusion reactors. This will allow for remote removal of any reactor component or structure. Since fusion plants are designed modularly, massive components can be disassembled to sizes appropriate for shipment. It is expected that most of the reactor disassembly and packaging of radioactive materials and parts can be carried out by the normal operating crew. The STARFIRE study [3.10] has indicated that this procedure could be performed in an 18 month period.

Concurrent with these activities, turbine, cryogenic and electrical systems could be dismantled. Subsequent to this, decontamination of the reactor hall, the hot cell and the tritium processing facilities would occur. These actions would require approximately twelve to sixteen months, leaving the facility in the "green grass" state.

The cost of accelerated decommissioning can be found knowing the decommissioning cost at the end of plant life. Assuming that the decommissioning cost incurred after plant decontamination will not be significantly different from the end of life cost, the cost of accelerated decommissioning as given by Burke [3.1] is:

$$C_{AD} = S\left(1 - e^{-(t_{pl}-t_D)r}\right) \tag{3.18}$$

where

C_{AD}= cost due to accelerated decommissioning ($)

S= end of life decommissioning cost (includes labor costs, health detriment costs and the cost of radioactive waste removal and disposal) ($)

t_{pl}= expected plant lifetime (yrs)

t_D= time at which decommissioning starts, measured from the start of commercial operation of the plant (yrs)

r= real societal discount rate

Implicitly accounted for in this formula is the time required for plant decontamination, which must be carried out before decommissioning can begin. The cost due to accelerated decommissioning will be greater the earlier in plant life the accident occurs. However, this cost will likely be small relative to other costs resulting from the event. Additionally, those areas of the fusion reactor most vulnerable to severe damage (e.g. first wall/blanket) are of modular design and are replaced on a regular basis. Hence, decommissioning may be avoided if the damage resulting from an accident is localized to such regions.

3.7.1.2 Capital Investment Loss

Severe reactor accidents may result in such severe plant damage that a significant capital investment loss occurs. If the entire capital investment in the plant or plant components is not recovered at the time of the accident, the unrecovered capital represents an investment loss. If the plant must be shutdown sooner than originally planned, the capital costs necessary to replace the electrical generation capacity of the plant and the cost of replacement power must be included in the net cost to society of a permanent shutdown.

The unrecovered capital cost can be calculated by first determining the depreciated value of the plant or the destroyed plant components at the time of the event which results in premature permanent shutdown. The remaining book value represents the capital investment loss. Using the sinking fund method for calculating depreciation (as recommended in reference 3.14), this loss would be given by:

$$C_{BV} = I_0 \left[1 - \left(\frac{(1+r)^{t_a} - 1}{(1+r)^{t_{pl}} - 1} \right) \right] \tag{3.19}$$

where

C_{BV}= book value of the initial investment at the time of the severe accident (\$)

I_o= initial capital investment (\$)

r= real societal discount rate

t_a= time of occurrence of the severe accident (years after initial investment)

t_{pl}= plant lifetime (yrs)

Since this represents an accelerated depreciation schedule (to allow for earlier capital depreciation tax deductions), and assuming the plant to have no salvage value, it is possible that the depreciated capital value may be zero.

The total capital cost incurred in replacing the destroyed plant or plant components should include design and construcion cost as well as materials costs. These costs should be assessed at the time of occurrence of the severe event.

If the plant must be decommissioned, the cost of replacement power will be incurred for a period of 6 years [3.10], in which time a new plant can be built to replace the generation capacity of the shutdown plant. This can be calculated as outlined in appendix C. Burke [3.1] included the cost of replacement power, which must be supplied while a new reactor is being built, as part of the capital investment loss. In this study, it was kept as a separate cost component (C_P). In this way, the possibility of double counting replacement power costs when assessing the total cost of a reactor accident is avoided. If the total capital investment loss is desired, then the cost of replacement power during the construction of new generating capacity can be added to the other capital investment loss components just discussed.

The total capital investment loss after a severe accident, not including the replacement power cost, is given by:

$$C_{CI} = C_{BV} + C_{NP} \tag{3.20}$$

where

C_{CI}= capital investment loss resulting from the severe accident (\$)

C_{BV}= book value of the initial investment at the time of the severe accident ($)

C_{NP}= capital investment of the new plant components to replace those destroyed or of the new plant built to replace the productive capacity of the shutdown plant ($)

3.7.2 Offsite Economic Risks From Large Consequence Fusion Reactor Accidents

The incorporation of safety considerations into designs at the conceptual level has been the practice of the fusion community. In this way, the environmental and safety advantages inherent in fusion may be fully realized. Because of this philosophy, offsite impacts of fusion reactor events are expected to be small.

The first wall/blanket and shield regions of a fusion reactor are major sources of radioactivity that could potentially be released during an accident and give rise to offsite impacts. The large majority of the activation products are locked into the structural material and are not intimately a part of the heat source, as in a fission reactor. Consequently, they are not foreseen to be of concern in terms of public safety, except in the very unlikely event of vaporization of the structure due to a very large energy release. Liquid lithium fires have been identified as posing a threat to first wall integrity [3.11]. Some fraction of the structural activity of a fusion device could be volatilized and released to the environment in the event of a lithium fire [3.5, 3.7, 3.12, 3.17]. However, because of the inherent features of the fire, and the oxidation rate of steel, this threat is not capable of mobilizing a significant fraction of the first wall and hence may not lead to serious public exposures [3.5, 3.11]. Furthermore, employing a less active form of lithium would eliminate this concern [3.12, 3.13]. First wall damage or melting may result subsequent to a loss-of-coolant accident. A large fraction of this material would have to somehow be released to the environment to produce any offsite health effects [3.13].

The degree of offsite impact can be minimized by decisions made at the design level. It may be possible to design a fusion reactor system which precludes volatilization and release of induced activity from containment [3.5]. Once potential safety problems have been identified, design efforts can be concentrated so as to reduce the hazard [3.13].

A major consideration in reducing the hazard is that of materials choice. Piet [3.13] has carried out an extensive safety analysis of candidate materials for the fusion reactor breeder, coolant and structural material. He has indicated that, with the appropriate choice of materials, radioactive inventories can be minimized. Other studies [3.18, 3.19] have also investigated the influence of materials selection on induced activity and have reinforced the importance of this issue to fusion reactor safety. Elemental and isotopic tailoring of materials has been indentified as an approach for further reducing activity levels in fusion reactors [3.20, 3.21, 3.22].

Fusion reactors are expected to be safer than fission reactors [3.23]. The risk of fusion reactor accidents will probably be less than that of LWRs [3.11]. It has been concluded that the consequences of an estimated maximum possible release from a properly designed fusion reactor are substantially less than the maximum LWR accident consequences [3.5, 3.24]. Thus, offsite economic impacts of fusion reactor events should be correspondingly reduced, and may even be negligible.

In this section, the models for assessing offsite economic consequences of fusion reactor accidents are presented. It is essentially a summary of Burke's work [3.1], with the incorporation of minor changes. Although offsite impacts are expected to be small or non-existant, the necessary models for their assessment have been included for the sake of completeness.

3.7.2.1 Discussion Of Terms And Model Application

With a type III reactor event, a large release of radioactivity to the environment may have occurred. Consequently, offsite accident costs are generally associated with population protective measures. These costs include radiation-induced human health effects, land and property decontamination, agricultural product disposal, population evacuation, temporary or permanent relocation, and land condemnation (or interdiction). Other economic impacts include litigation costs and secondary economic effects which occur outside directly contaminated areas.

It is necessary to clarify terms used to describe offsite emergency responses to reactor accidents. These definitions are taken from Burke's study [3.1], and are similar to those used in the Reactor Safety Study [3.16]. "Decontamination" concerns the process of cleanup and restoration of land in an affected area by reducing dose rates through the implementation of techniques which remove surface deposited radionuclides. "Agricultural product disposal" costs arise from the disposal of crops which have become contaminated. These disposal costs will continue to contribute to the total economic risk until projected population doses from ingestion are acceptable. "Evacuation" describes the immediate movement of a population out of an area. It may be implemented before any radioactive release, as a precautionary measure. "Temporary relocation" refers to the movement of individuals from an area which has been classified as unsafe subsequent to the release of radioactive materials, based on measured levels of radiation. "Permanent relocation" costs include lost income, productivity and moving costs incurred while a population is relocating from a region which has been acclaimed condemned. The prohibition of inhabitation or use of an area of land for any extended period of time, as a means of long term exposure reduction is known as "land interdiction".

Burke [3.1] has developed an offsite cost model for estimating the economic consequences of protective actions and radiation-induced health effects after severe

LWR accidents. Although the radionuclides will be different for fusion reactors, the acute offsite doses could approach those associated with the most hazardous fission products released in severe fission reactor accidents [3.7]. Therefore, a similar approach to population protective measures could be envisioned for fusion reactor accidents.

Acute doses are incurred within a short time span after the radioactive material has been released to the environment. Exposure pathways include groundshine, cloudshine and inhalation of radionuclides which may be deposited by or contained in a cloud of radioactive material passing by an area. Sheltering, possibly followed by short term relocation or evacuation (not a likely choice for fusion) are effective measures in reducing acute exposures.

Chronic doses occur over longer periods of time. This may result from groundshine exposure or from contaminated milk or food ingestion. Land decontamination and agricultural product disposal may avoid doses being incurred via this pathway.

Modelling of offsite protective measure implementation for severe LWR events has been performed by Burke [3.1]. Although the radionuclides involved will be different, a similar analysis is applicable to fusion reactor accidents.

Evacuation of individuals may begin after the start of an accident sequence, but before any release of radioactive material to the environment. If a release takes place, teams will begin collecting dose rate information from surface-deposited nuclides in affected areas. This activity will begin within hours of a significant radioactive release. This period, as described by Burke [3.1], is known as the "emergency phase". If projected long term individual doses during this time exceed a pre-established criterion, temporary relocation of individuals, in addition to those already evacuated will ensue. Evacuation will probably not be a necessary consideration for fusion.

As more information is collected, doses in affected areas may decrease below dose limits and the return of evacuees would follow. Dose rates in other areas may still prohibit re-entry. This time period, in which more dose rate information is obtained has been defined as the "intermediate phase". Monitoring of milk and crops will also take place at this time to assess the need for agricultural product disposal.

After dose rates in affected areas have been accurately assessed, a long term dose to individuals from surface deposited nuclides can be projected. Areas requiring decontamination or interdiction can be determined. If decontamination operations in a particular area will be unsuccessful at reducing dose rates to acceptable levels, this area should be condemned. If decontamination efforts are expected to be successful, costs will be incurred from the actual decontamination operations, from doses to workers and from relocating the population.

The staged implementation of protective measures is considered to be a realistic scheme to follow in the post accident time period. The duration of specific protective measures is consistent with the expected variation of dose rates with time after the accident. It should be noted that certain stages of this process may not be necessary (e.g. evacuation).

3.7.2.2 Discussion Of The Offsite Economic Models

The appropriate models for assessing the offsite economic consequences of severe fusion reactor events are summarized in table 3.5. Details of the model development, as applied to LWRs, can be found in Burke's dissertation [3.1]. In this section, key aspects of the model are highlighted and the adaptations either to improve the model or to make it more appropriate for fusion applications are discussed.

3.7.2.2.1 Health Effects And Health Care Costs

The occurrence of a category III accident at a fusion power plant may result in exposing the public and offsite decontamination workers to radioactive materials. As a result, a cost will be incurred due to medical treatment for health effects and lost income during illness and after death of individuals. The cost of radiation induced health effects to the public can be estimated using equation 3.21. This estimate represents purely economic costs and does not include any reflection of individual preferences for avoidance of pain, suffering or anguish. Decontamination worker health effects costs are given by equation 3.22. If an overall value for offsite health effects costs (C_{H_o}) is required, it can be obtained by summing the public and offsite decontamination worker health effects costs.

3.7.2.2.2 Land And Property Decontamination Costs

Burke [3.1] discusses decontamination cost estimates, obtained from a detailed review of decontamination costs and effectiveness performed at Sandia National Laboratory (SNL). The cost of the decontamination program is found to depend on the level of the decontamination effort. Estimates can be obtained for either farmland or residential, business and public property. The effectiveness of decontamination techniques are dependent on the specific radionuclides, particle sizes and the chemical forms of the deposited materials.

Decontamination costs in farm areas can be estimated based on low and high level efforts. Low level effort costs can be predicted from the costs to plow grassland and cropland areas and reseed all grassland areas. High level efforts involve costs for deep ploughing of grassland, and scraping and burial of cropland (in order not to degrade the quality of the cropland surface soil). Table 3.2 displays farmland decontamination costs and effectiveness values. Three levels of effort are given, each

Table 3.2: Decontamination Cost and Effectiveness Values for Farm Areas [3.1]

Dose Rate Reduction Factor After Decontamination (f)	Approximate Costs (\$/acre) (DF_f)	Fraction of Cost for Paid Labor (FL_f)	Worker Dose Reduction Fraction (Estimated Worker Dose/Dose From Continuous Exposure) (WF_f)
3	160	0.30	0.10
15	440	0.35	0.25
20	480	0.35	0.33

Table 3.3: Decontamination Cost and Effectiveness Values for Non-farm Areas [3.1]

Dose Rate Reduction Factor After Decontamination (f)	Approximate Costs ($/person) ($DR_f$)	Fraction of Cost for Paid Labor (RL_f)	Worker Dose Reduction Factor (Estimated Worker Dose/Dose From Continuous Exposure) (WR_f)
3	2600	0.7	0.33
15	6900	0 .5	0.33
20	7400	0.5	0.33

having a specific decontamination effectiveness (i.e. dose rate reduction factor), cost estimate, labor cost fraction and worker dose reduction factor (ratio of estimated worker dose to the total dose from constant exposure to surface deposited radionuclides during the decontamination period). The worker dose reduction factor is estimated based on shielding which may be furnished by tractors and other heavy equipment used in farmland decontamination operations.

Non-farmland decontamination costs have been estimated on a per capita basis. The Reactor Safety Study (RSS) economic consequence model, as well as the SNL review, has taken this approach. Estimates obtained on a per capita basis are appropriate since it is expected that tangible assets in an area are roughly proportional to the population in the area and decontamination costs are expected to be proportional to the tangible assets in an area requiring cleanup. More detailed cost analyses would be difficult due to the large uncertainties in reactor accident radionuclide release processes, atmospheric transport and deposition, decontamination effectiveness and actual decontamination costs. Table 3.3 presents non-farm area decontamination costs and effectiveness factors. The decontamination cost estimates have been weighted using national average statistics to account for the many different methods possible for decontamination of residential, commercial, industrial and public land use areas. Each level of decontamination effort will employ a combination of different techniques.

To estimate the total cost of a decontamination program in an area, farm costs, for the appropriate decontamination factor, must be weighted by the affected farm acreage, and non-farm costs, for the appropriate decontamination factor, must be weighted by the affected population. The total cost is given by equation 3.23. A labor cost component is included and can be calculated using equation 3.24. Estimated paid labor fractions for farm and non-farm areas are given in tables 3.2 and 3.3. These values have been obtained from studies carried out at SNL which are discussed by Burke [3.1].

Since it is anticipated that cleanup efforts would begin as quickly as possible after the accident has occurred, decontamination costs are not discounted. Delaying decontamination operations may appear beneficial, since this would allow for the decay and weathering of radionuclides. However, migration of these species and fixation onto surfaces would lead to more difficult and costly procedures.

Doses incurred by workers during a decontamination endeavor can be found. Burke [3.1] estimates the total person-years of effort for the decontamination program using equation 3.25. Knowing the total person years of effort, the number of decontamination workers required to complete the program within a specified amount of time can be found using equation 3.26. To evaluate the doses incurred by workers during the decontamination program, the time spent in contaminated areas and possible shielding effects of equipment, should be accounted for. The total dose incurred is given by equation 3.27.

Worker doses in farm areas are expected to be slightly reduced from non-farm areas for the same level of contamination (see tables 3.2 and 3.3) because the machinery used in cleanup adds distance and provides shielding between radioactive materials and workers. Worker protective measures would ensure that beta doses from radionuclides deposited directly on the skin and from inhalation of resuspended radionuclides are eliminated. In non-farm areas, no dose reduction is afforded by machinery shielding since most of the decontamination effort will be carried out manually. The dose ratios for workers in non farm areas are estimated assuming eight hours of work per day, beginning each day in an area yet to be decontaminated.

If acceptable dose rates are not maintained during decontamination operations, temporary relocation of the population in certain areas may be warranted. The cost of relocating the population is described by equation 3.28.

Although costs of the decontamination effort have only been discussed here, it must also be recognized that a large scale decontamination effort may stimulate the economy somewhat. This would occur as a result of increased activity in certain industrial sectors due to the labor, building materials and equipment needs of the effort.

3.7.2.2.3 Agricultural Disposal Costs

Crop contamination after a severe fusion reactor accident could result by either direct deposition of radionuclides on the crops or by incorporation into the vegetation by absorption from the soil. Hence, an individual may be exposed by directly eating contaminated crops. In order to avoid consuming contaminated goods, affected crops must be disposed of. Cost estimates for these procedures are based on the Reactor Safety Study [3.16], as presented by Burke [3.1].

If radionuclides are deposited on crops during the growing season, it will be necessary to dispose of the harvest. It is expected that crops will be disposed of in all areas requiring long term protective actions. If the accident occurs outside the growing season, it will be unnecessary to dispose of any crops. The crop disposal cost can be estimated using equation 3.29.

3.7.2.2.4 Population Evacuation Costs

Immediate evacuation costs, as given by equation 3.30 in table 3.5, include the cost, per individual, of food, housing and transportation, using either commercial or mass care facilities. The cost to supply supervising personnel for the evacuation process has also been considered. Hans and Sell [3.25] have estimated these evacuation costs. Upated values are given in table 3.4. Military pay indexes have been used to estimate the cost to supply evacuation supervisory personnel. It is assumed that 80 % of the evacuated population use commercial care facilities (restaurants, motels and private vehicles) and 20 % use mass care facilities [3.16]. These assumptions lead to an average daily evacuation cost per individual of approximately \$24.60.

Lost personal and corporate income during the evacuation period should be included in the evacuation costs. This cost component accounts for lost wages of(it does not include interest, dividends or transfer payments) and corporate income and profits during the evacuation period. Variations in regional incomes can be accounted for. The national average personal income (excluding dividends, interest and transfer payments) plus corporate profits and interest has been estimated as \$27 per person day [3.16, 3.25].

Short duration evacuation periods (one to three days) may not involve costs for lost income and productivity. This is possible if the economy is sufficiently flexible so that lost productivity, wages and profits can be largely recovered through increased activity after the evacuation period terminates.

It has been shown that a large fraction of the first wall would have to reach the public in order for health effects to result, and an even larger fraction would have to reach the public in order for evacuation to be justified [3.13, 3.26]. The likelihood of such a threat existing is not great. Thus, evacuation will likely never be required.

Table 3.4: Costs of Evacuation per Evacuee Day [3.25]

Commercial Care Facililties:

Lodging	$17.75
Food	$5.40
Transportation (private)	$2.45
	$25.60/evacuee day

Mass Care Facilities:

Lodging	$7.25
Food	$3.80
Transportation (mass)	$1.35
	$12.40/evacuee day

Evacuation Personnel (2 % of total number of evacuees)

Compensation	$60.00/day
Food, Lodging and Transportation	Same as evacuees

Total weighted Cost (E) (Based on 80 % commercial care, 20 % mass care facilties):

$24.60/evacuee day

3.7.2.2.5 Emergency Phase Relocation Costs

The emergency phase relocation time period includes the time required for measurement of groundshine doses, the time to compare these doses to the safe level criterion and the time required to temporarily relocate the population in areas where levels are unacceptable. If these individuals have already been evacuated, before any release of material, it would only be necessary to extend the duration of their stay outside the area. Emergency phase relocation costs include food, lodging, transportation and income losses, as given by equation 3.31 in table 3.5. It should be noted that wage and income losses may be recoverable for short duration emergency phase relocation periods.

3.7.2.2.6 Intermediate Phase Relocation Costs

The intermediate phase relocation time period includes the time required for obtaining more detailed dose rate information, the time to make decisions on whether or not long term protective actions are necessary and the time needed for the relocated population to return to safe areas. Intermediate phase relocation costs are estimated in a similar fashion to emergency phase relocation costs, using equation 3.32. The intermediate phase relocation period is assumed not to overlap with the emergency phase relocation ($t_{1IP} > t_{2EP}$). It is likely that by the time the intermediate phase relocation has been implemented, the duration of the temporary relocation will have been long enough to result in income losses.

3.7.2.2.7 Land Interdiction Costs

In some areas, decontamination by the maximum achievable factor may not be sufficient to reduce individual doses to acceptable levels. If this is the case, land interdiction must be implemented as a population protective measure. Permanent relocation of the population originally inhabiting the area of concern will be carried out. It is possible that after decay, weathering and future decontamination efforts, the population would return to the affected area. Discounting must be utilized in the estimation of land interdiction costs, since costs may be incurred over a considerable length of time. Also, the fact that some portion of the initial value of the property may be recovered if the area can be used in the future must be accounted for.

The cost of land interdiction can be estimated using Burke's approach [3.1], which deals with the concept of wealth. Wealth is comprised of the total present value of land and other natural resources, tangible assets, inventory stocks and the societal productivity of an area. Further details concerning this concept are found in Burke's discussion, as well as in references 3.27 and 3.28.

The wealth contained in farm areas can be estimated using equation 3.33. Market values for farmland and structures can be obtained using the 1978 census of agriculture [3.29], updated to the current year.

The total tangible wealth in a residential, business or public area can be obtained from average national wealth estimates. Since wealth is an indication of income producing capacity, the national average should be weighted by region-specific personal income statistics to obtain the appropriate value for the tangible wealth of an affected region. This would account for areas with higher incomes having more tangible wealth amd more potential for creating wealth than areas with lower incomes. The wealth contained in residential, business and public properties is given by equation 3.34.

Since the period of interdiction may be lengthy, estimates of wealth must account for depreciation. Buildings and structures in an interdicted area would depreciate at a more rapid rate than the land due to lack of upkeep [3.16]. However, it is likely that some portion of the initial value of the property will be recovered at the termination of the interdiction period. Burke [3.1] assesses the cost of land interdiction in an area by subtracting this reclaimed value from the initial present value of the region's wealth, as indicated in equation 3.35.

The duration of land interdiction is dependent on the time required for radioactive decay, weathering and decontamination efforts to reduce the integrated long term population dose to an acceptable level. Beyond 30 years of interdiction, the entire wealth of a region is assumed to be lost.

3.7.2.2.8 Secondary Impacts

Burke [3.1] describes possible secondary impacts of fission reactor accidents. It is probable that similar effects will occur subsequent to a fusion reactor accident. These effects are highlighted below.

Population protective measures could result in secondary costs or ripple effects. These effects are expected to be small relative to the direct costs of the protective measures. It is likely that these costs would be further reduced due to the flexibility in the economy, which has been observed subsequent to most disasters [3.1].

These effects include an increase in the price of affected crops or dairy products, land devaluation or increased labor costs due to population emigration. This last item would directly affect a region's productivity. The magnitude of the impact depends on the actual size of the area being analyzed. In addition, a societal cost in one region may be balanced by a benefit in another region, resulting in a small net cost to society.

One further secondary impact following a reactor shutdown is an increase in the cost of electricity in the affected region. This may be transmitted through the economy affecting prices, employment, incomes and productivity in a region. The net societal effects are again expected to be small, due to a cancellation of costs and benefits in different regions.

These impacts have not been included in this study. Since the costs are expected to be small, it was felt unnecessary to pursue the level of detail required to estimate the secondary risks.

3.7.2.2.9 Offsite Litigation Costs

Since the population in the immediate vicinity of the fusion plant has been unwillingly exposed to radiation, it is expected that some degree of compensation will be sought. This will result in litigation costs. The cost of the litigation process will likely be large for individual parties, but the cost to society will likely be small. Hence, these costs were not included in this study.

Table 3.5: Summary of Offsite Cost Components

Public Health Effects[m]:

$$C_{HP} = H \cdot D_{pop} \tag{3.21}$$

Decontamination Worker Health Effects[m]:

$$C_{HW} = H \cdot D_{DW} \tag{3.22}$$

Decontamination Program[1]:

$$C_d = (F_f \cdot A \cdot DF_f) + (P_d \cdot DR_f) + C_{dl} \tag{3.23}$$

Decontamination Labor[1]:

$$C_{dl} = (F_f \cdot A \cdot DF_f \cdot FL_f) + (P_d \cdot DR_f \cdot RL_f) \tag{3.24}$$

Decontamination Program Completion Time[1]:

$$T_{my} = \left(\frac{C_{dl}}{C_{al}}\right) \tag{3.25}$$

Number of Decontamination Workers[1]:

$$N_w = \left(\frac{T_{my}}{t_D}\right) \tag{3.26}$$

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[m] modified form of Burke's model

[1] taken directly Burke's work [3.1]

Decontamination Worker Dose[1]:

$$D_{DW} = \left(\frac{D_c}{C_{al} \cdot t_D} \right) \left[(F_f \cdot A \cdot DF_f \cdot FL_f \cdot WF_f) + (P_d \cdot DR_f \cdot RL_f \cdot WR_f) \right] \tag{3.27}$$

Population Relocation During Decontamination[1]:

$$C_r = P_r \left(E + I \cdot R_{ri} \right) t_D \cdot 365 \tag{3.28}$$

Crop Disposal[m]:

$$C_{cd} = F_f \cdot A \cdot F_P \cdot f_c \cdot Z \tag{3.29}$$

Population Evacuation[1]:

$$C_E = P_E \cdot t_E \left(E + I \cdot R_{ri} \right) \tag{3.30}$$

Emergency Phase Relocation[m]:

$$C_{EP} = \left[P_E \left(t_{2EP} - t_E \right) + P_{EP} \left(t_{2EP} - t_{1EP} \right) \right] \left(E + I \cdot R_{ri} \right) \tag{3.31}$$

Intermediate Phase Relocation[1]:

$$C_{IP} = P_{IP} \left(t_{2IP} - t_{1IP} \right) \left(E + I \cdot R_{ri} \right) \tag{3.32}$$

Farm Area Wealth[1]:

$$W_f = F_f \cdot A \cdot F_v \cdot RV_f \tag{3.33}$$

Residential, Business and Public Property Wealth[1]:

$$W_r = P_i \cdot R_v \cdot RV_r \tag{3.34}$$

Land Interdiction[1]:

$$\begin{aligned} C_I = (W_f + W_r) - e^{-rt_I}\Big\{&W_f\left[(1.0 - I_f) + I_f\,(1.0 - s)\right] \\ &+W_r\left[(1.0 - I_r) + I_r\,(1.0 - s)\right]\Big\} \end{aligned} \tag{3.35}$$

$$s = \left(\frac{e^{rt_I} - 1}{e^{rk} - 1}\right) \tag{3.36}$$

List of Variables for Table 3.5:

C_E= cost of evacuation (\$)

P_E= size of initially evacuated population (persons)

t_E= duration of the evacuation (days)

E= cost of food, lodging and transportation for each evacuee (\$/person day)

I= national average per capita and corporate income (\$/person day)

R_{ri}= ratio of region specific to national average personal incomes

C_{EP}= emergency phase population relocation cost(\$)

t_{1EP}= time at the start of the emergency phase relocation in areas where no evacuation has occurred (days from the accident occurrence)

t_{2EP}= time at the end of the emergency phase relocation (days from the accident occurrence)

P_{EP}= number of persons which must be relocated in addition to those previously evacuated (persons)

C_{IP}= intermediate phase relocation cost (\$)

P_{IP}= size of affected population during the intermediate phase (persons)

t_{1IP}= time at the start of the intermediate phase relocation (days from the accident occurrence)

t_{2IP}= time at the end of the intermediate phase relocation (days from the accident occurrence)

C_d= cost of the decontamination program (\$)

F_f= fraction of the region which is farmland

A= total area to be decontaminated (acres)

DF_f= cost to decontaminate farmland by a factor of f (\$/acre)

P_d= population of area affected by the decontamination program (persons)

DR_f= cost to decontaminate residential, business and public property by a factor of f (\$/person)

C_{dl}= labor cost for the decontamination program (\$)

FL_f= fraction of the farm decontamination cost, for the appropriate decontamination factor, which is estimated to be paid labor

RL_f= fraction of the residential, business and public property decontamination cost, for the appropriate decontamination factor, which is estimated to be paid labor

T_{my}= total person-years of effort required to decontaminate an area (person yr)

C_{al}= average cost of decontamination labor (\$/person yr)

N_w= number of decontamination workers required to complete the program within a specified amount of time (persons)

t_D= specified amount of time to complete the decontamination effort (yrs)

D_{DW}= total dose incurred by the decontamination workers due to exposure to surface deposited radionuclides (person Sv)

D_c= dose which would be incurred by an individual from constant exposure to surface deposited radionuclides for the entire decontamination period (Sv)

$WF_f =$ ratio of decontamination worker dose, for an appropriate level of decontamination effort, in farm areas, to the dose which would be incurred by an individual from constant exposure during the decontamination period

$WR_f =$ ratio of decontamination worker dose, for an appropriate level of decontamination effort, in residential, business and public areas, to the dose which would be incurred by an individual from constant exposure during the decontamination period

$C_r =$ cost of relocating a population from an area during the decontamination period (\$)

$P_r =$ size of population to be relocated during decontamination operations (persons)

$W_f =$ total farm wealth (prior to reactor accident) in an area from farmland and associated structures (\$)

$F_v =$ average national market value of farmland and structures in the area (\$/acre)

$RV_f =$ ratio of region specific to national average market value of farmland and structures in the area

$W_r =$ total residential, business and public wealth in an area (prior to reactor accident) (\$)

$P_i =$ total number of persons affected by the reactor accident (persons)

$R_v =$ average national per capita tangible wealth (farmland and structures) in the area (\$/person)

$RV_r =$ ratio of region specific to nation average personal incomes in the area

$C_I =$ present value of the total cost due to land interdiction (\$)

$I_f =$ fraction of farm wealth in improvements in the affected area

I_r= fraction of non-farm wealth in improvements in the affected area

t_I= duration of the interdiction period (yrs)

s= sinking fund depreciation factor

k= useful life of depreciating assets (yrs)

C_{cd}= cost of crop disposal ($)

F_P= average annual farm production (sales) for the area ($/acre)

f_c= fraction of farm sales from crops

Z= seasonal factor

= 1.0 during growing season

= 0.0 outside growing season

C_{HP}= total health effects cost due to exposure of the public to radiation ($)

H= estimate of the total societal detriment due to radiation exposure

= 3,800 $/person Sv

D_{pop}= projected long term dose to the affected population (person Sv)

C_{HW}= total health effects cost due to exposure of offsite decontamination workers ($)

3.8 Assessing The Cost Effectiveness Of An Accident Consequence Mitigation Action

With all cost components defined, the total cost of implementing a particular accident consequence mitigation measure can be evaluated. Before the cost effectiveness can be determined, the resulting dose reduction must be known, and is given by:

$$D_{aT} = \Delta D_D + \Delta D_R + \Delta D_{AD} + \Delta D_{DW} + D_{ap} \tag{3.38}$$

where

$D_{aT}=$ total dose savings during a given accident scenario when an accident consequence mitigation proposal has been implemented (person Sv)

$\Delta D_D=$ change in the dose incurred during onsite plant decontamination procedures (person Sv)

$\Delta D_R=$ change in the dose incurred during plant repair procedures (person Sv)

$\Delta D_{AD}=$ change in the dose incurred during accelerated decommissioning operations (person Sv)

$\Delta D_{DW}=$ change in the total dose incurred by decontamination workers at offsite locations (person Sv)

$D_{ap}=$ public dose savings (difference in D_{pop} with and without the use of an accident consequence reduction action) (person Sv)

It should be noted that some of the contributions to the total dose may not be relevant to certain accident scenarios (e.g. D_{ap} and ΔD_{DW} result from offsite considerations). Also, D_{ao} referred to in section 3.3, would consist of all contributions to worker exposure (i.e. $\Delta D_D, \Delta D_R, \Delta D_{AD}$ and ΔD_{DW}).

Knowing this, a value for β_a can be computed (see equation 3.4). This can then be compared to α'_a. If several alternatives are being compared, the alternative having the minimum value of β_a should be selected, as long as it is less than α'_a.

3.9 References

(3.1) R.P Burke, Economic Risks of Nuclear Power Reactor Accidents, Doctoral Thesis, Department of Nuclear Engineering, Massachusetts Institute of Technology, October 1983.

(3.2) J. Powell, Aspects of Safety and Reliability for Fusion Magnet Systems, First Annual Report, Brookhaven National Laboratory, BNL-50542, January 1976.

(3.3) F. Arendt and P. Komarek, Potential Failures and Hazards in Superconducting Magnet Systems for Fusion Reactors, Nuclear Technology/Fusion, 1, p. 552, October 1981.

(3.4) J.B. Cannon, Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy, Oak Ridge National Laboratory, DOE/ER-0170, August 1983.

(3.5) M.S. Kazimi and R.W. Sawdye, Radiological Aspects of Fusion Reactor Safety: Risk Constraints in Severe Accidents, Journal of Fusion Energy, 1, No. 1, p. 87, 1981.

(3.6) W.E. Kastenberg and D. Okrent, Some Safety Considerations for Conceptual Tokamak Fusion Power Reactors, Prepared at the University of California, Los Angeles, for the Electric Power Research Institute, EPRI-546, July 1978.

(3.7) J.P. Holdren, Contribution of Activation Products to Fusion Accident Risk: PartI. A Preliminary Investigation, Nuclear Technology/Fusion, 1, p. 79 January 1981.

(3.8) E. Karaian, M.I.T. Nuclear Reactor, private communication, December 1984.

(3.9) United States Nuclear Regulatory Commission Rules and Regulations, 10CFR20, May 1984.

(3.10) C.C. Baker et al., STARFIRE - A Commercial Fusion Tokamak Power Plant Study, Argonne National Laboratory, ANL/FPP-80-1, 1980.

(3.11) M.S. Kazimi, Risk Considerations for Fusion Energy, Nuclear Technology/Fusion, 4, p. 527, September 1983.

(3.12) J.G. Crocker and D.F. Holland, Safety and Environmnetal Issues of Fusion Reactors, Proceedings of the IEEE, 69, No. 8, August 1981.

(3.13) S.J. Piet, Potential Consequences of Tokamak Reactor Accidents: The Materials Impact, Doctoral Thesis, Department of Nuclear Engineering, M.I.T., May 1982.

(3.14) S.C. Schulte et al., Fusion Reactor Design Studies - Standard Accounts for Cost Estimates, Pacific Northwest Laboratory, PNL-2648, May 1978.

(3.15) P.G. Voilleque and R.A. Pavlick, Societal Cost of Radiation Exposure, Health Physics, 43, No. 3, p. 405, 1982.

(3.16) United States Nuclear Regulatory Commission, Appendix VI to the Reactor Safety Study: Calculation of Reactor Accident Consequences, WASH-1400 (NUREG 075/14), October 1975.

(3.17) J.P. Holdren and S. Fetter, Contribution of Activation Products to Fusion Accident Risk: Part II. Effects of Alternative Materials and Designs, Nuclear Technology/Fusion, 4, p. 599, November 1983.

(3.18) J.A. Blink and G.P. Lasche, The Influence of Steel Type on the Activation and Decay of Fusion Reactor First Walls, Nuclear Technology/Fusion, 4, p. 1146, September 1983.

(3.19) M.Z. Youssef and R.W. Conn, Induced Radioactivity and the Influence of Materials Selection in Deuterium-Deuterium and Deuterium-Tritium Fusion Reactors, Nuclear Technology/Fusion, 3, p. 361, May 1983.

(3.20) R.W. Conn and A.W. Johnson, Minimizing Radioactivity and Other Features of Elemental and Isotopic Tailoring of Materials for Fusion Reactors, Nuclear Technology, 41, p. 389, December 1978.

(3.21) J.D. Gordon, J.J. Thompson and S.N. Suchard, Isotopically Tailored HT-9 Steel for Radioactive Waste Management, TRW, 1983

(3.22) M.Z. Youssef and R.W. Conn, On Isotopic Tailoring for Fusion Reactor Radioactivity Reduction, Nuclear Technology/Fusion, 4, p. 1177, September 1983.

(3.23) M. Stiefel, Accident Analysis/ Social Acceptance, Fusion Safety Library of M.S. Kazimi.

(3.24) M.S. Kazimi, Safety Methodology and Risk Targets, Proceedings of a Workshop Organized by the IAEA, p. 65, Vienna Austria, March 1981.

(3.25) J.A. Hans Jr. and T.C. Sell, Evacuation Risks: An Evaluation, Office of Radiation Programs, United States Environmental Protection Agency, EPA-520/6-74 002, 1974.

(3.26) S.J. Piet, EG & G Idaho, Inc., private communication by letter, January 1985.

(3.27) J.W. Kendrick, The Formation and Stocks of Total Capital, National Bureau of Economic Research, No. 100, General Series, Columbia University Press, New York, 1976.

(3.28) J.W. Kendrick, K.S. Lee, and J. Lomask, The National Wealth of the United States: By Major Sectors and Industry, A Research Report from the Conference Board's Division of Economic Research, Conference Board Report No. 698, New York, 1976.

(3.29) United States Department of Commerce, Bureau of the Census, 1978 Census of Agriculture, Washington D.C., 1978.

(3.30) N.X. Hartunian, C.N. Smart and M.S. Thompson, The Incidence and Economic Costs of Cancer, Motor Vehicle Injuries, Coronary Heart Desease and Stroke: A Comparative Analysis, American Journal of Public Health, 70, p. 1249, 1980.

(3.31) T. Straume and R.L. Dobson, Leukemia and Cancer Risk Estimates from Recalculated Hiroshima and Nagasaki Doses, Proceedings of the 26th Annual Meeting of the Health Physics Society, Louisville Kentucky, 1981.

(3.32) International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Oxford, Pergammon Press, 1977.

(3.33) Economic Report of the President to Congress, Washington D.C., February, 1984.

(3.34) United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States: 1984, 104th edition, Washington D.C., 1984.

(3.35) D.R. Strip, Estimates of the Financial Consequences of Nuclear Power Reactor Accidents, Sandia National Laboratory, NUREG/CR-2723 (SANDIA82-1110), September 1982.

(3.36) J.V. Cartwright, R.M. Beemiller, E.A. Trott Jr. and J.M. Younger, Estimating the Potential Impacts of a Nuclear Reactor Accident: Methodology and Case Studies, Washington D.C., NUREG/CR-2591, April 1982.

(3.37) D.W. Rasmussen and C.T. Haworth, Economics: Principles and Applications, Science Research Associates Incorporated, Chicago, 1979.

(3.38) E. Mansfield, Economics: Principles, Problems, Decisions, 4th Edition, W.W. Norton and Company, New York, 1983.

(3.39) J.A. White, M.H. Agee and K.E. Case, Principles of Engineering Economic Analysis, John Wiley and Sons, Inc., 1977.

Chapter 4

Assessment Of The Cost Effectiveness Of The Low Activation STARFIRE Design

The use of low activation materials, including graphite, silicon carbide and aluminum alloys, for the structural components of fusion reactors has been proposed to reduce the problems and hazards associated with activation. Some effort has been given to a design study for a low activation tokamak fusion reactor based on the STARFIRE design [4.1]. In this section, the costs associated with changing to the low activation STARFIRE design from the reference design are estimated. The methodology developed in Chapter 2 is then applied to assess the cost effectiveness of the design change.

4.1 Description Of The Reference STARFIRE Design

The STARFIRE study was a comprehensive conceptual design of a 1200 MWe fusion power plant in which the tokamak reactor and all subsystems were described. The objective was to produce a safe, economically attractive design, having minimal environmental impact. The design was developed assuming STARFIRE was the tenth commercial plant constructed from a standardized design.

It was the intent of the STARFIRE project to give particular attention to enhancing reactor maintainability and improving plant availability. Remote maintenance of all equipment within the reactor building was accounted for. However, personnel entry into the reactor building is also possible. A plant availability of 75 % was the design goal. This was estimated as a realistic objective on the basis of a maintainable design and a first wall life of at least six years. Some features aimed at improving reactor maintainability and increasing plant availability include steady-state operation with current drive, optimized modular design and a limiter/vacuum system for impurity control and exhaust.

A major effort was devoted to safety and environmental considerations for STARFIRE. A solid tritium breeder, $LiAlO_2$, was selected. A particular safety advantage of this choice is its chemical stability. The tritium bred in this solid breeding material will be extracted and the new fuel will be introduced to the plasma chamber by gas puffing through two gas ports. Safety and environmental considerations are evident in the limiter/vacuum system which was designed to maximize tritium burnup and to minimize the vulnerable tritium inventory in the fueling and pumping systems. Provision of adequate shielding in addition to the remote maintenance capabilities will minimize radiation exposure of personnel. An additional safety feature is the beryllium coating on the first wall and limiter which will provide an inherent plasma shutdown mechanism in the event that the metal surface exceeds 900 °C.

Pressurized water was selected as the coolant. Important aspects associated with this choice include acceptable neutronics performance, accommodation of first wall heat fluxes and minimal recirculating power. The steam cycle and conventional materials used in the STARFIRE heat transport and energy conversion system make it a state of-the-art technology.

The stuctural material selected for STARFIRE was PCA (Prime Candidate Alloy), a titanium modified austenitic stainless steel. Principal advantages of this material include low swelling and high irradiated ductility. A major disadvantage of employing PCA is the high induced activity which results subsequent to reactor operation.

The STARFIRE blanket is divided into large sectors to allow for replacement with a minimum number of maintenance actions. Twenty-four toroidal sectors of two different sizes will be used, permitting installation between adjacent toroidal field coils. Simplification of the overall blanket installation was accomplished by mounting the limiter, rf duct and ECRH duct on the sector for removal as a unit. The limiter consists of 96 elements forming a nearly continuous toroidal ring at the outer midplane of the blanket. Four limiter elements will be mounted on each blanket sector in front of a slot through the blanket which provides a pathway for the particles leaving the chamber. Twelve rf ducts and twenty-four ECRH ducts will be mounted on each blanket sector, between toroidal field coils.

The magnet systems are required to confine the plasma as well as provide a stable equilibrium configuration and some current initiation. All magnets, except for a few control coils carrying small currents, will be superconducting. The toroidal field (TF) and poloidal field (PF) coils will consist of a copper stabilizer and NbTi superconductor, except for the inner turns of the TF coils which will require Nb_3Sn as the superconductor to provide fields in excess of 9 T. In order to maintain the coils in the superconducting range, they will be bath-cooled by pool boiling liquid helium at 4.2 K. Each conductor will be contained within a stainless steel structure.

The preceeding discussion has highlighted some features of the reference STARFIRE design. Further details can be found in the STARFIRE design report [4.2].

4.2 Description Of The Low Activation STARFIRE Design

The advantages of using low activation materials to overcome the problems associated with activated structures have been identified. For the low activation STARFIRE design, radioactive inventories have been projected to be reduced by a factor of one million within a short time after shutdown. This will relieve safety concerns arising from the need to contain large quantities of radioactive material. Post shutdown radiation fields will be correspondingly reduced, allowing direct personnel access to most regions of the plant. Problems associated with decay heat, leading to meltdown situations, will essentially be eliminated. In addition, it will be possible to store radioactive waste materials in surface facilities, avoiding many potential waste disposal problems.

An investigation has been undertaken in which the nuclear design aspects of using materials such as silicon carbide and aluminum alloys for fusion reactor first wall, blanket and shield applications was explored [4.3]. A design study was carried out for a low activation tokamak fusion reactor based on STARFIRE [4.1]. A fusion reactor design was developed in which low activation materials were substituted for the major components of the first wall, blanket, limiter, shield and toroidal field coils. The major features of the reference STARFIRE design were not changed and the basic plasma parameters and functional requirements of STARFIRE were retained in the low activation design. However, detailed component designs were altered to best utilize the properties of the low activation materials.

The first wall will consist of a simple helium cooled SiC tube-bank which will be independently mounted from the blanket module. For an inlet temperature of 400 °C, an exit coolant temperature of 500 °C will be achievable without exceeding design constraints.

Each blanket module will consist of Li_2O breeding material and re-entrant coolant thimbles contained in an outer ceramic SiC box. A flow of gas at low pressure over the Li_2O will allow the bred tritium to be collected. The ceramic SiC box will be mechanically attached to a SiC fiber reinforced aluminum composite plenum which will be joined to an aluminum framework forming the vacuum vessel. Beryllium will be used in the inboard region of the module to maintain the breeding ratio greater than 1.1.

The limiter is a toroidal belt centered around the midplane on the outer side of the plasma chamber. It will basically consist of tube assemblies and a header, and will employ water as the coolant. The material used for the limiter will be a SiC fiber reinforced aluminum composite. This has been found to be suitable for applications in the temperature range of interest.

The shield serves to protect the reactor components, especially the superconducting toroidal field coils, from radiation damage and to reduce radiation exposure to plant personnel. A low activation material is desirable for this component since it can become activated as well, and contribute to shutdown dose rates. The outboard shield in the low activation design will be composed of SiC and B_4C. Due to space limitations in the inboard region, a tungsten shield will be employed here. This will both optimize performance and minimize the cost. The high levels of radioactivity and accompanying decay dose rate associated with the use of tungsten are accommodated by the concept of a removable and storable shield component. The tungsten shield will be inserted during normal operation to function as an efficient neutron and gamma ray attenuator. At shutdown, the tungsten shield will be removed and stored in a shielded area until it is required for reuse.

To allow for maximum personnel access to the region exterior to the blanket and shield, the superconducting toroidal field coils must be composed of low activation materials. In the low activation design, high purity aluminum has been substituted for the copper stabilizer and a SiC fiber reinforced aluminum composite will be used to replace the SS316 structure. A graphite fiber/polyimide composite will be used for the helium vessel and glass/epoxy will be used for the coil case. A suitable low activation insulator with good radiation damage resistance is a polyimide/Al_2O_3 composite. No low activation alternate exists for the NbTi and Nb_3Sn superconductors, but their activation can be tolerated as they comprise only 4 % of the toroidal field coil volume.

The low activation tokamak design realizes the advantages of low residual radioactivity and appears technically feasible in that the fundamental nuclear design requirements of adequate tritium production and acceptable shielding of the superconducting magnets are satisfied. For greater detail on the status of the low activation fusion reactor design concept, references 4.1, and 4.3 through 4.11 should be consulted.

4.3 Assessment Of The Cost Effectiveness Of The Low Activation STARFIRE Design

In this section, the methodology presented in Chapter 2 will be illustrated. The cost effectiveness of the low activation STARFIRE design will be assessed. Since the change to low activation materials will most directly affect doses incurred by plant workers, the ceiling on safety expenditures will be defined based on occupational exposures (public exposures, which are expected to be small to begin with, will not be considered). Knowing the ceiling on safety spending, it will be determined if the change to the low activation design is justified.

4.3.1 Ceiling On Safety Expenditures For Design Changes To STARFIRE

The procedure for assessing the cost effectiveness of design changes has been outlined in Chapter 2. Using this approach, a maximum value for spending on design changes for STARFIRE (α), aimed at improved safety, can be found.

The ceiling on safety expenditures is defined by equation 2.1. The most difficult parameter to specify in this case is R, the actual dose rate to which plant workers are exposed. Since the switch to low activation materials will affect many areas of the plant where there are varying levels of radiation, the occupational dose rate cannot be accurately represented by the value at one location. In addition, there is no actual operating experience for fusion reactors. Hence, no data base to draw from exists.

In order to overcome these difficulties, information from fission reactor operating experience was used to estimate exposures at different areas of the fusion plant. Knowing the estimated number of person-hours spent annually at a certain dose rate, an overall representative occupational exposure rate for STARFIRE was obtained using the fractional time spent in each area.

Easterly [4.12] has tried to estimate the occupational exposures at a fusion power station. The estimates and judgements were based for the most part on STARFIRE. Since this is a conceptual design, which is not fully engineered, very few specific numbers were estimated with certainty. Nevertheless, a rough idea of expected exposures was provided.

A major contributor to the total dose incurred at a fusion power plant will result from tasks performed on the coolant/steam generator system. The STARFIRE design team selected pressurized water as the coolant [4.2]. The coolant/generating system will therefore be similar to that of Pressurized Water Fission Reactors (PWRs). Hence, current technology can describe the system design. Operation and maintenance of the system in a similar manner to PWRs would be an appropriate assumption. Expected exposures from fusion coolant systems during reactor operation and maintenance were discussed in section 2.3. It was pointed out that the activity within the coolant system to which personnel are exposed, will be quite similar for STARFIRE and various LWR fission reactors (see table 2.3). Furthermore, the calculated activity deposited in the steam generator tubes of STARFIRE was comparable to measured values in several fission reactors (see table 2.4). For similar work procedures involving the coolant/generator system, radiation doses at a fusion plant are expected to be essentially the same as at fission plants. Hence, the estimated exposure for steam generator related procedures for a 1200 MWe water cooled fusion reactor, after several years of operation employing current practices, is approximately 6.0 person Sv per year [4.13].

Easterly [4.12] has given an estimate for the radiation field in the primary system piping of a PWR. His value for the exposure rate is 1.5×10^{-3} Sv/h. Since this radiation dose is dominated by Co^{58} and Co^{60}, and the expected levels of these nuclides for STARFIRE are similar to fission reactors (see tables 2.3 and 2.4), this value should be representative of the expected exposure rate at the fusion plant. Knowing an estimate of the dose rate and the total cumulative dose incurred, an estimate of the total person-hours spent on activities in this radiation field can be obtained. This was valued at 4,000 person-hours.

Some degree of personnel exposure will result from contact maintenance carried out in the vicinity of the plasma chamber. Extensive diagnostic and other support equipment will be located adjacent to the reactor, and it is unlikely that all maintenance on this equipment can be carried out remotely. The STARFIRE reactor shielding was designed to reduce the radiation dose to the level of a few millirem per hour or less, one day after shutdown. At these levels, plant personnel could work up to 40 hours per week within the reactor containment during an outage period. Tasks performed would not include any work within the outboard shield or on components associated with penetrations (e.g. fueling devices) since these would be more highly activated than the components protected by the outboard shield due to the higher neutron fluxes to which they are exposed. Nevertheless, access to the toroidal field coils, cryogenic systems and other components external to the outboard shield appears feasible.

In order to obtain an estimate of the total dose incurred during maintenance tasks carried out in the vicinity of the plasma chamber, use was made of a total reactor maintenance assessment provided in the STARFIRE report [4.2]. A listing of expected maintenance tasks and estimates of the time required to carry out these tasks were provided. Using these numbers, an estimate of 1,000 person-hours for the total time spent on contact maintenance of reactor equipment beyond the outboard shield was obtained. An estimate of the dose rate encountered in these areas during maintenance outages was found to be approximately 3.0×10^{-8} Sv/h [4.11]. This estimate is less than a value obtained from another source [4.14] for the dose from background radiation. It was therefore thought appropriate to use the higher value of 1.5×10^{-7} Sv/h for the dose rate encountered during these activities.

A major operation carried out during fusion plant outages will be that of first wall and blanket replacement. Some contribution to the total cumulative dose incurred at the plant is expected as a result of these procedures. Operations associated with this activity include disconnecting coolant lines and support equipment, disconnecting first and second walls, preparation and installation of new blanket assemblies and reconnecting coolant and support equipment. Dismantling the reactor and replacing first wall and blanket structures resembles some of the activities involved in decommissioning a fission reactor (e.g. breaking coolant lines and segmenting large radioactive vessels). Easterly [4.12] states that during the dismantling of fission reactors, shielding is normally provided to reduce the exposure rate to 5 to 10 x 10^{-5} Sv/h. It is anticipated that similar amounts of shielding will be used during the operations carried out for blanket replacements. However, since the specific activity of the materials being handled is ten times that encountered during PWR dismantling (see table 2.5), it is likely that the shielding for fusion reactor activities will not reduce the dose rate to the same degree. Hence, ten times the average exposure rate encountered during fission reactor dismantling, or approximately 7.5 x 10^{-4} Sv/h was thought to be an appropriate estimate of the dose rate encountered during blanket changeouts (a direct ratio of specific activities was applied, since for both STARFIRE and PWRs, the penetrating radiations arise from the activation of steels [4.13]). This dose rate would allow a previously unexposed person to work for 16 hours without exceeding the ICRP quarterly exposure limit of 1.25 x 10^{-2} Sv. This should not pose a limitation on the activities of regular plant employees since it is expected that contract workers will be hired to carry out the first wall and blanket replacements. The expected duration of these procedures is 240 person-hours [4.2].

Tritium handling systems will be an integral part of all D-T reactors, since tritium is required for fuel. Exposure of plant personnel to tritium will add to the total dose incurred at the plant. The STARFIRE reactor was designed to maintain a breathing atmosphere in habitable locations at a level below 5 x 10^{-6} Ci/m^3.

At this limit, the dose rate would be 1.3 x 10^{-6} Sv/h. Since tritium is quite mobile, it will be found in most locations throughout the plant. Hence, workers carrying out maintenance of any sort will encounter tritium. Using the reactor maintenance assessment provided in the STARFIRE report [4.2], an estimate of 1,049 person-hours of annual contact maintenance, where exposure to tritium was thought possible, was obtained.

Waste handling is another area where the potential for exposure to radiation exists. Complete onsite recycle of reactor components such as blanket modules, first walls, etc., will likely not be carried out. However, preparatory measures prior to shipment offsite may be required. Most of the waste management activities will consist of daily replacement of spent resin beds, air filters, tritium traps etc., and will involve most of the activities carried out at fission plants. The operations at fission plants result in relatively small occupational exposures and have been reported to give rise to 5 to 7 % of the total occupational dose. Easterly [4.12] expects fusion power plant waste operations to result in a similar occupational exposure and from his estimated range, an intermediate value of 0.65 person Sv was chosen for the total cumulative dose. Assuming 10 % of the plant workers (65 persons, see next paragraph) to be continually involved in waste handling, an average dose rate of 5.0 x 10^{-6} Sv/h was obtained for these activities.

The STARFIRE study [4.2] included an estimate of personnel requirements and personnel distribution. The total given for operation and maintenance personnel was 101 persons. Easterly [4.12] perceives this estimate to be somewhat low. He states that, on average, fission power plants employ approximately 250 workers. Since fusion reactors will be much more complicated than fission reactors, requiring operation and maintenance of numerous auxiliary systems (such as heating, fueling, confinement, cryogenic and fuel purification), it is likely that fusion plants will employ many more workers than fission plants. He estimates a total fusion plant staff of at least 1,000 persons. Approximately two-thirds of these, or 650 people, would actually be performing plant maintenance tasks (as in the STARFIRE estimate [4.2]). Assuming each person works 40 hours per week, 50 weeks per year, the total amount of time spent by operation and maintenance personnel at the power station will be 1.3 x 10^6 person-hours. An additional 240 person-hours [4.2] each year would be spent by outside workers on the plant site during blanket changeouts. This gives a total of 1,300,240 person-hours spent in measurable radiation fields. Of this, 136,048 person-hours has been accounted for in operation, maintenance and waste handling tasks carried out by the plant workers. This leaves a difference of 1,163,952 person-hours, which can be assumed to be spent in comparatively low radiation fields. For the present purposes, 1.5 x 10^{-7} Sv/h, the level of background radiation [4.14], will be used as an estimate of this dose rate.

Knowing estimates of the dose rates encountered in different areas of the plant, and the approximate number of person-hours spent in these areas, an overall estimate of the dose rate (R) was found. A summary of the expected exposure rates encountered at a fusion plant is given in table 4.1. A weighting procedure, using the fraction of total person-hours spent at a given exposure, resulted in a value of 5.4 x 10^{-6} Sv/h for the overall average exposure rate at the STARFIRE plant.

Before the ceiling on safety spending can be specified, the cost of replacement labor must be provided. A value of 57,000 \$/yr was obtained for the average annual salary per staff member from the STARFIRE report [4.2] (updated to current dollars using price indexes [4.15]). Knowing that the ICRP occupational exposure limit is 5.0 x 10^{-2} Sv/yr or 2.5 x 10^{-5} Sv/h (for 40 hours per week, 50 weeks per year), a value for α was calculated. Using equation 2.1, the maximum justified spending for safety on STARFIRE was found to be \$529,824 per person Sv averted.

Table 4.1: Estimates of Exposure Rates and Times Spent in Radiation Fields at the STARFIRE Plant

Activity	Exposure Rate Estimate (Sv/h)	Annual Time Spent at Estimated Exposure Rate (person-hours)	Fractional Time Spent at Estimated Exposure Rate
Coolant/Steam Generator Maintenance	1.5×10^{-3}	4,000	0.00308
Contact Maintenance of Reactor Equipment	1.5×10^{-7}	1,000	0.00077
First Wall and Blanket Replacement	7.5×10^{-4}	240	0.00018
General Maintenance Tritium Exposures	1.3×10^{-6}	1,049	0.00081
Waste Handling	5.0×10^{-6}	130,000	0.09998
Other	1.5×10^{-7}	1,163,952	0.89518
Total		$1,300,240^{+}$	1.00000

The weighted average occupational exposure rate is:

$$R = 5.4 \times 10^{-6} \text{ Sv/h}$$

$^{+}$ based on 650 regular plant workers, 40 hours per week, 50 weeks per year, and assumes outside workers are brought in for blanket changeouts.

4.3.2 Cost Of The Change To The Low Activation STARFIRE Design

As described in section 2.3, the total cost of implementing a dose reduction measure consists of four components: the incremental capital cost of the dose reduction measure, and the change in each of operation, maintenance and waste handling costs. Due to the lack of detailed information on the low activation STARFIRE design at this time, it was not possible to assess all of the economic implications. However, an attempt was made to obtain a best estimate for each of the cost components.

4.3.2.1 Incremental Capital Cost Of The Low Activation STARFIRE Design

Capital cost refers to the total expense of constructing the facility and placing the facility into operation. In analyzing the cost effectiveness of a dose reduction measure, only incremental capital costs over those which would be incurred in the reference design, need be considered.

The major capital cost accounts that should be used in estimating costs are given in table 4.2. These were taken from the DOE Fusion Reactor Design Studies - Standard Accounts for Cost Estimates [4.16]. Costs affected by the design change, costs which are expected to be affected but are not accounted for due to lack of design detail, and costs which are expected to be unaffected by the design change are indicated.

Capital costs are comprised of direct, indirect and time related costs. Direct costs are directly associated with some phase of construction or startup and are primarily composed of material, equipment and labor costs. The basic purchase price, as well as expenses associated with testing and shipment to the site are included.

Formally, the research and developmental costs should also be included. However, this information is not available at this time, and this cost has been omitted. As will be seen later, the methodology being applied can provide an estimate of the justified research and development expenditures. The contribution from labor to the total capital cost should include total payroll costs for construction, installation, preoperational testing and plant site inspections. A contingency allowance is included as part of the direct capital cost to account for unforeseen or unpredictable expenses incurred during construction and startup. A spare parts allowance is also needed to account for the purchase cost and inventorying cost of the initial inventory of spare parts required on site.

Indirect costs result from the support activities required to accomplish direct cost activities. These include construction facilities, equipment and services, engineering and construction management services, taxes, insurance, staff training and plant startup. Additionally, miscellaneous expenses incurred by the facility owner during construction and startup, such as licensing fees, legal fees, public relations programs etc., contribute to the indirect costs.

Time related costs are a consequence of the opportunity cost associated with money and the changes which occur in the purchasing power of the dollar over the period of time required for plant design, construction and startup. Time related costs are comprised of interest during construction and escalation (inflation) during construction.

The effort to date on the low activation STARFIRE design does not provide sufficient information for all affected costs to be estimated. It is expected that the cost of plant structures and site facilities will be affected. Since the inventory of activation products for the low activation design will consist of nuclides having much shorter half lives and different decay characteristics, the basic building structures will likely have more relaxed design requirements. Since the first wall will be cooled by helium in the low activation design, in place of pressurized water as in the reference design, some changes in the turbine plant equipment and associated systems are anticipated. Sufficient information is not currently available to assess the change in capital costs associated with these items. Of the direct costs, only an estimate of the reactor plant equipment cost could be obtained, and is indicated in table 4.2. There is some skepticism as to the accuracy of the price of silicon carbide used in obtaining this cost. According to the low activation STARFIRE design study [4.5, 4.11], an installed cost of 30 \$/kg for silicon carbide components will lead to a significant reduction in the cost of reactor plant equipment. However, the feeling that 30 \$/kg is too low for the installed cost of silicon carbide components has been expressed [4.17, 4.18]. (Note that this feeling is not shared by those at G A Technologies.) Upon further investigation of this issue, an estimate of 315 \$/kg as the current day installed cost of a high purity, complex shaped silicon carbide component was found [4.19]. Although the components required for first wall construction may not be complex shapes or require grinding to close tolerance [4.20], the use of 315 \$/kg would serve as an upper limit for this study. It should be noted that a cost reduction by a factor of two or three may be possible if a large demand (as would be the case in a mature fusion economy) allowed manufacturing process scale-ups and efficiencies [4.20]. An intermediate value for the cost of silicon carbide components of 110 \$/kg was also used in this study. This price corresponds roughly to the expected reduced installed price of high purity complex shaped components in a mature fusion economy. The cost effectiveness of the low activation design was assessed using each of the low, intermediate and high values for the cost of silicon carbide. In this way, the uncertainty in cost was accounted for and the sensitivity of the analysis to the cost of silicon carbide was illustrated.

The capital costs associated with each estimate of the installed cost of silicon carbide are indicated in table 4.2. The spare parts allowance for those components affected by the change to the low activation design was taken as 2 % of the direct cost of the installed equipment [4.16]. A further allowance has been included as part of the total unaffected direct costs for those components which are not affected by

Table 4.2: Effect of the Change to the Low Activation STARFIRE Design on Capital Cost

Account Number	Account Title	Effect	Cost for RD† (M$)	Cost for LAD† @ 30 $/kg (M$)	Change in Cost (M$)	Cost for LAD @ 110 $/kg (M$)	Change in Cost (M$)	Cost for LAD @ 315 $/kg (M$)	Change in Cost (M$)
Direct Costs:									
20	Land and Land Rights	*	√	√	-	√	-	√	-
21	Structures and Site Facilities	*	√	√	-	√	-	√	-
22	Reactor Plant Equipment	+	332.0[a]	197.2[a]	-134.8	385.5	+53.5	867.9	+535.9
23	Turbine Plant Equipment	*	√	√	-	√	-	√	-
24	Electric Plant Equipment	*	√	√	-	√	-	√	-
25	Miscellaneous Plant Equipment	*	√	√	-	√	-	√	-
26	Special Materials	*	√	√	-	√	-	√	-
	Spare Parts Allowance[b]	+	6.6	3.9	-2.7	7.7	+1.1	17.4	+10.8
	Contingency Allowance[b]	+	49.8	29.6	-20.2	57.8	+8.0	130.2	+80.4
	Total Affected Direct Cost		388.4	230.7	-157.7	451.0	+62.6	1015.5	+627.1
	Total Unaffected Direct Cost[c]		1689.9	1689.9	0	1689.9	0	1689.9	0
	Total Direct Cost		2078.3	1920.6	-157.7	2140.9	+62.6	2705.4	+627.1

Account Number	Account Title	Effect	Cost for RD† (M$)	Cost for LAD‡ @ 30 $/kg (M$)	Change in Cost (M$)	Cost for LAD @ 110 $/kg (M$)	Change in Cost (M$)	Cost for LAD @ 315 $/kg (M$)	Change in Cost (M$)
Indirect Costs:									
91	Construction Facilities, Equipment and Services	+	207.8	192.1	-15.7	214.1	+6.3	270.5	+62.7
92	Engineering and Construction tion Management Services	+	166.3	153.6	-12.7	171.3	+5.0	216.4	+50.1
93	Owner's Costs (taxes, insurance, other miscellaneous expenses)	+	103.9	96.0	-7.9	107.1	+3.2	135.3	+31.4
	Total Indirect Cost		478.0	441.7	-36.3	492.5	+14.5	622.2	+144.2
	Total Direct plus Indirect Cost		2556.3	2362.3	-194.0	2633.4	+77.1	3327.6	+771.3
Time Related Costs:									
94	Interest during Construction	+	807.8	746.5	-61.3	832.2	+24.4	1051.5	+243.7
95	Escalation during Construction	+	485.7	448.8	-36.9	500.3	+14.6	632.2	+146.5
	Total Time Related Cost		1293.5	1195.3	-98.2	1332.5	+39.0	1683.7	+390.2
	Total Capital Cost		3849.8	3557.6	-292.2	3965.9	+116.1	5011.3	+1161.5

Notes:

† RD - Reference STARFIRE Design

‡ LAD - Low Activation STARFIRE Design

⋆ expected to be unaffected by the change to the low activation design; cost is included in the total unaffected costs

* expected to be affected to some degree by the change to the low activation design, but the effect cannot be accounted for at this time due to the lack of detailed information; cost is included in the total unaffected costs

+ expected to be affected by the change to the low activation design; and attempt is made to account for the change in cost

√ cost is included in the total unaffected costs

[a] cost data from reference 4.11, updated to current dollars by price indexing [4.15] (represents fabrication and installation costs of relevant reactor components [4.21])

[b] allowance due to affected direct costs; a further contribution to the allowance is included as part of the total unaffected costs

[c] cost data from reference 4.2, updated to current dollars by price indexing [4.15]

the design change. The recommended contingency allowance of 15 % of the cost of the installed equipment was used [4.16]. Again, an additional contingency allowance for unaffected plant equipment was included as part of the total unaffected direct costs. Indirect costs were estimated using the indirect cost percentages employed in the reference STARFIRE design economic analysis [4.2]. Time related costs were obtained using relationships provided in the DOE costing guidelines [4.16], using a six year construction period [4.2]. Possible reductions in costs due to easier liscensing, fewer regulatory delays and faster construction can be envisioned for the low activation design. However, lack of information prevented these factors from being incorporated into the present cost estimate. Values, in current dollars, for the reference and low activation STARFIRE designs are given in table 4.2. The total capital cost for each design is also given. Calculations have indicated that changing to the low activation design will lead to a reduction of 292 M$ in the total capital cost, or an annual reduction over the plant lifetime of 19.3 M$/yr, if the cost of silicon carbide is taken as 30 $/kg. This figure alone provides inpetus for further development of the low activation concept. However, if the installed cost of silicon carbide is 110 $/kg, an increase in the total capital cost of 116 M$, or 7.6 M$/yr over the 30 year plant lifetime, will result. For the case where the installed cost of silicon carbide components is 315 $/kg, the increase in the plant capital cost will be 1,162 M$ or 76.7 M$/yr. It was necessary to investigate these last two cases further before it could be determined if the increased expenditure is justified.

4.3.2.2 Change In Normal Operation Costs For The Low Activation STARFIRE Design

Normal operation costs consist of routine day to day expenditures incurred while the reactor is operating. This includes the cost of materials, labor and overhead (e.g. support services, administrative costs, etc.). An additional cost element which must be considered is the health detriment due to radiation exposure. Applying the CERRM methodology of Chapter 2 requires that only incremental costs be considered. In this section, the incremental costs associated with normal plant operation resulting from switching to the low activation STARFIRE design will be estimated.

In section 2.3.1.2, a formula was given for estimating the change in normal operation costs. Four cost elements were identified: the change in materials, labor, overhead and health detriment costs. Unfortunately, the lack of detailed information for the present application of this methodology has prohibited estimating all of these cost elements individually. A less detailed approach, more consistent with the level of the design effort, was used to estimate several of the components at one time.

The DOE costing guidelines [4.16] suggest that annual operating and maintenance costs be estimated as 2 % of the total direct and indirect capital cost. This would include materials, labor and overhead costs for both normal operation and maintenance. Since the STARFIRE reference design has an availability of 75 %, it was assumed that three-quarters of this estimate, or 1.5 % of the total direct and indirect capital cost, would represent the materials, labor and overhead costs during normal plant operation (note that since it is the total cost which is of concern, the accuracy of the actual division between operation and maintenance costs is not important). Similarly, since the low activation STARFIRE design was found to have an availability of 76 % (see section 4.3.2.3), 1.52 % of the total direct and indirect capital cost would represent the materials, labor and overhead costs for this design. The costs associated with the reference design and each of the three cases for the low activation design are given in table 4.5.

It was necessary to obtain estimates for health detriment costs for each design. This required obtaining a value for doses incurred to plant workers during normal plant operation.

While the fusion reaction is occurring, the large flux of high energy neutrons and the associated capture gamma rays will preclude access to the plasma chamber and surrounding regions. Hence, human exposures to neutrons will probably be rare and have not been considered.

Exposures to tritium will occur during reactor operation since it is transported through many areas of the plant. Due to its permeation characteristics, tritium may also be found in plant components not directly associated with the fuel cycle. Potential for exposure exists due to the possibility of leakage of contaminated coolant as well as from work on tritium processing or tritium bearing components requiring attention during plant operation. Assuming similar contamination levels, the quantity of tritium escaping will be approximately the same for both the reference and low activation STARFIRE designs. If the plant atmosphere in both cases is maintained at the same tritium level by clean up systems, then it is expected that the total dose incurred by both tritium and nontritium workers during normal plant operation and maintenance will be the same. Since the reference STARFIRE design has an availability of 75 %, it was assumed that three-quarters of the total tritium dose will be incurred during plant operation. The low activation STARFIRE design has increased availability, and the dose incurred from tritium during plant operation will be correspondingly higher. The estimates for these exposures are given in table 4.6.

The radioactivity associated with reactor materials during operation has been shown to be the same order of magnitude for the reference and low activation STARFIRE designs [4.1, 4.4, 4.5, 4.6, 4.11] (although the radioactivity is much lower subsequent to reactor shutdown in the low activation design). It was assumed that similar amounts of shielding will be provided in both cases (i.e. no change in materials costs), and that this shielding will effectively eliminate exposure to decay gammas emitted directly by the activated structure during normal operation.

Some of the activated structural material will be carried by the coolant throughout the heat transport system. For the water-cooled reference design, in addition to this, corroded materials from those areas of the heat transport system external to the blanket will eventually be carried through the reactor and be exposed to the neutron flux. Consequently, these materials may become activated and may be deposited, along with the corroded activated structural material, in some different area of the plant. Most of the mobile activation products for the helium-cooled low activation design will result from sputtering and other physical processes within the blanket. The transport of out-of-blanket materials to the reactor region and their subsequent activation is not expected to occur to a large extent. Exposure to the radiation fields created by these deposited materials will be possible if work must be performed on any part of the coolant/steam generator system. Estimates for exposures while carrying out procedures on the coolant/steam generator system during normal plant operation and maintenance outages for both reactor designs are given in table 4.6. It is expected that the fraction of this dose incurred while the reactor is operating will be small. Because of this, and since it is the total dose incurred which is of interest, an attempt was not made to subdivide the dose due to activated corrosion products into the normal operation and maintenance components. The dose given in table 4.6 for the coolant/steam generator system then represents the total dose incurred during operation and maintenance.

The total costs for normal operation for each reactor design are given in table 4.5. As can be seen, health detriment costs are small in comparison with materials, labor and overhead costs. The change in costs associated with the use of the low activation materials in place of the reference materials, for all three estimates of the installed cost of silicon carbide, are also given.

4.3.2.3 Change In Maintenance Costs For The Low Activation STARFIRE Design

Maintenance tasks are those carried out during downtime. Included in the total maintenance costs are materials, labor, overhead, health detriment and replacement power costs incurred while the reactor is not operating. In this section, the change in these costs resulting from using the low activation STARFIRE design will be estimated.

Section 2.3.2.3 presented a formula for estimating the change in maintenance costs. As with the normal operation costs, the lack of detailed information prevented each cost component from being estimated individually. However, the same approach as in the last section has been taken, and several components have been estimated at one time.

As recommended in the DOE costing guidelines [4.16], the annual materials, labor and overhead costs for normal operation and maintenance can be taken as 2 % of the total direct and indirect capital cost. Since, for the reference design, 25 % of the year is taken for downtime, an estimate of these costs can be found using 0.5 % of the total direct and indirect capital cost. Since implementing the low activation design will result in slightly improved availibility (as shown further in this discussion), only 24 % of the year is accounted for as downtime. This results in an estimate for annual materials, labor and overhead costs for maintenance being 0.48 % of the total direct and indirect capital cost. Not included in the above estimate is the cost of the annual reactor first wall module replacement. This is treated separately since it represents such a major cost contribution. This cost includes all major materials required to rebuild or replace one-sixth of the reactor first wall components, as well as labor costs incurred in disassembling the reactor, moving the irradiated components to storage cells, moving rebuilt components to the reactor and reassembling the reactor. The materials component of this cost will include the wall, wall modifier, neutron multiplier, breeder, reflector, structure, limiter and a portion of the rf and ECRH ducts. An estimate of this cost was obtained using life-of-unit requirements calculated in a previous study [4.5] (updated to current dollars using price indexes [4.15]) and the assumption of a 30 year lifetime. The annual replacement costs for each reactor design are summarized in table 4.3. Since the prices used in estimating the annual replacement costs were installed costs, this

would account for the associated labor. Additionally, some materials can be recycled after a cool down period. These include Zr_5Pb_3 and $LiAlO_2$ for the reference design, and possibly Li_2O for the low activation design. However, the annual savings from recycle is expected to be offset by the extra handling, storage and refabrication preparation costs, and no cost benefit is foreseen. The total annual materials, labor and overhead costs, including the additional costs incurred for replacing the blanket modules, are given in table 4.5 for both designs.

In order to determine health detriment costs associated with each design, values for doses incurred during maintenance were required. Maintenance activities considered in obtaining the dose estimate were any activities where exposure to tritium may occur, maintenance of the coolant/steam generator system, contact maintenance of reactor equipment and first wall/blanket changeouts.

As with plant operation, tritium exposures during maintenance may occur in many areas of the plant. Since maintenance procedures were taken to be those tasks carried out during downtime, 25 % of the total tritium exposures for the reference design and 24 % of the total tritium exposures for the low activation design were assumed to be incurred during maintenance. The dose estimates are summarized in table 4.6. Note that the total dose from tritium exposures during operation and maintenance is the same for both designs. No effect on the total tritium exposures is foreseen in switching to the low activation materials.

For the water cooled reference design, a large fraction of the total dose incurred during outages will result from maintenance of the coolant/steam generator system. The use of helium coolant and low activation materials will significantly reduce doses incurred during coolant/steam generator maintenance. The activity resulting in the low activation materials will generally be due to short lived nuclides which almost all decay away within one day after shutdown [4.6]. Beyond this time, doses will be dominated by the activity due to the impurity elements found in these materials. The chief impurity is iron. Although aluminum will result in long term activity (due to $Al^{27}(n,2n)Al^{26}$, where Al^{26} has a half life of 7.3 x 10^5 years), it is expected to contribute much less to the total activity and resulting biological dose rate than the iron impurity [4.6]. Hence, biological dose rate calculations have focused on the iron impurity, at a level of 1 appm. Bickford [4.22] has estimated the radiation field at the steam generator for a helium cooled reactor employing a steel structure to be 10^{-3} Sv/h (100 mrem/h). The low activation design will employ a silicon carbide structure with an iron level of 10^{-4} %, while the steel structure on which Bickford bases his dose rate estimate contains 64.4 % iron (SS316). Based on activity levels for steels given by Easterly [4.12], the fraction of the total deposited activity in the coolant system caused by iron was estimated for the reference design. Knowing this, an estimate of 4.72 x 10^{-6} person Sv for the dose incurred during coolant/steam generator maintenance of the low activation design was obtained. This is negligible compared to 6.0 person Sv, the dose incurred during coolant/steam generator maintenance of the reference design (see section 4.3.1). Hence, the dose savings during these activities for the switch to the low activation design will be 6.0 person Sv.

During downtime, some degree of contact maintenance of reactor equipment will be necessary. An estimate of the dose incurred during these activities for the reference design was obtained. Using the maintenance downtime estimates (both scheduled and unscheduled) provided in the STARFIRE report [4.2], along with a representative dose rate behind the shield [4.11], the total dose incurred during contact maintenance of reactor equipment was determined (see table 4.6). (The dose rate used was 3.0 x 10^{-8} Sv/h, which is the value given at two weeks after shutdown for the reference STARFIRE design [4.11]. Since the activity in the reference design does not decrease to a large degree even within one year [4.11], the value for the dose rate at the two week point was thought to adequately represent the dose rate during the entire outage.) For the low activation design, a direct benefit of the reduced structural activity is the fact that personnel access to a larger fraction of the plant is possible. The most important region for gaining access to is just behind the blanket. A complex array of coolant headers and piping, vacuum ducts and instrumentation, having high maintenance requirements, will exist here. The use of low activation materials will reduce the dose rate from a level where no personnel access is permitted (10 Sv/h) to a level where a worker could spend five hours per week and not exceed the ICRP dose limit. Accessibility to this region will prove valuable in that some jobs, formerly carried out entirely remotely, can be assisted by contact maintenance, resulting in considerable savings in replacement power costs.

Using the STARFIRE downtime estimates, a revised maintenance schedule for the reactor equipment of the low activation design was formulated. The degree of remote maintenance would be determined by a trade-off between operating costs for remote maintenance and human occupational exposure costs. With the limited information available for the low activation design, this could not be accurately determined. However, an attempt to revise STARFIRE's maintenance schedule for the low activation design was made. Activities in which assistance by contact maintenance was thought possible were identified. It was then assumed that 30 %[†] of each task could be carried out manually. Finally, it was assumed that a time savings of 30 %[†] would result for that part of the task performed manually. With these assumptions in mind, a total time savings of 3.25 days for these tasks was estimated (see appendix D). Assuming that all tasks considered were on the critical path, the total downtime would be reduced by 3.25 days. This resulted in an availability of 76 % for the low activation design.

The tasks carried out manually for the reference design were also assumed to be carried out manually for the low activation design. However, the dose incurred during these activities would be reduced for the low activation design since the dose rate to which workers are exposed at these locations is expected to decrease to 1.0×10^{-8} Sv/h (maximum estimate for the dose rate at two weeks after shutdown). The increased contact maintenance for tasks performed just behind the blanket

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[†] These percentages are rough estimates based on information contained in references 4.23 and 4.24.

would result in exposure to a dose rate of 2.1 x 10^{-4} Sv/h. (For the low activation design, the dose rates were based on the iron impurity. Since the main nuclides produced from this impurity are Fe^{55} and Mn^{54} [4.5], with half lives of 2.7 years and 313 days respectively, which would not decay to a great extent during the outage, it was felt that the value at two weeks after shutdown would be a reasonable estimate of the dose rate during the entire period. Note that although the formula (2.12) has specified a time dependent dose rate for calculating the dose incurred, the limited information has provided only a single constant value for this case. This increased exposure will result in the total cumulative dose incurred during these maintenance activities to be larger for the low activation design than for the reference design by approximately 4.9 x 10^{-2} person Sv. It will be determined, as part of this analysis, whether or not the savings in downtime resulting from this increased exposure is justified. The actual values for dose estimates for each design are summarized in table 4.6.

Replacement of the first wall and blanket will lead to the exposure of personnel. The dose rate encountered during blanket changeouts was estimated at 7.5 x 10^{-4} Sv/h for the reference design (see section 4.3.1). Consequently, contract workers will likely be employed at these times to avoid exceeding exposure limits for plant workers (1.25 x 10^{-2} Sv per worker per calendar quarter). Since dose rates inside the plasma chamber (to which workers will be exposed during blanket changeouts, once the shield is opened) are a factor of 10^6 lower for the low activation design than for the reference design, the total dose incurred during replacement of the first wall and blanket for the low activation design will be correspondingly reduced. For a total exposure time of 240 person-hours, the estimated cumulative dose during these operations for the reference STARFIRE design was 0.18 person Sv. Thus, an appropriate estimate of the total dose incurred during first wall/blanket changeouts for the low activation design was taken as 1.8 x 10^{-7} person Sv.

The total dose incurred during plant maintenance was found by summing the estimated doses during all activities. Table 4.6 gives the values for each reactor design and shows that a total dose savings of 6.13 person Sv will be possible in switching to the low activation design. The health detriment costs for each design are given in table 4.5. The use of the low activation design will result in an annual health detriment cost savings of $23,294.

A further implication of the decreased activity of the low activation design will be the reduced requirements on remote maintenance equipment. Substitution of low activation materials will result in a considerable reduction in component masses (the material volumes are approximately equal but due to the lower densities of aluminum and silicon carbide, the total mass will be reduced by more than 50 % [4.5]). Since much lower mass components will be handled, the load capacity requirements of the maintenance equipment will be reduced. It is expected that this will result in a reduced capital cost for maintenance equipment and a reduced cost for replacement parts for the maintenance equipment. Also, the lower structural activation levels will result in a less severe remote handling environment. This will lead to a reduction in equipment degradation, which in turn will lead to a less frequent need for replacement of affected components. As well, the reduced demands on remote maintenance equipment will lead to fewer delays from breakdowns and non-routine faults in the equipment, leading to improved chances of satisfying availability goals. Unfortunately, these effects cannot be quantified at this time and no adjustment to the costs involved has been incorporated.

Finally, the change in replacement power costs associated with using low activation materials must be considered. As stated previously, the reduction in downtime has been estimated at 3.25 days for the low activation design. Using the replacement power cost estimation model described in appendix C, and assuming that the plant will be located in the SPP National Electric Reliability Council region (mid United States), the savings in replacement power costs will amount to 1.9 million dollars annually.

The total cost incurred during maintenance for each reactor design is given in table 4.5. As can be seen, health detriment costs are negligible compared to the other cost components.

4.3.2.4 Change In Waste Handling Costs For The Low Activation STARFIRE Design

During the lifetime of a fusion power plant, it will be necessary to handle and dispose of radioactive wastes. Costs associated with waste handling include the cost of materials and equipment required to carry out waste operations, labor costs, overhead costs, health detriment costs and the actual cost of disposing of the contaminated materials. The change in these costs resulting from the use of low activation materials will be estimated in this section.

In section 2.3.3.3, a formula was presented which can be used to estimate the change in waste handling costs. Insufficient information has prevented each cost element from being individually evaluated. As with the other cases, the materials, labor and overhead cost elements have been estimated together. The health detriment and disposal costs have been estimated individually.

The DOE costing guidelines [4.16] recommend that the annual materials, labor and overhead costs for operation and maintenance be estimated as 2 % of the total direct and indirect cost. To estimate the materials, labor and overhead costs associated with waste handling, it was assumed that these costs would be proportional to the number of workers in that area. It was previously estimated that 10 % of the plant workers would be employed in waste handling operations. Hence, it is expected that 0.2 % of the total direct and indirect cost would account for the materials, labor and overhead costs incurred during waste handling. The corresponding values for the reference and low activation STARFIRE designs are listed in table 4.5.

The majority of waste handling at a fusion power station will deal with daily operations such as: (1) wastes from various processing systems designed to minimize radioactivity in plant effluent streams; (2) mops, swabs, clothing and other miscellaneous items used in various plant operation and maintenance tasks; and (3) wastes generated from tritium handling procedures. The relatively small volume of waste created during these activities will be low level waste, being either contaminated with tritium and/or activated corrosion products from the coolant systems. A much larger volume of waste will be due to the first wall/blanket structure, which will contain the bulk of the induced radioactivity. The quantities of these wastes expected from plant operation are discussed below.

In order to minimize routine releases of radioactive materials from a fusion plant, liquid and gaseous effluent streams from radioactive waste treatment systems will be passed through chemical and mechanical process equipment which will retain most of the radioactivity. The major streams to be purified will be the coolant streams. For the water cooled reference STARFIRE reactor, this will lead to the generation of wet and dry low activity wastes. Such wastes will be generated continuously from operations to purify the primary and secondary coolants, from cleaning water used in the blanket sector storage pool and from cleaning airborne discharges. These operations will generate ion exchange resins, liquid phase and gas phase filters, reverse osmosis packages and filter sludges. It is expected that the reference STARFIRE reactor will produce a similar volume of this type of low activity waste to a PWR, since both the design of and the radioactivity contained in the coolants and coolant clean up systems are similar. The annual production of low activity waste from PWRs has been estimated at 640 m^3/GWe-year [4.13]. From this figure, Cannon [4.13] has estimated a value of 900 m^3/GWe-year as the volume of low activity wastes from the routine operations of a water cooled fusion reactor. A more conservative value (approximately a 50 % increase) was selected to ensure that the actual volume of waste generated was not underestimated. For the 1200 MWe reference STARFIRE reactor, this corresponds to a volume of

1,080 m^3 of low level waste produced each year.

The low activation STARFIRE design will employ helium as the coolant. Consequently, waste volumes derived from coolant clean up streams and miscellaneous maintenance operations will differ from those for a water cooled reactor. In a water cooled reactor, more than 90 % of the radioactivity in the liquid waste processing streams arises directly from the primary coolant [4.13]. Different mechanisms of radioactivity generation and transport occur for the helium cooled system, and a smaller volume of solidified concentrates, filters, sludges, resins etc. will be associated with the process streams. The total volume of low activity wastes from the helium cooled reactor has been estimated by Cannon [4.13] to be about one half that for the water cooled reference reactor, or 450 m^3/GWe-year. Since the reactor has been designed to produce 1200 MWe, the annual volume of low level waste generated will be 540 m^3.

Tritiated wastes will be generated in both liquid and solid form. Liquid wastes will include tritiated water, cleaning solvents, and oil. Solid wastes will be derived from blanket sectors, replaced auxiliary components, depleted catalysts, molecular sieve beds and other miscellaneous wastes (e.g. paper, rags, tools, clothes, etc.). Many reactor components which must be replaced will be contaminated with tritium. Decontamination of this equipment will generate effluent which must be processed prior to release to the environment. Additionally, any components containing significant quantities of activation products (for the reference design only) will be stored under water in a waste handling pool. Any residual tritium on the equipment will contaminate the pool water. It is expected that the volume of waste generated from tritium handling and processing will not be largely affected by the coolant used. Hence, volumes of waste produced from tritium processing for the reference and low activation designs will be similar. Cannon [4.13] has indicated that 30 m^3/yr of additional low activity solid waste would be an appropriate estimate. The reference design will also generate storage pool wastes, estimated at 100 m^3/yr [4.13]. The low activation design will have no need for a water storage pool since the level of afterheat associated with the blanket modules (being primarily composed of ceramic material) will be very low [4.21].

The volume of low activity wastes generated at the reference STARFIRE plant (not including the storage pool wastes) is expected to be 1,110 m^3 each year. Based on the use of 0.2 m^3 drums (55 gal), 5,550 drums of waste per year would require disposal. For the low activation STARFIRE plant, approximately 570 m^3 of waste would be generated annually, and 2,850 drums would need to be disposed of. The cost of the disposal drums would be included in the cost of materials for waste handling (i.e. included in the 0.2 % of the total direct and indirect capital cost used as the estimate for materials, labor and overhead costs during waste operations). To estimate the shipping and disposal costs, it was assumed that shallow-land burial was acceptable and that a licensed facility would be located 640 km [4.13, 4.25] from the fusion power plant. Cannon [4.13] has stated that based on the curie content of the waste, 14 drums of the low level waste can be transported in each shipment. This implies 397 shipments per year for the reference design and 204 shipments per year for the low activation design. The wastes generated from the low activation design may contain a smaller quantitiy of radioactivity, allowing for a greater number of drums to be transported per shipment. This would reduce the number of shipments per year. However, due to uncertainties in the actual reduction in activity, this possibility was not accounted for in the cost estimate. The reference plant is expected to produce an additional 100 m^3 of storage pool wastes, which could be placed in 500 drums. The curie content of this waste will be very low, allowing for the transport of 50 drums per shipment. This would then require ten additional waste shipments per year for the reference reactor design.

Shipping charges, using a truck with two drivers, were taken as \$0.82/km, plus a fuel surcharge of 15 % of the basic charge (from reference 4.25, updated to current dollars using price indexes [4.15]). The cost per shipment was then \$605. This resulted in an annual shipping cost for low level wastes of \$246,235 for the reference STARFIRE design and \$123,420 for the low activation design.

The disposal cost for low level wastes in a shallow land burial site is 229 $/m^3 (from reference 4.26, updated to current dollars using price indexes [4.15]). The total volume of low level waste from the reference reactor will be 1,210 m^3, resulting in a disposal cost of $277,090. The total annual shipping and disposal costs for the reference design will amount to $523,325. For the 570 m^3 of low level waste from the low activation plant, the disposal cost will be $130,530. The total of shipping and disposal charges was found to be $253,950. These costs are summarized in table 4.5.

Waste handling operations for activated structures are expected to be dominated by the replacement of the first wall/blanket sectors. Handling, processing and storing blanket segments will involve more complex operations than low activity wastes, essentially due to the much greater volume, weight, activity levels and processing requirements which must be dealt with. Due to the large mass and high levels of radioactivity associated with these components, it is anticipated that the majority of these operations will be carried out remotely.

In a fusion reactor, more than 98 % of the generated activity will be retained as activation products in the first wall and blanket structure of the reactor. The use of low activation materials in the blanket structure can significantly alter the induced radioactivity and hence, the final disposition of the reactor wastes. It has been shown that at shutdown, the low activation design contains approximately three times less radioactivity than the reference design [4.6]. The majority of the induced radionuclides will be short-lived. Consequently, at one day after shutdown, the radioactivitiy concentration of the low activation design blanket structure will be six orders of magnitude less than the concentration at shutdown. Beyond this time, the radioactivity in the low activation design will be dominated by the iron impurity. The reduction in radioactivity and the rapid decay associated with the low activation materials significantly impact radioactive waste generation and waste management procedures. Additionally, the masses of components in the low activation design will be much less than the masses of the corresponding components in the reference design. This will reduce the load capacity requirements of waste handling equipment. The lower radioactivity and afterheat levels will ease the storage and packaging procedures for the waste. The ensuing reduction in costs associated with these benefits are difficult to quantify at this time. However, neglecting to consider them will provide a conservative estimate of the reduction in cost of waste handling for the change to the low activation design.

An assessment of the disposal classifications of the first wall/blanket radioactive wastes of the reference and low activation designs has been performed [4.5]. Waste from the low activation design will be eligible for shallow-land burial. The $LiAlO_2$ and graphite waste from the reference design will be suitable for near-surface burial. The Zr_5Pb_3 requires deeper burial or can be disposed of in a shallow facility with an accompanying engineered structural barrier. The PCA will be highly activated and will require geologic storage. The masses and disposal classifications for wastes generated annually from the reference and low activation reactors are given in table 4.4.

Annual disposal costs for blanket sector wastes for each design have been estimated. Cannon [4.13] has stated that the 48 drums (0.89 m^3 each) of PCA waste from the reference STARFIRE reactor can be shipped in a cask similar to the type used for the transport of spent LWR fuel. Four drums can be transported in each shipment, requiring 12 shipments annually. Because of the radiation level and significant heat generation rate, this waste will not be acceptable for shallow-land burial. It was assumed for the purposes of this study, that this waste would be disposed of in a geological repository located 1,600 km from the fusion plant. The previously stated shipping cost information along with a value of 450,634 $\$/m^3$ for disposal (from reference 4.26, updated to current dollars using price indexes [4.15]) resulted in an estimate of 19.3 M$ for the annual shipping and disposal costs of this waste. The rest of the waste associated with the reference design can be disposed of in a shallow-land disposal site. Cannon [4.13] has stated that the Zr_5Pb_3 would require 23 shipments annually, 4 drums (0.2 m^3 size) being shipped in each instance. The

Table 4.4: Radioactive Waste Classification for the Reference and Low Activation STARFIRE Designs

Material	Mass (MT/yr)	Number of Drums	Disposal Class
Reference Design:			
PCA	71	48	D
Zr_5Pb_3	55	90	C
$LiAlO_2$	100	375	A
Graphite	27	115	A
Low Activation Design:			
Al	3	12	A
SiC and Li_2O	141	123	A
Graphite	28	115	A

Disposal Classes:

A: Shallow-land burial with minimum requirements on waste form and packaging (cost $\sim 229\$/m^3$[4.26]).

B: Shallow-land burial, but waste form must be stabilized and packaged so that it does not degrade for 150 years.

C: Shallow-land burial with waste form requirements of class B and special measures at the disposal facility, such as deeper burial or engineered structural barriers (cost $\sim 379\$/m^3$[4.26]).

D: Wastes excluded from shallow-land burial; requires geologic storage (cost $\sim 450,634\$/m^3$[4.26]).

graphite will be placed in 115 drums (0.2 m^3 size) and disposed of in 3 shipments. The lithium aluminate will require 9 shipments annually to dispose of the 375 drums (0.2 m^3 size). The annual cost to transport this waste to the shallow burial site will be $21,175; the disposal costs will amount to $29,416. The total cost to dispose of the first wall/blanket wastes from the reference STARFIRE design were found to be 19.3 M$. The total waste disposal cost for the reference STARFIRE design, including the disposal of all low level waste and the high level PCA waste, will be approximately 19.8 M$ (see table 4.5).

The need to dispose of high activity waste will be eliminated with the low activation design. The levels of activity in these wastes will be low. Hence, minimal precautions will be needed during shipment. It is estimated that all the waste associated the the low activation design can be shipped to the disposal site in no more than 9 trips annually. Shipping costs were estimated at $5,445 and disposal costs were estimated at $16,717. The total disposal cost for first wall/blanket waste from the low activation design will be $22,162. Including the contribution of the low level waste from stream clean up resulted in a total waste disposal cost of $276,112 (see table 4.5).

Evaluation of the health detriment costs for each design required values for doses incurred during waste handling operations. As discussed earlier, it is expected that relatively small doses will be incurred during waste management operations. In section 4.3.1, an estimate of 0.65 person Sv was given for the total cumulative dose incurred at the reference STARFIRE plant. This will mainly be due to the daily waste handling tasks. The waste from first wall/blanket changeouts is expected to be handled remotely and processed offsite. Hence, a small contribution to the dose incurred is anticipated. Neglecting this dose will provide a conservative estimate of the dose savings since the dose incurred during these operations for the low activation design will be less than that for the reference design. At the low activation STARFIRE plant, the volume of daily waste handled is expected to be approximately one-half that of the reference STARFIRE plant. The dose incurred will be proportional to the volume of waste and the level of activity handled. Cannon [4.13] has estimated the radionuclide concentration in these wastes for a helium-cooled standard design to be diminished by two orders of magnitude. It is expected that the use of low activation materials in conjunction with the helium coolant will further reduce this dose. Since the activity levels of these wastes is not well known, this reduction was not specifically accounted for. However, neglecting this further reduction should not lead to erroneous conclusions since the estimate of the dose incurred for the helium-cooled design is already significantly below the reference design. Hence, an estimate of the dose incurred would be 3.25×10^{-3} person Sv.

A savings in the dose incurred during the transport of plant wastes to the disposal site will result from the use of the low activation design. Doses incurred during shipment of wastes from the reference plant are expected to be comparable to that for LWRs. Transport of high activity PCA waste is analagous to the transport of irradiated fuel; transport of low activity wastes is analagous to the transport of solid waste generated at LWRs. Values for the doses incurred can be estimated using information given by Cannon [4.13]. The annual dose incurred during shipment of wastes from the reference plant was assessed at 5×10^{-2} person Sv. Since the number of shipments per year is roughly half, and only low activity wastes will be transported from the low activation plant, the annual dose incurred during the shipment of waste was estimated as 1×10^{-2} person Sv. (Note that this only includes a reduction in the activation of the wastes resulting from the use of helium as the coolant; the effect of the low activation materials on the activity of the waste is not accounted for.)

The total dose incurred during waste handling operations is given in table 4.6. Health detriment costs and the total cost associated with waste handling are given in table 4.5. Again, health detriment costs appear to be negligible in comparison to the other costs.

4.3.2.5 Conclusions Regarding The Cost Effectiveness Of The Low Activation Design

The previous sections have discussed the capital, operating, maintenance and waste handling costs associated with the reference and low activation STARFIRE designs. Table 4.5 summarizes the annual cost contributions for the reference STARFIRE design and the low activation STARFIRE design over a range of prices for silicon carbide components. A pictoral representation of the annual costs associated with each design is given in figure 4.1. It is evident that the capital cost component is dominant for all cases, while the waste handling costs contribute the least. From figure 4.1, it appears that the reference and low activation STARFIRE designs result in nearly identical annual costs if the installed cost of silicon carbide components is approximately 110 $/kg. Small increases in the annual capital, operating and maintenance costs for the low activation design are offset by the reduction in waste handling costs, keeping the total cost nearly the same as for the reference design.

The methodology of Chapter 2 requires that a value be obtained for β in order for the cost effectiveness of a dose reduction measure to be assessed. This represents the actual spending on the dose reduction. The change in total costs associated with the modification to the low activation design are given in table 4.5. An annual savings of 45.1 M$ is foreseen in switching to the low activation design if the installed cost of silicon carbide components is 30 $/kg. Accompanying this cost savings is an annual dose savings of 6.82 person Sv. Hence, the reduction in the dose incurred is achieved with an actual savings in expenditures. With these facts, the low activation design appears very attractive. However, if the installed cost of silicon carbide components is 110 $/kg, an increase in costs of 0.1 M$ is foreseen. If the installed cost of silicon carbide components is 315 $/kg, the increase in costs accompanying the change to the low activation design is 115.3 M$. The resulting reduction in dose for these two cases is still 6.82 person Sv.

The ceiling on safety expenditures (α) was calculated as 529,824 \$/person Sv in section 4.3.2.1. Using equation (2.4), a value of -6.61 M\$/person Sv was obtained for the actual spending on the dose reduction measure (β) for the 30 \$/kg case. If the cost of silicon carbide is 110 \$/kg, the actual spending on dose reduction is 0.015 M\$/person Sv (14,663 \$/person Sv), while if the cost is 315 \$/kg, the spending is 16.9 M\$/person Sv.

For the lower bound estimate of 30 \$/kg as the installed cost of silicon carbide, a negative value for β was obtained. This does not render the analysis invalid, but indicates that if this price is attainable, the low activation materials design option should definitely be pursued.

The cost of silicon carbide used in this study did not include a research and development component. The justified spending on research and development was estimated using:

$$\left(\frac{C_T + C_{RD}}{D_T}\right) = \alpha \tag{4.1}$$

where

C_{RD}= the justified annual spending on research and development of low activation materials (\$/yr)

and the other parameters have been previously defined. Using the appropriate values for these parameters for a silicon carbide cost of 30 \$/kg allowed the justified spending on research for the development of low activation materials to be ascertained. The resulting value for C_{RD} was 48.7 M\$/yr. Thus, during the life of the plant it would be justified to spend 48.7 M\$ annually on the research and development of low activation materials.

Since fusion power has not yet been demonstrated, it would be more useful to know the justified research and development expenditures at the current point in time. Assuming that the cost of 30 \$/kg will be achievable once fusion power is realized on a commercial scale and that this will occur 30 years from now, the justified annual spending on the research and development of low activation materials is 10.9 M\$/yr. For an accelerated research program, it would be justified to spend 38.2 M\$/yr during each of the next five years, or 21.5 M\$/yr during each of the next ten years for the development of low activation materials (see figure 4.3).

Since the value of β obtained when the cost of silicon carbide was assumed to be 110 \$/kg was less than α , the use of low activation materials is justified. The margin between α and β was used to indicate the justified spending on research and development for low activation materials. Applying equation 4.1, an estimate of 3.51 M\$/yr for C_{RD} was obtained. If the cost of silicon carbide 30 years from now is actually 110 \$/kg, then the justified annual spending on research and development of low activation materials up until this time is 0.78 M\$/yr. Alternately, it would be justified to spend 2.75 M\$/yr over the next five years or 1.55 M\$/yr over the next ten years on the research and development of low actvation materials (see figure 4.3).

Examining the case of the upper bound cost estimate for the price of silicon carbide lead to the conclusion that if the cost of silicon carbide is as high as 315 \$/kg 30 years from now, then it would be unjustified to employ the low actvation design.

The sensitivity of the total annual costs of the low activation design to the price of silicon carbide is illustrated in figure 4.2. This also indicates the variation of β with the cost of silicon carbide since β is proportional to the total annual cost. It appears that a linear relationship exists between the installed cost of silicon carbide components and the resulting total annual cost. The cost of silicon carbide for which β is equal to α represents the point where the low activation design is just cost effective. Using the value of 529,824 \$/person Sv for β (i.e. equating it to α) and 6.82 person Sv for D_T, gives a change in annual costs, or C_T, of 3.6 M\$/yr. Adding this to the total annual cost for the reference design of 399.1 M\$/yr (see table 4.5) gives an annual cost of 402.7 M$/yr. The maximum annual cost for which the low actvation design would be cost effective is then 402.7 M$/yr. Applying the equation given in figure 4.2, a maximum installed cost for silicon carbide components of 116 $/kg was obtained. This would not allow for any research and development costs. Before a more definite conclusion on the cost effectiveness of low activation materials can be drawn, a more accurate estimate for the cost of silicon carbide is required. If, once more detailed studies are performed, a projected cost of silicon carbide less than 116 $/kg is obtained, then the low activation design effort should be augmented.

Figure 4.1: Annual Cost Contributions for the Reference and Low Activation STARFIRE Designs

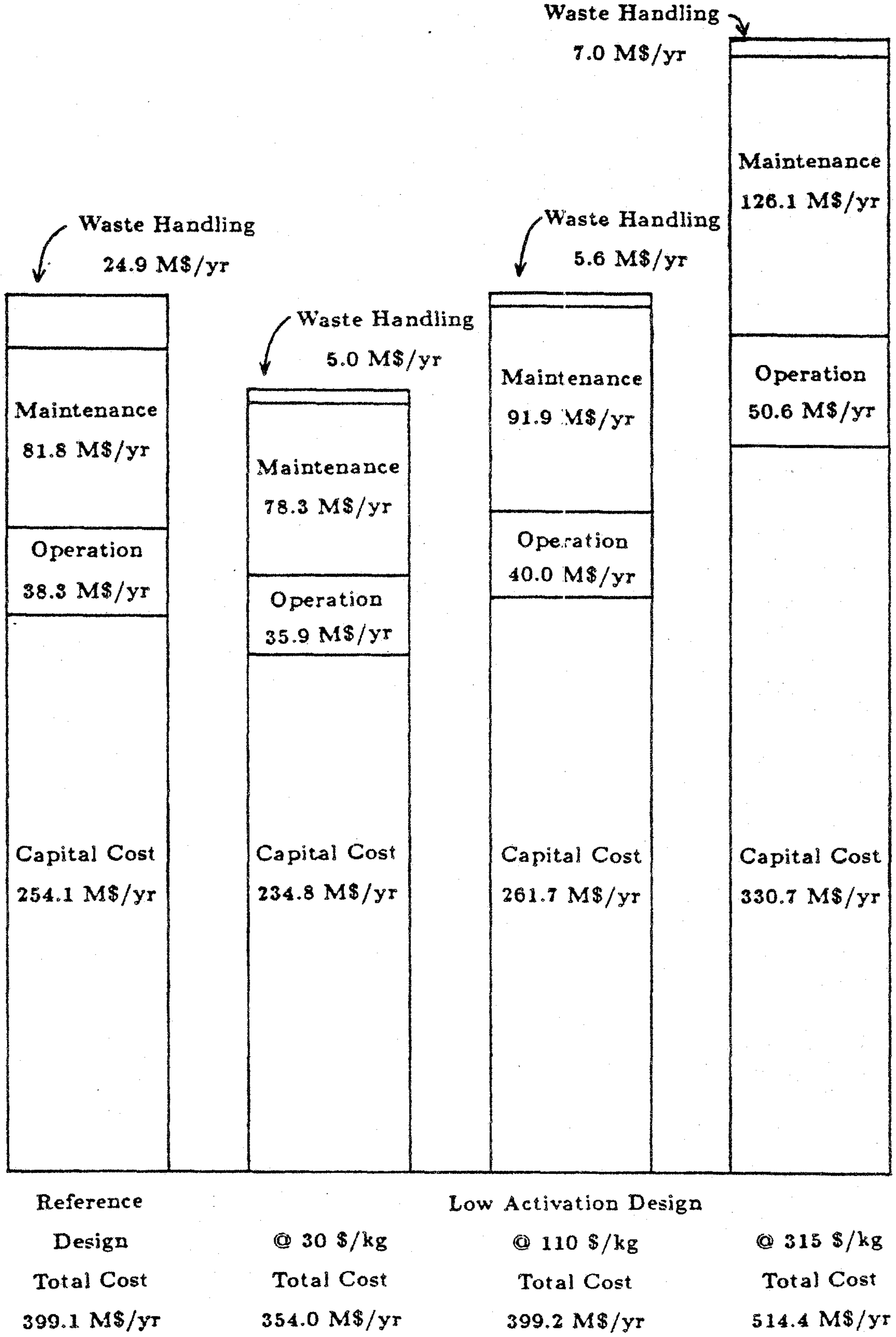


Figure 4.2: Total Annual Cost for the Low Activation STARFIRE Design versus Installed Cost of Silicon Carbide Components

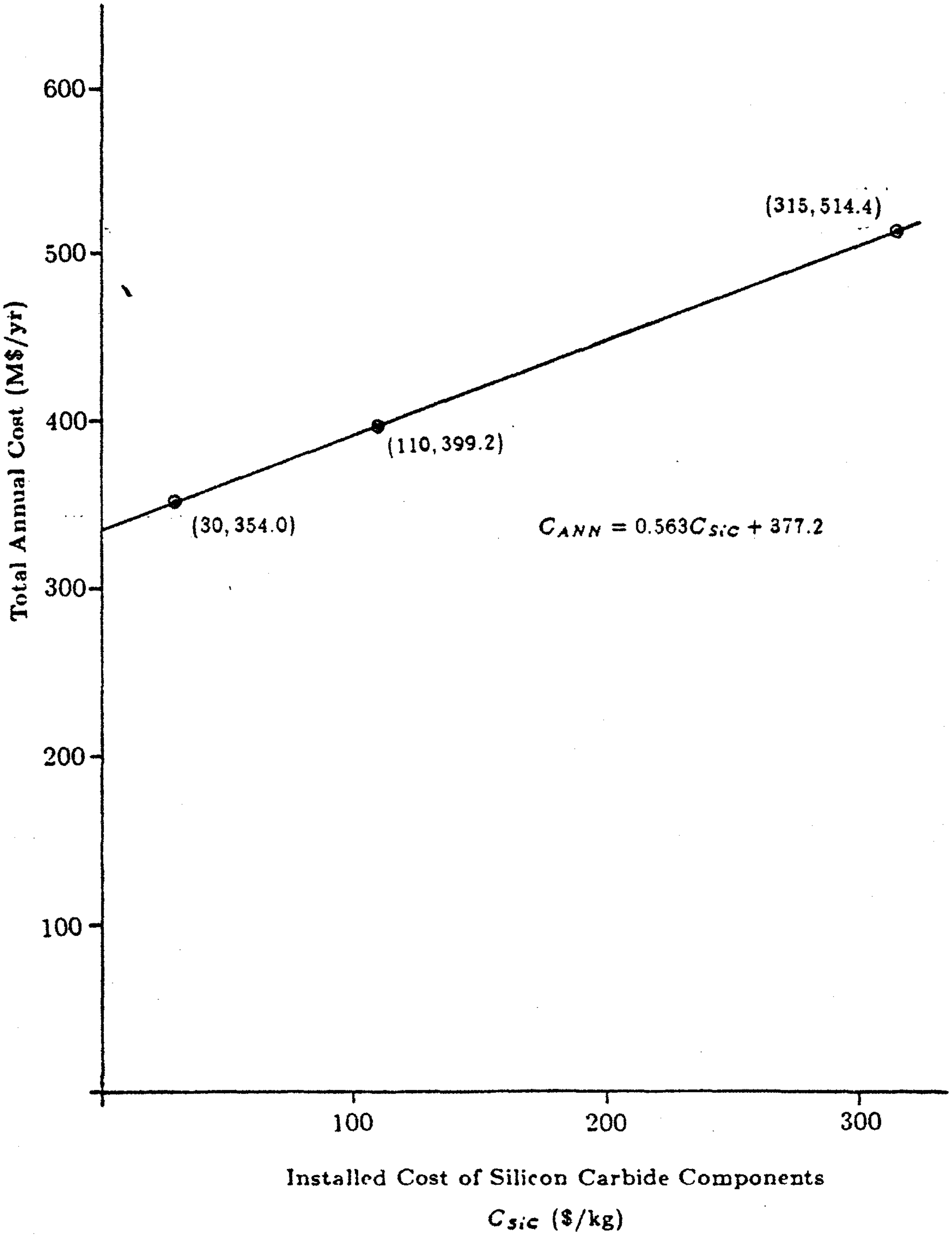


Figure 4.3: Possible Financial Plans for Low Activation Materials Research and Development

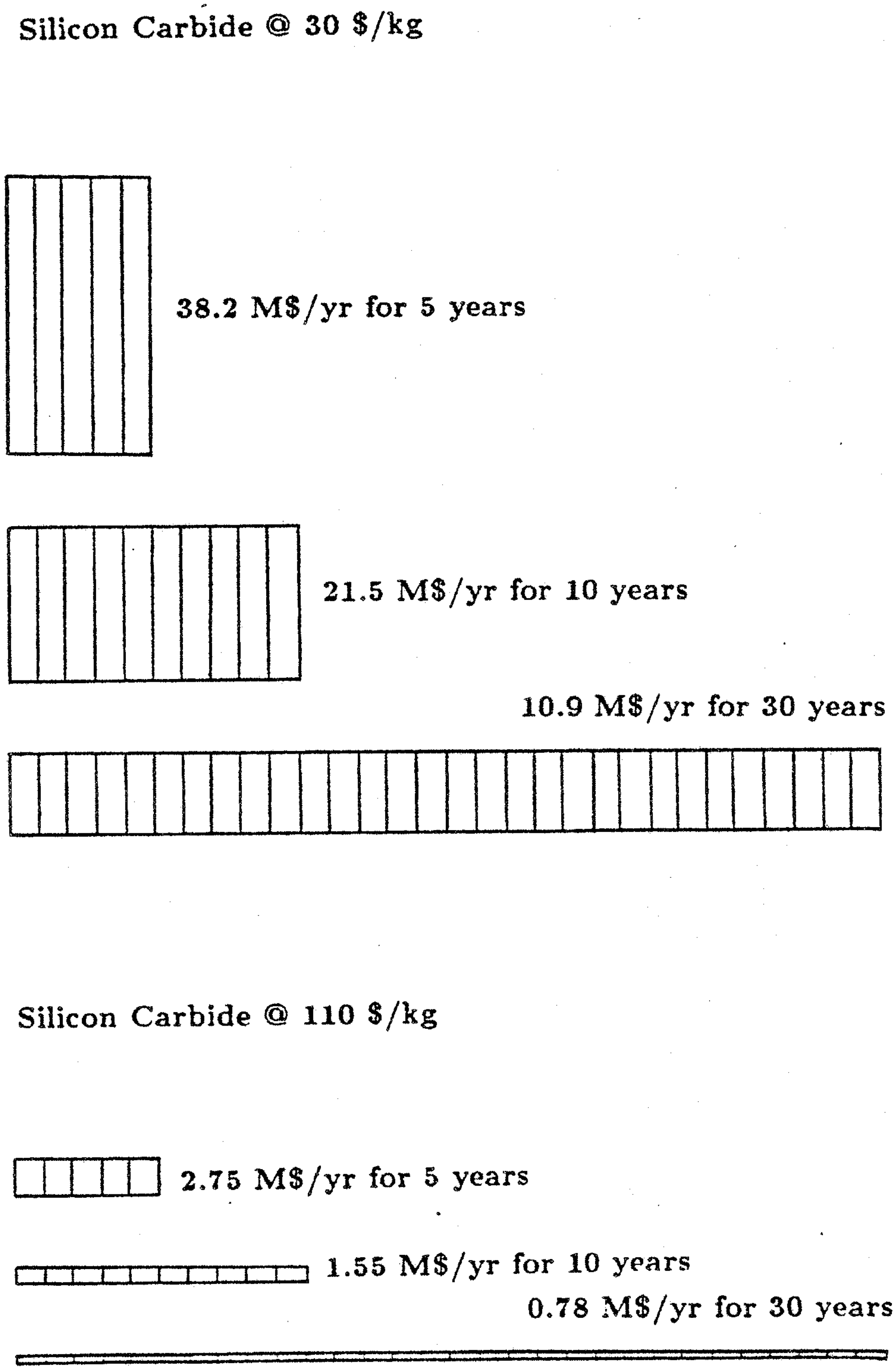


Table 4.5: Cost Estimates for Plant Operation, Maintenance and Waste Handling

Cost Component	Cost for RD (M$/yr)	Cost for LAD @ 30 $/k (M$/yr)	Change in g Cost (M$/yr)	Cost for LAD @ 110 $/kg (M$/yr)	Change in Cost (M$/yr)	Cost for LAD @ 315 $/kg (M$/yr)	Change in Cost (M$/yr)
Normal Plant Operation:							
Materials, Labor, Overhead	38.3	35.9		40.0		50.6	
($C_{MO} + C_{LO} + C_{OHO}$)			-2.4		+1.7		+12.3
Health Detriment	3.9×10^{-6}	4.0×10^{-6}		4.0×10^{-6}		4.0×10^{-6}	
(C_{HO})			$+1.0 \times 10^{-7}$		$+1.0 \times 10^{-7}$		$+1.0 \times 10^{-7}$
(excluding contribution from the coolant/steam generator system)							
Total for Normal Operation	38.3	35.9		40.0		50.6	
(C_{TO})			-2.4		+1.7		+12.3
Plant Maintenance:							
Materials, Labor, Overhead	12.8	11.3	-1.5	12.7	-0.1	16.0	+3.2
(not including FW/B changeouts)							

Cost Component	Cost for RD (M$/yr)	Cost for LAD @ 30 $/k (M$/yr)	Change in g Cost (M$/yr)	Cost for LAD @ 110 $/kg (M$/yr)	Change in Cost (M$/yr)	Cost for LAD @ 315 $/kg (M$/yr)	Change in Cost (M$/yr)
First wall/blanket Changeouts	9.8	9.7	-0.1	21.8	+12.0	52.8	+43.0
Total Materials, Labor, Overhead ($C_{MM} + C_{LM} + C_{OHM}$)	22.6	21.0	-1.6	34.5	+11.9	68.8	+46.2
Health Detriment (C_{HM}) (including contribution from coolant/steam generator system during operation)	2.35 x 10^{-2}	1.87 x 10^{-4}	-2.33 x 10^{-2}	1.87 x 10^{-4}	-2.33 x 10^{-2}	1.87 x 10^{-4}	-2.33 x 10^{-2}
Replacement Power (C_{PM})	59.2	57.3	-1.9	57.3	-1.9	57.3	-1.9
Total for Maintenance (C_{TM})	81.8	78.3	-3.5	91.9	+10.0	126.1	+44.3

Cost Component	Cost for RD (M$/yr)	Cost for LAD @ 30 $/k (M$/yr)	Change in Cost (M$/yr)	Cost for LAD @ 110 $/kg (M$/yr)	Change in Cost (M$/yr)	Cost for LAD @ 315 $/kg (M$/yr)	Change in Cost (M$/yr)
Waste Handling:							
Materials, Labor, Overhead ($C_{MW} + C_{LW} + C_{OHW}$)	5.1	4.7	-0.4	5.3	+0.2	6.7	+1.6
Disposal of Low Level Waste (from stream clean up)	0.52	0.25	-0.27	0.25	-0.27	0.25	-0.27
Disposal of first wall/ blanket Waste	19.3	2.2×10^{-2}	-19.3	2.2×10^{-2}	-19.3	2.2×10^{-2}	-19.3
Total for Waste Disposal (C_{DW})	19.8	0.27	-19.5	0.27	-19.5	0.27	-19.5
Health Detriment (C_{HW})	2.7×10^{-3}	5.1×10^{-5}	-2.7×10^{-3}	5.1×10^{-5}	-2.7×10^{-3}	5.1×10^{-5}	-2.7×10^{-3}
Total for Waste Handling (C_{TW})	24.9	5.0	-19.9	5.6	-19.3	7.0	-17.9

Cost Component	Cost for RD (M$/yr)	Cost for LAD @ 30 $/k (M$/yr)	Change in g Cost (M$/yr)	Cost for LAD @ 110 $/kg (M$/yr)	Change in Cost (M$/yr)	Cost for LAD @ 315 $/kg (M$/yr)	Change in Cost (M$/yr)
Total Capital Cost	254.1	234.8		261.7		330.7	
(C_C)			-19.3		+7.6		+76.6
Total Cost	399.1	354.0		399.2		514.4	
(C_T)			-45.1		+0.1		+115.3

Table 4.6: Estimates of Annual Doses Incurred During Plant Operation, Maintenance and Waste Handling

Reason for Incurring Dose	Cumulative Dose Incurred (person Sv/yr)		
	RD	LAD	Dose Savings
Tritium exposures during plant operation ($\sim D_{TO}$)	1.02×10^{-3}	1.03×10^{-3}	-1.0×10^{-5}
Tritium exposures during plant maintenance	3.41×10^{-4}	3.27×10^{-4}	$+1.4 \times 10^{-5}$
Total tritium exposures	1.36×10^{-3}	1.36×10^{-3}	0
Coolant/steam generator system maintenance (including any doses during operation)	6.0	4.72×10^{-6}	+6.0
Contact maintenance of reactor equipment	2.99×10^{-5}	4.90×10^{-2}	-4.90×10^{-2}
First wall/blanket replacement	0.18	1.8×10^{-7}	+0.18
Total dose during maintenance (including a small contribution from coolant/steam generator exposures during operation) ($\sim D_{TM}$)	6.18	4.93×10^{-2}	+6.13

Reason for Incurring Dose	Cumulative Dose Incurred (person Sv/yr)		
	RD	LAD	Dose Savings
Handling of daily plant wastes (low level)	0.65	3.3×10^{-3}	+0.65
Shipment of wastes	5.0×10^{-2}	1.0×10^{-2}	$+4.0 \times 10^{-2}$
Total during waste handling (not including dose from first wall/blanket processing) (D_{TW})	0.70	1.33×10^{-2}	+0.69
Total dose (D_T)	6.88	6.37×10^{-2}	+6.82

4.4 References

(4.1) G. Hopkins, E. Cheng, R. Creedon, I. Maya, K. Schultz, P. Trester and C. Wong, Low Activation Fusion Reactor Design Studies, General Atomic Technologies, GA-A17018, June 1983.

(4.2) C.C. Baker et al., STARFIRE - A Commercial Tokamak Fusion Power Plant Study, Argonne National Laboratory, ANL/FPP-80-1, September 1980.

(4.3) E. Cheng and G. Hopkins, The Nuclear Design of a Very Low Activation Fusion Reactor, General Atomic Technologies, GA-A17012, June 1983.

(4.4) Low Activation Materials Safety Studies Project Staff, Annual Report for Fiscal Year 1980, General Atomic Technologies, GA-A16005, December 1980.

(4.5) Low Activation Materials Design Study Project Staff, Annual Report for Fiscal Year 1981, General Atomic Technologies, GA-A16426, September 1981.

(4.6) Low Activation Materials Safety Studies Project Staff, Annual Report for Fiscal Year 1981, General Atomic Technologies, GA-A16425, September 1981.

(4.7) S. Burnett, G. Hopkins, E. Cheng, R. Price and K. Schultz, The Low Activation Fusion Reactor Concept, General Atomic Technologies, GA-A16810, September 1982.

(4.8) Low Activation Design Study Project Staff, Annual Report for Fiscal Year 1982, General Atomic Technologies, GA-A16874, November 1982.

(4.9) E. Cheng, Radioactivation Characteristics for Fusion Reactors, General Atomic Technologies, GA-A16948, November 1982.

(4.10) W. Chen and E. Cheng, A Minumum Thickness Low Activation Toroidal Field Coil Concept for Tokamak Reactors, General Atomic Technologies, GA-A17016, June 1983.

(4.11) G. Hopkins and E. Cheng, Low Activation Fusion Rationale, General Atomic Technologies, GA-A16961, January 1983.

(4.12) C.E. Easterly, Occupational Radiation Exposures at a Fusion Power Station, Nuclear Technology/Fusion, 2, p. 723, October 1982.

(4.13) J.B. Cannon, Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy, Oak Ridge National Laboratory, DOE/ER-0170, August 1983.

(4.14) G.F. Knoll, Radiation Detection and Measurement, John Wiley and Sons, New York, 1979.

(4.15) United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States: 1984, 104th edition, Washington D.C., 1984.

(4.16) S. Schulte et al., Fusion Reactor Design Studies - Standard Accounts for Cost Estimates, Pacific Northwest Laboratory, PNL-2648, May 1978.

(4.17) M.S. Kazimi, M.I.T. Nuclear Engineering Department, private communication, August 1984.

(4.18) D. Smith, Argonne National Laboratory, private communication, August 1984.

(4.19) I. Maya, General Atomic Technologies, private communication, based on information obtained from Carborundum, September 1984.

(4.20) K. Schultz, General Atomic Technologies, private communication by letter, November 1984.

(4.21) K. Schultz, General Atomic Technologies, private communication, July 1984.

(4.22) W.E. Bickford, Transport and Deposition of Activation Products in Helium Cooled Fusion Power Plants, Pacific Northwest Laboratories, PNL-3487, September 1980.

(4.23) M.A. Abdou, G. Fuller, E. Hager and W. Vogelsang, Shielding and Maintainability in an Experimental Tokamak, Argonne National Laboratory, ANL/FPP/TM-127, p. 54, November 1979.

(4.24) M. Sniderman, Fusion Reactor Remote Maintenance Study, Electric Power Research Institute, EPRI-ER-1046, April 1979.

(4.25) I. Maya, H Levine, D. Peterman, S. Stausberg and K. Schultz, Assessment of Alternative Dispositions for Irradiated Magnet Materials, General Atomic Technologies, GA-A16879, October 1982.

(4.26) R.C. Maninger and D.W. Dorn, Some Issues in Waste Management of Activated Structural Materials in Fusion Power Reactors, Presentation at the Low Activation Materials Panel Meeting, University of California Los Angeles, April 1982.

(4.27) Report of the DOE Panel on Low Activation Materials for Fusion Applications, University of California Los Angeles, PPG-728, June 1983.

(4.28) Report of INFCE Working Group 7, Waste Management and Disposal, International Atomic Energy Agency, Vienna, 1980.

(4.29) L. Rovner, R. Bourque and K. Chen, Applications of Low Atomic Number Ceramic Materials to Fusion Reactor First Walls, Electric Power Research Institute, EPRI-ER-216, August 1976.

(4.30) R. Kramer, E. Franz, R. Wagner, R. Guerra, S. Ray and W. Wahnsiedler, Low Activation Structural Materials for Fusion Reactors - Extreme Purity Base Aluminum Alloys, Electric Power Research Institute, EPRI-AP-2220, February 1982.

(4.31) R.D. Wittmeier and E.G. Schmidt, Cooper Nuclear Station: Decommissioning Alternatives, Costs and Considerations, March 1983.

(4.32) D.L. Kummer, ed., Conference Proceedings: Low Activation Materials Assessment for Fusion Reactors, Electric Power Research Institute, EPRI-ER-328-SR, March 1977.

(4.33) J.A. White, M.H. Agee and K.E. Case, Principles of Engineering Economic Analysis, John Wiley and Sons, Inc., New York, 1977.

Chapter 5

Assessment Of The Cost Effectiveness Of Emergency Detritiation Systems for INTOR

Tritium control is a major concern for D-T fueled fusion reactors. In the event of an accidental release of a relatively large quantity of tritium, some provision must be made for returning the hall atmosphere to acceptable tritium levels. The major economic issues are the capital and operating costs associated with a given system capability. In this section, several emergency detritiaion systems for INTOR are examined. The purpose of this chapter is to determine which system is most cost effective.

5.1 Description Of The Detritiation Systems

An air detritiation system is composed of several parts: a blower, an air preheater, a catalytic reactor after cooler and a water removal system. The emergency systems are identical to those used during normal plant operation, and are required to increase the total tritium removal capability during an accident situation.

The emergency systems considered were all assumed to be of the same design, and varied only in their processing capacity. The approach of using several smaller units as opposed to a single larger system for emergency situations was adopted. Each system would be composed of units having a capacity of 140 m^3/min. Such units have been designed but not yet built at Lawrence Livermore Laboratory [5.1]. Using the smaller units in this assessment would avoid uncertainties arising from scaling up from existing technology. Other potential problems, associated with manufacturing, handling and installation of large sized equipment and the possibility of inefficient flow behavior through larger diameter reactor and dryer beds, would be avoided. Several smaller units provide system flexibility and redundant capabilities in the event that one of the units fail.

The emergency detritiation systems were evaluated for a given accidental release of tritium. The source term was considered to be the cryopumps, from which a release of 25 g (2.4 x 10^5 Ci) of tritium was assumed to occur. This accident can be categorized as a type II event. Although some radioactivity has been released, it is expected to be well contained in the reactor building. Hence, no offsite consequences will result. For the purpose of this analysis, the release was assumed to occur instantaneously, to consist entirely of elemental tritium and to disperse rapidly within the reactor building resulting in an immediate uniform concentration. A previous study [5.1] concluded that it did not appear economically justified to maintain the reactor building at a level below 50 μCi/m^3. Hence, this value was adopted as the tritium concentration to which the reactor building must be returned.

Four clean up options were examined for the 25 g release, consisting of three, two, one or no detritiation units. All systems were assumed to remove tritium at an efficiency of 90 %. The reactor building volume into which the tritium is released was taken to be 50,000 m^3. The capital cost associated with reactor building detritiation includes the cost of the detritiation system, the cost of the building to contain the system and the cost of the tritiated water recovery unit. Approximate capital costs associated with each clean up option were taken from reference 5.1 and are summarized in table 5.1. As expected, the shortest clean up time, requiring the largest number of clean up units results in the highest capital cost. A shorter clean up time would correspond to an improved reactor availability and a reduced period of potential worker exposure. Hence, it was necessary to determine if these benefits outweighed the increased cost.

Table 5.1: Detritiation Options Capital Costs [5.1]

Clean up Option	Number of Units	Capital Cost (M$)
A	0	0.0
B	1	21.0
C	2	25.5
D	3	30.0

5.2 Assessment Of The Cost Effectiveness Of The Emergency Detritiation Systems

The methodology of Chapter 3 will be illustrated in this section. The cost effectiveness of the proposed detritiation systems will be assessed. The relevant economic risks associated with each system will be evaluated. Since the detritiation systems will affect doses incurred by plant workers, the ceiling on safety expenditures will be defined based on occupational exposures. Knowing the radiation dose incurred employing each system, the most cost effective alternative will be selected.

5.2.1 Ceiling On Expenditures For The Accident Being Studied

The cost effectiveness of a particular option for reducing accident consequences can be assessed using the procedure outlined in Chapter 3. A maximum value for spending on accident consequence mitigation (α_a) can be found.

The ceiling on expenditures was given by equation 3.1 in section 3.3. The value used for R, the actual exposure rate, should be the maximum dose rate, immediately after the accident occurrence, since this is the maximum dose rate to which there is a potential for exposure. Assuming that the 25 g of tritium is released in the form of HT, and applying a dose conversion factor of $7.717 \times 10^{-7}\ \frac{\text{Sv/min}}{\text{Ci/m}^3}$ [5.2], the dose rate immediately after the release has occurred would be 3.70×10^{-6} Sv/min, for a reactor building volume of 50,000 m^3. Note that this dose rate exceeds the exposure limit for normal conditions of 9.51×10^{-8} Sv/min (0.05 Sv/yr).

In calculating α_a, labor costs were assumed to be 57,000 \$/person yr, as for normal plant operation. Using this value and the previously mentioned dose rate, a value for α_a was obtained. This was found to be 7.11×10^6 \$/person Sv.

Comparison with currently employed spending limits in the fission power industry placed this value on the high end of the scale. Vivian [5.3] has surveyed national and international organizations to assess current trends on spending for radiation protection [5.4, 5.5, 5.6, 5.7]. Values ranged from tens of thousands of dollars per person sievert to millions of dollars per person sievert. In one instance, a recommended spending limit if \$$10^5$ per person sievert for individual doses in the range from 5 x 10^{-4} to 5 x 10^{-3} Sv was given. In the present study, the release of 25 g of tritium could lead to doses for unprotected workers (i.e. no bubble suits worn) greater than 5 x 10^{-3} (doses taken from table 5.5, increased by a factor of 100 for unprotected workers). Increasing the spending limit to allow for this possibile increased exposure would lead to values of the same order of magnitude as the value determined in this study. Vivian [5.3] also quoted another source which gave a justified spending limit of \$2.5 x 10^6 per person sievert [5.6, 5.7]. This estimate was just slightly below the value calculated here.

The numbers quoted above refer to normal plant conditions. It has been suggested that when individual doses approach the dose limit, it may be appropriate to arbitrarily increase the accepted spending on safety by an order of magnitude [5.8]. In this way, further impetus for dose reduction would be provided. Since the possibility of exceeding dose limits subsequent to an accident is greater than in normal situations, the appropriate expenditure ceiling for accident situations can be taken to be an order of magnitude higher than under normal conditions. This would place the expenditure ceiling calculated here in agreement with other values. Furthermore, some uncertainty in the value of the expenditure ceiling could arise from the exposure limit used in the calculation. The exposure limit chosen for this case was that used for normal conditions. If the total dose limit of 0.25 Sv was employed, then an exposure limit in the area of 0.03 Sv/hr would result (for a worker continually exposed for an eight hour shift). This would considerably reduce the expenditure ceiling. However, it was felt that exposure of a worker to this extreme was unnecessary. Use of the exposure limit for normal conditions was felt to be suitable in this case.

5.2.2 Health Effects Costs

Subsequent to the accidental release of 25 g of tritium from the cryopumps, it will be necessary to implement a cleanup and repair program. This will involve worker entry into the reactor hall and hence, worker exposure. In this assessment, it has been assumed that worker entry will be prohibited until the tritium concentration has been reduced to below 500 μCi/m^3. At this time, workers wearing bubble suits and supplied air may enter to perform clean up tasks. A protection factor of 100 against tritium can be provided by wearing these suits [5.1].

One further consideration is that of worker exposure due to induced structural activity. The reactor has been designed to allow personnel entry into the reactor building at a minimum of 24 hours subsequent to shutdown. The delay of entry will allow the induced gamma background to decay to an acceptable level for personnel access. This stipulation only comes into play when assessing option D, since for the other systems, it is the tritium concentration which controls the time of worker entry (for option D, the tritium level falls below 500 μCi/m^3 before 24 hours has passed). The gamma dose rate was assumed constant at 2.5 x 10^{-5} Sv/hr (2.5 mrem/hr), the value expected 24 hours after shutdown. Since the time periods of concern are shortly after shutdown (< 3 days), assuming that this dose rate is constant should not introduce a large error.

Since the tritium transported in the fueling system will be in its elemental form, it was assumed that the release consisted entirely of HT. Tritium activity levels were based on a clean up system efficiency of 90 %, a decay half life of 12.3 years and a conversion half life to HTO of 6.5 years [5.4]. The quantity of HTO present is an important consideration since it is a much more hazardous form of tritium, due to the efficient uptake of water by the human body. Dose conversion factors used were 1.893 x 10^{-3} $\frac{\mathrm{Sv/min}}{\mathrm{Ci/m^3}}$ for HTO and 7.717 x 10^{-7} $\frac{\mathrm{Sv/min}}{\mathrm{Ci/m^3}}$ for HT (calculated from information given in reference 5.2).

System time constants were calculated assuming that clean up was essentially complete once the tritium level was within 5 % of the steady state operating room concentration. According to the work performed by Finn and Rogers [5.1], maintenance of levels below 50 μCi/m^3 does not appear justified from an economic standpoint (for average tritium losses of 100 Ci/day). Adopting this value as the normal operating tritium concentration in the reactor building resulted in the "end of clean up" concentration (5 % above the steady state level) being 52.5 μCi/m^3.

In order to estimate the cumulative dose incurred, it was assumed that a crew of 5 men would enter the reactor building after the tritium level had been reduced to 500 μCi/m^3. The crew would then perform the necessary repair tasks to return the plant to normal operation. Additionally, any other maintenance tasks, unrelated to the accident could also be carried out at this time. In this way, the downtime would be used to its fullest. Once the tritium level had achieved 52.5 μCi/m^3, all maintenance operations would be terminated and the reactor would commence operation. Thus, the crew of 5 men would be present in the reactor building from the time when the activity level had reached 500 μCi/m^3 until it had been reduced to 52.5 μCi/m^3.

Important parameters describing the clean up systems are given in table 5.2. Contact maintenance times and the cumulative doses incurred are summarized in table 5.3. Details of the dose determinations are given in appendix E. A profile of the tritium activity with time for each detritiation option is shown in figure 5.1. The remote clean up period occurs until a level of 500 μCi/m^3 is achieved. Beyond this time, contact clean up and maintenance can be carried out, and is terminated when the tritium level has decreased to 52.5 μCi/m^3.

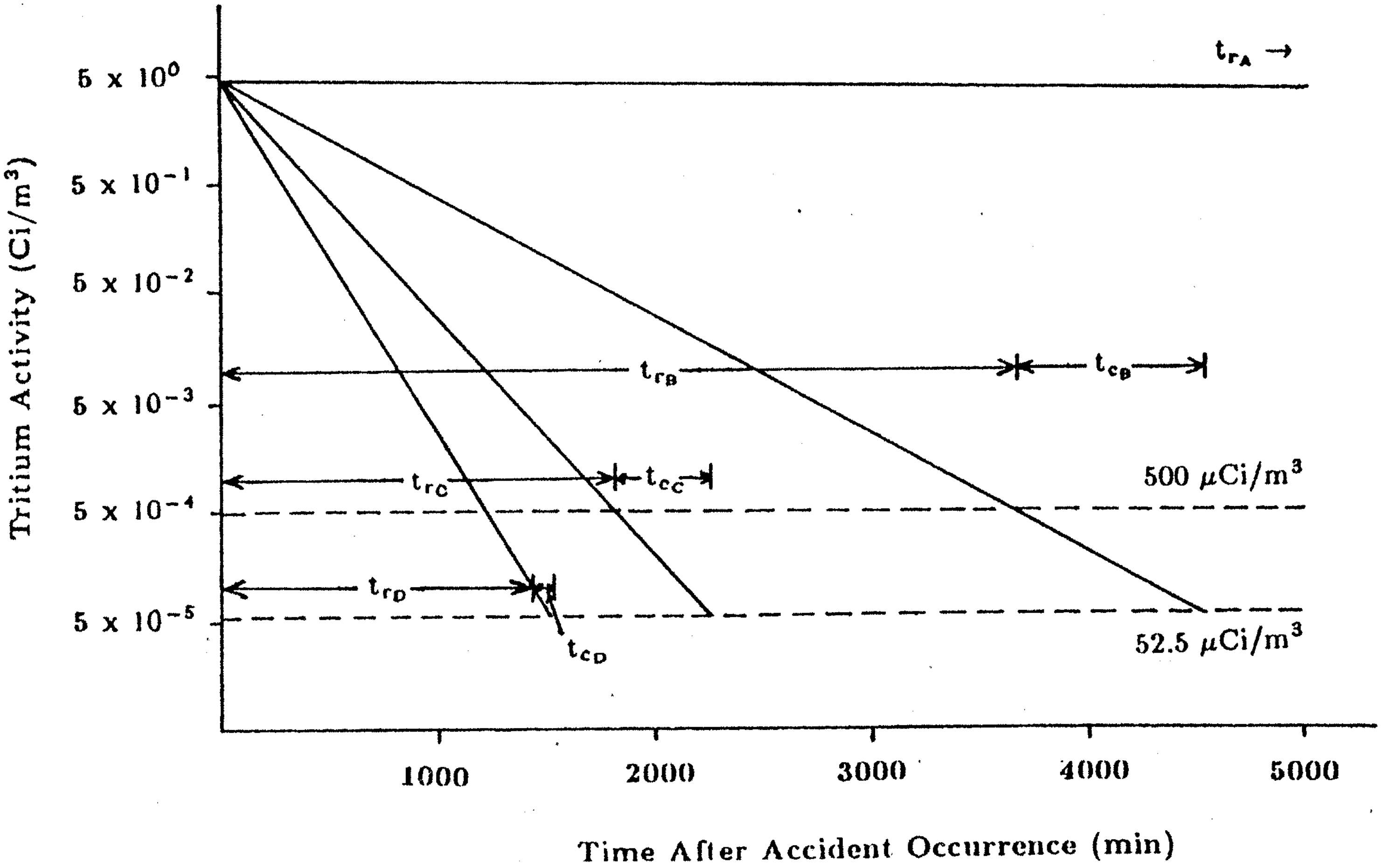
Table 5.2: Clean Up Option Parameters

Option	No. of Clean Up Units	Clean Up Time (min)	Duration of Remote Work (min)	Duration of Contact Work (min)
A	0	1.066×10^8	8.558×10^7	2.102×10^7
B	1	4,533	3,639	894
C	2	2,266	1,819	447
D	3	1,511	1,440	71

Table 5.3: **Doses Incurred During Clean Up**

Option	Duration of Contact Work (min)	Total Dose (person Sv)
A	2.102×10^{7}	4.39
B	894	1.88×10^{-5}
C	447	9.35×10^{-6}
D	71	1.48×10^{-6}

Figure 5.1: Tritium Activity versus Time for Detritiation Options



5.2.3 Replacement Power Costs

Subsequent to the accidental release of tritium, it was assumed that the reactor will be shutdown for clean up and repair. Consequently, it will be necessary to provide replacement power for the service area of the reactor. Although the duration of reactor shutdown may be short, it was assumed that the utility had no other option for meeting the needs of its service area, and replacement power had to be purchased.

The replacement power costs were estimated using the model described in appendix C, assuming the power plant was located in the SPP National Electric Reliability Council region (mid United States). Calculations were based on an electric power generating level of 186 MWe for INTOR (620 MWth [5.9], with an assumed thermal conversion efficiency of 30 %).

The replacement power costs incurred subsequent to the accident were determined to be 744 M$ for option A, 0.321 M$ for option B, 0.160 M$ for option C and 0.107 M$ for option D.

5.2.4 Decontamination Costs

As outlined in Chapter 3, a clean up program must be defined in order to assess decontamination costs. Specific tasks, their duration, the required crew size and the point in time at which the tasks should be carried out must be specified. The decontamination program can be subdivided into phases or periods in which similar tasks are carried out. Since the actual details of the accident and the resulting condition of the plant are not known, it was not possible to specify the decontamination program in detail. However, it was possible to define two distinct decontamination phases: the remote clean up phase and the contact clean up phase.

An estimate of the time at which the manual phase should begin was obtained. However, specific tasks, their duration and commencement times were not identified.

Decontamination costs should include the cost of removal and disposal of radioactive wastes, labor costs, decontamination equipment operating costs and health detriment costs (see equation 3.9 in section 3.6.1.2). Since the accident sequence and the resulting state of the plant were assumed to be the same for all of the systems being examined, the cost of radioactive waste disposal should be the same for all alternatives. Since marginal costs are only important in comparing the alternatives, it was not necessary to include the waste disposal costs.

Table 5.4 presents decontamination costs for each clean up system being considered. Labor costs were based on an assumed crew size of 5 persons and a remuneration rate of 25 \$/hr [5.1]. Decontamination equipment operating costs were assessed on the basis of a unit operating cost of 89 \$/hr (estimated from information given in reference 5.1). This cost would include the utilities costs, water clean up costs and the associated labor costs for the operation of a decontamination unit. Remote maintenance costs were estimated at 350 \$/hr (based on information in reference 5.1). This assumes the use of five robotic units and would include any power requirements, labor costs and maintenance costs resulting from their use during this period.

It should be noted that for options B, C, and D, the effects of discounting and escalation as specified in equation 3.9 in section 3.6.1.2 need not be considered. The periods of time of concern are quite short and the effects of discounting and cost escalation will be negligible. Consequently, each of the cost components in equation 3.9 can be given in dollars, rather than in dollars per year, as would be necessary during a longer decontamination program when discounting and escalation are important. In the case of option A, where no detritiation units are employed, much longer times are involved, and the effects of discounting were considered.

Table 5.4: Decontamination Costs for the Detritiation Options

	Option A ($)	Option B ($)	Option C ($)	Option D ($)
Phase 1: Remote Clean Up				
Equipment Operating Cost (C_{O1})	6.00×10^7	2.66×10^4	1.60×10^4	1.48×10^4
Total Phase 1 Cost (C_{d1})	6.00×10^7	2.66×10^4	1.60×10^4	1.48×10^4
Phase 2: Manual Clean Up				
Labor Cost (C_{L2})	5.54×10^3	1.86×10^3	9.31×10^2	1.48×10^2
Equipment Operating Cost (C_{O2})	0	1.33×10^3	1.33×10^3	3.16×10^2
Health Detriment Cost (C_{H2})	2.11	7.13×10^{-2}	3.55×10^{-2}	5.63×10^{-3}
Total Phase 2 Cost (C_{d2})	5.54×10^3	3.19×10^3	2.23×10^3	4.64×10^2
Total Decontamination Program Cost (C_D)	6.00×10^7	2.98×10^4	1.83×10^4	1.53×10^4

Equation 3.12 also applies a discounting factor. Once again, since the decontamination programs for options B,C, and D are of short duration, this effect can be neglected. The costs incurred during each phase of the decontamination program can simply be added. For option A, it was necessary to apply a discounting factor to the costs incurred during phase two of the decontamination program in order to obtain their present value.

Plant stabilization costs (costs incurred to ensure no further damage will result or to prevent further releases of radioactive materials) should be added at this point, but have not been included in this study. Since the exact condition of the plant is not known, these costs could not be quantified. This should not affect the outcome, since marginal costs are only of concern and plant stabilization costs will be the same for all cases considered (assuming identical accident sequences).

From table 5.4, it appears that the shorter clean up time (option D) gives the lowest decontamination cost. This results from the fact that the equipment is operating for a shorter period of time, resulting in lower operating costs. Phase 1 appears to be the dominant contributor to the decontamination program cost. This is due to the fact that the cost of operating equipment remotely is relatively high. It can also be seen that health detriment costs are almost negligible.

5.2.5 Other Costs

Other cost components which will contribute to the total economic risk of the accident include plant repair costs and possibly fusion power industry costs, electric utility business costs and onsite litigation costs. Decommissioning costs and plant capital investment costs are not expected to contribute to the total economic risk of the accident studied.

Since the same accident sequence was assumed to have occurred for all the detritiation systems being studied, the plant will be in the same condition subsequent to the accident for all cases. Hence, plant repair costs will be the same. Unfortunately, the condition of the plant is not known and hence, repair costs could not be estimated. However, only marginal costs affect the analysis being undertaken and not incorporating the repair costs into the total economic risk will not affect the outcome. Additionally, fusion power industry costs, electric utility business costs and onsite litigation costs will be the same for all systems (and will likely be quite small). These costs are also difficult to quantify and have not been included in this assessment.

The accident being examined does not result in a significant release of radioactivity to areas external to the plant. Consequently, there were no offsite health effects or health care costs to be considered.

5.3 Conclusions Regarding The Cost Effectiveness Of The Detritiation Systems for INTOR

The methodology of Chapter 3 requires that a value be obtained for β_a in order for the detritiation systems to be assessed. The total costs associated with each of the systems being evaluated are required. Approximate capital costs for each option were given in table 5.1. Table 5.5 lists the accident related costs. Since these costs will only be incurred if the accident occurrs, they must be multiplied by the probability of the accident occurring to obtain the appropriate economic risk. Similarly, the doses given in table 5.3 for each option should be multiplied by the accident probability to give the health risk. It was assumed that the probability of the given accident occurring was 10^{-4} over the 30 year plant lifetime (i.e. failure frequency of the pump was assumed to be 3.3×10^{-6} yr^{-1}). The economic and health risks associated with each detritiation option are found in table 5.5.

From table 5.5, it can be seen that with no detritiation capabilities, the economic risk is the least. This occurs since the costs associated with this option will only result if the accident does in fact occur. However, the health risk for this option is the greatest. Examining options B, C and D, having one, two and three detritiation units respectively, it can bee seen that the economic risk increases as the health risk decreases. Whether or not it is justified to spend more on a clean up system to reduce the health risk must be determined.

The incremental economic risks of options B, C and D, over option B, with their corresponding dose reductions, are given in table 5.6. In order to determine which detriation system should be employed, it must be determined if the increased costs associated with options B, C and D, compared to option A, are justified. Values for β_a for clean up options B, C and D are also given in table 5.6. Comparing these to 7.11×10^6 \$/person Sv, the value calculated for α_a, it is apparent that, for the accident being studied, none of the options are cost effective.

In the evaluation of β_a, the value used for the probability of the accident occurring was 10^{-4}. The minimum probability of occurence of the given accident, up to which it is justified to spend the extra money for options B, C and D can be determined. By equating β_a to α_a and substituting known quantities, these probabilities can be found. It would be justified to invest 21.0 M$ in option B (one unit) if the accident occurs with a probability of atleast 2.52×10^{-2}. For option C (two units), the minimum probability of the accident occurring for which this system is economically justified is 3.05×10^{-2}. The initial expenditure of 25.5 M$ for this system would then be justified. The capital expenditure for option D (three units) of 30.0 M$ would be justified if the accident were to occur with a probability of atleast 3.59×10^{-2}. From these results, it can be seen that the methodology allows for increased expenditures for more probable events.

If the probability of the accident occurring exceeds 3.59×10^{-2}), then all three options would be justified. Option B should then be selected since it has the minimum value of β_a.

Table 5.5: **Economic and Health Risks for the Detritiation Options**

Option	Accident Related Costs ($)	Economic Risk ($)	Health Risk (person Sv)
A	8.04×10^{8}	8.04×10^{4}	4.39×10^{-4}
B	3.50×10^{5}	2.10×10^{7}	1.88×10^{-9}
C	1.79×10^{5}	2.55×10^{7}	9.35×10^{-10}
D	1.22×10^{5}	3.00×10^{7}	1.48×10^{-10}

Table 5.6: **Incremental Economic Risks and Health Risk Reductions for Detritiation Options B, C and D**

Option	Increase in Economic Risk compared to Option A ($)	Reduction in Health Risk compared to Option A (person Sv)	β_a Expected Cost ($/person Sv)
B	2.09×10^{7}	4.39×10^{-4}	4.76×10^{10}
C	2.54×10^{7}	4.39×10^{-4}	5.79×10^{10}
D	2.99×10^{7}	4.39×10^{-4}	6.82×10^{10}

5.4 References

(5.1) P.A. Finn and M.L. Rogers, The Effects of Tritium Contamination in the FED/INTOR Reactor Hall, Nuclear Technology/Fusion, 4, p. 99, September 1983.

(5.2) C.E. Easterly, Occupational Radiation Exposures at a Fusion Power Station, Nuclear Technology/Fusion, 4, p. 723, October 1982.

(5.3) G.A. Vivian, The Optimization of Radiation Protection, Ontarion Hydro, Memorandum to ASP Staff, File No. 967 N-03400 P, March 1983.

(5.4) J.E. Till, E.L. Etnier and H.R. Meyer, Methodologies for Calculating the Radiation Dose to Man from Environmental Releases of Tritium, Nuclear Safety, 22, No. 2, March-April 1981.

(5.5) I. Handyside, G. Hunt and C. Partington, Control of Radiocesium Discharges to the Irish Sea: ICRP In Practice, Symposium on the Dose Limitation System in the Nuclear Fuel Cycle and in Radiation Protection, IAEA-SM-258/32, Madrid, October 1981.

(5.6) G.A. Webb, A.B. Fleishman and M.J. Clark, Optimization of Protection of the Public: The Application of Cost-Benefit Analysis, Symposium on the Dose Limitation System in the Nuclear Fuel Cycle and in Radiation Protection, IAEA-SM-258/14, Madrid, October 1981.

(5.7) R. Collins and R. James, Design Worth of Radiation Exposure Reduction, Proceedings of the Fifth International Conference on Reactor Shielding, Knoxville, 1977.

(5.8) P.G. Voilleque and R.A. Pavlick, Societal Cost of Radiation Exposure, Health Physics, 43, No. 3, p. 405, September 1982.

(5.9) P.A. Finn et al., USA Contribution (INTOR), Nuclear Data Base Assessment - Group H, Tritium Systems, Report Number ETR-INTOR/DIS/NUC-2.

(5.10) J.A. Strand and R.C. Thompson, Biological Effects of Tritium Releases from Fusion Power Plants, Battelle Pacific Northwest Laboratories, Report Number BNWL 2022, September 1976.

(5.11) P. Otaduy, C.E. Easterly, R.S. Booth and D.G. Jacobs, Factors Affecting Calculations of Dose Resulting from a Tritium Release into the Atmosphere, Oak Ridge National Laboratory.

(5.12) A.E. Sherwood, Tritium Accident Containment Within a Large Fusion Enclosure: Cost, Benefit and Risk Considerations, Report Number UCRL-88932, Lawrence Livermore Laboratory, prepared for submittal to US Japan Workshop on Tritium Handling, Los Alamos National Laboratory, March 1983.

(5.13) J.R. Lamarsh, Introduction to Nuclear Engineering, Addison-Wesley Publishing Company, Reading, Massachusetts, 1977.

Chapter Six

Conclusions And Recommendations

6.1 Summary And Conclusions

The intent of this study was to develop an analytical tool which would aid in achieving a balance between safety and economic constraints in fusion reactor designs. The methodology is for the assessment of the cost effectiveness of proposed design changes, aimed at improving plant safety. It can be applied to both normal and accident conditions.

To determine whether further dose reduction measures are justified, the costs involved with a particular proposal are compared to the maximum justified expenditure.. This maximum value is calculated from economic and social factors, administrative/legal dose limits and the actual magnitude of the radiation risk.

Implementing a dose reduction measure will often result in increased costs. For normal plant conditions, the total cost associated with a protective action is comprised of four major components: the capital cost, and the change in annual operating, maintenance and waste handling costs. The capital cost of the dose reduction action includes the cost of materials and installation for those items directly responsible for the dose reduction. Annual operating, maintenance and waste handling costs are comprised of several elements including the cost of additional materials and equipment required for carrying out tasks, the change in labor costs, the change in health effects costs, the change in overhead costs, the change in replacement power costs and the change in waste disposal costs. Knowing the costs due to a protective action and the resulting dose savings for workers and the public, the cost per unit dose saved can be found. Comparing this to the expenditure ceiling, it can be determined if it is justified to invest in the proposed dose reduction measure.

The methodology for risk management under normal plant conditions has been applied to assess the cost effectiveness of the low activation STARFIRE design. The expenditure ceiling on design modifications to STARFIRE was evaluated at $530,000 per person Sv averted. To determine the cost effectiveness, the costs associated with changing to low activation materials from the reference design materials were estimated. Costs were estimated using DOE costing guidelines. There was some uncertainty as to the cost of high purity silicon carbide components. Hence, in the determination of costs, a range of prices for silicon carbide was used. If the installed price of high purity silicon carbide components is 30 $/kg, the annualized capital cost for STARFIRE will in effect decrease by 19.3 M$/yr (to 235 M$/yr, from 254 M$/yr for the reference design). This would decrease the initial capital investment in the plant by 292 M$ from 3,850 M$ to 3,556 M$. If the price of silicon carbide is 110 \$/kg, the inital capital investment would increase by 116 M\$ to 3,996 M\$. This corresponds to an annual increase in capital cost of 7.6 M\$/yr, giving a value of 262 M\$/yr. The initial capital investment if silicon carbide costs 315 \$/kg would be 5,011 M\$, resulting in an increase of 1,162 M\$. On an annual basis, this corresponds to an increase of 77 M\$/yr, giving a value of 331 M\$/yr. Since it has been found that the capital cost component dominates the total cost, it is important that these costs be determined as accurately as possible. Unfortunately, all the necessary information to accomplish this is not available at this time. These costs may have been overestimated since economic savings from faster construction/liscensing, fewer safety systems, higher thermal efficiencies and cheaper containment for the low activation design were ignored. If the necessary information is provided in the future, these factors can be included. It appears that these considerations would favor the low activation design.

In addition to the capital cost component, another large contributor to the total cost is that of replacement power. A rough estimate of a maintenance schedule for reactor equipment was provided in this study. From this, the downtime savings for the low activation design was found to be 3.25 days. Perhaps, if this was looked at in greater detail, the downtime savings for the low activation design would be altered. This would impact the replacement power costs, and hence the total costs of the low activation design. Major savings in waste handling costs were also found to result for the low activation design. If the installed cost of silicon carbide components is 30 \$/kg, the total annual costs for the low activation design would decrease by 45.1 M\$/yr, from 399.1 M\$/yr to 354.0 M\$/yr. An increase in annual costs of 0.1 M\$/yr to 399.2 M\$/yr would result if the cost of silicon carbide is 110 \$/kg. At a cost of 315 \$/kg, the total annual costs would become 514.4 M\$/yr, increasing by 115.3 M\$/yr.

It was found that the annual dose incurred would decrease by 6.82 person Sv/yr for the low activation design. Major areas impacted by the change in materials include coolant/steam generator maintenance, first wall/blanket replacement and waste handling.

Knowing the costs associated with the change to the low activation design and the resulting dose savings, the cost effectiveness could be assessed. At 315 \$/kg, the change would be unjustified. The change to the low activation design was found to be justified for silicon carbide at a cost of 30 \$/kg or 110 \$/kg. For these cases, justified research and development costs were estimated. If silicon carbide costs 30 \$/kg, it would be justified to spend 10.9 M\$/yr in each of the next 30 years, 21.5 M\$/yr during each of the next 10 years or 38.2 M\$/yr during each of the next five years on research and development of low activation materials. Justified spending on research and development if the silicon carbide costs 110 \$/kg would be 0.78 M\$/yr for each of the next 30 years, 1.55 M\$/yr during each of the next ten years or 2.75 M\$/yr for each of the next five years.

The variation of total costs with the price of silicon carbide was found to be linear. A break even value of 116 \$/kg for silicon carbide was found. However, this does not allow for any research and development costs. A maximum cost in the neighbourhood of 110 \$/kg would allow for some research and development expenditures. If the installed cost of high purity silicon carbide components is less than this, then it would be justified to switch to the low activation design for STARFIRE.

Dose reduction measures may be proposed for reducing the hazard subsequent to an accident. Such measures may involve large capital expenditures. Using the methodology, it can be ascertained if this expenditure is justified in the event of a particular accident.

Subsequent to an accident, a cost will be incurred, the magnitude of which will depend on the severity of the accident. Accidents have been classified into three categories, based on accident severity or cost. Category I events are currently defined as having only onsite consequences including replacement power costs, plant repair costs and worker health effects and health care costs. Category II, or medium consequence events result in replacement power costs, decontamination costs, plant repair costs and health effects costs being incurred. Additionally, offsite health effects and property damage may result. These costs may include health effects costs, decontamination costs, agricultural production disposal costs, evacuation costs, relocation costs and land interdiction costs. Category III events are large consequence events, possibly resulting in large capital investment losses and even plant decommissioning costs. In addition to this, replacement power costs, plant decontamination costs and health effects costs may be incurred. The offsite cost components mentioned in relation to category II events may also result subsequent to a category III accident.

The methodology for risk assessment for accident consequence mitigation proposals is similar in approach to that for normal plant conditions. The assessment must be performed from the perspective of a particular accident scenario. The ceiling on expenditures is determined using the maximum exposure rate estimated to exist subsequent to the accident. It should be pointed out again that the exposure limit for accident conditions does not necessarily have to be that employed for normal conditions. Since in abnormal situations, it is permissible for a worker to incur a dose of 0.25 Sv, the occupational dose limit may vary. If the duration of exposure can be postulated, then a more appropriate occupational exposure limit can be used. The public exposure limit should not be affected by this consideration.

To assess the cost effectiveness of an accident consequence mitigation proposal, the actual costs associated with it must be evaluated. These include the capital cost of the dose reduction measure and the costs incurred subsequent to the accident. Accident related costs will depend on the accident category. The change in costs subsequent to the accident and the change in dose incurred subsequent to the accident must be evaluated relative to the case where no accident consequence mitigation proposal is used, or relative to some base case (the minimum cost alternative). Since these costs and doses will only be incurred if the accident does occur, they must be multiplied by the probability of the accident occurring to determine the appropriate risks. Knowing the economic risk associated with a particular alternative and the resulting reduction in health risk, the cost per unit dose saved can be evaluated. As with dose reduction measures for normal plant conditions, this must be compared to the expenditure ceiling to determine if the proposal is justified.

The methodology for risk assessment for accident conditions has been applied to assess the cost effectiveness of emergency detritiation systems for INTOR. The expenditure ceiling for a release of 25 g of tritium into a reactor building volume of 25,000 m^3 was estimated at 7.11 x 10^6 \$/person Sv. The costs associated with using zero, one, two or three detritiation units for the 25 g release were estimated.

The use of any number of detritiation units would involve a large capital outlay. As the number of detritiation units used increased, the capital cost increased, but the accident related costs decreased (a result of more rapid removal of tritium). However, since the accident related costs will only be incurred if the accident does take place, they must be multiplied by the probability of the accident occurring. This resulted in the economic risk for the options with detritiation units being dominated by the capital costs. Consequently, the economic risk for the option employing no emergency detritiation units was least. However, the health risk was greatest for this option. A savings in health risk of 4.39 x 10^{-4} person Sv will result from the use of any number of detritiation units. From the analysis, it was determined that if the accident occurs with a probability over the plant lifetime of 10^{-4}, none of the detritiation options would be justified. In order for it to be justified to invest 21.0 M\$ in one emergency detritiation unit, the accident must occur with a probability of atleast 2.52 x 10^{-2}. For two emergency detritiation units, the cost of 25.5 M\$ would be justified if the accident occurred with a probability of 3.05 x 10^{-2}. The initial capital expenditure of 30.0 M\$ would be justified for three emergency detritiation units if the accident occurred with a minimum probability of 3.59 x 10^{-2}. If the accident did occur with a probability of 3.59 x 10^{-2}, and these four options were being considered, the most cost effective alternative would be using a single detritiation unit. Since using one, two or three units would result in nearly identical dose savings, the minimum cost justified alternative (having the minimum value of β_a) should be selected.

The procedure presented in this study is the first step for developing a methodology. Some areas still require attention. Future applications will serve to test the validity of the methodology or to determine any areas of weakness.

This methodology has many applications beyond the illustrations presented in this report. It is anticipated that the material presented in this study will be a useful tool to the designer and aid in the evolution of safer, more economical fusion reactor designs.

6.2 Recommendations For Future Work

In this study, the basic procedure for cost effective risk management was established. It is hoped that in the future, other factors affecting either the expenditure ceiling or the costs associated with a dose reduction measure will be recognized and incorporated into the methodology. Some considerations have been indentified throughout the course of this work and are summarized below.

If the occupational dose limits are reached, the availability of skilled workers, the cost of training new workers and the probable lower productivity of these workers due to lack of experience may be important. These considerations should be included as part of the socio-economic factors used to determine the expenditure ceiling. The fact that higher dose rates may lead to lower productivity, and hence increased task durations should be incorporated into the evaluation. The use of per capita income in determining the ceiling on public safety expenditures may seem unethical, since it implies that poorer countries can tolerate higher dose rates. A more appropriate economic factor is needed. Perhaps this would somehow be related to a country's investment in fusion power.

One further consideration which was neglected due to lack of information was that of reduced requirements on remote maintenance equipment. Since the low activation design will involve lower mass components, the load handling capabilities of the remote equipment will not need to be as great. Furthermore, lower structural activation levels will result in reduced equipment degradation, which will lead to less frequent replacement needs. It is expected that these considerations would lead to a reduction in capital cost for maintenance equipment and a reduced cost for replacement parts for the maintenance equipment.

This methodology is suited for a wide range of applications. A suggested area for study is the issue of increasing shielding to make certain areas of the plant accessible for contact maintenance. This would lead to a reduction in downtime and hence replacement power costs. The procedure presented in this study could be applied to determine if the investment in the increased shielding is justified.

In the current study, no monetary value was provided for the division between accident categories. In the future, such a guideline should be established. Perhaps, comparing accident costs to some percentage of the plant capital costs would serve as an appropriate means of distinguishing between accident categories.

For accident conditions, the methodology only considers one accident scenario. In fact, a dose reduction measure may be useful for reducing the consequences of more than one accident. If other events can be postulated where the used of a particular reduction measure would reduce the health risks, then they should be included in the analysis. This would involve determining the accident related costs and doses incurred for each additional event. The doses should be multiplied by the probability of occurrence of the corresponding accident to determine the health risk. The total health risk would be determined by summing the risks presented by each postulated event. The accident related costs should also be multiplied by the probability of occurrence of the corresponding accident. Summing these for all events considered would give the economic risk for the proposal. This must then be added to the capital cost to obtain the total economic risk associated with an option. Knowing both the total economic risk and total health risk, the cost per unit dose averted can be obtained. If several events are being included in the analysis, then the expenditure ceiling must somehow be modified to account for this. It would seem logical, that if a particular proposal was expected to impact the consequences of several events, then the expenditure ceiling should be augmented. This could come about by increasing R, the magnitude of the radiation risk used in assessing the maximum justified spending. If several events are being considered, the appropriate value of R could be determined by a simple sum of the radiation risks subsequent to each postulated event. However, the event probabilities should somehow be incorporated. Perhaps, some sort of weighting procedure would accomplish this. It is hoped that future work in this area will resolve this issue.

Nomenclature

$\alpha=$ ceiling on occupational safety expenditures (\$/person Sv)

$\alpha^*=$ ceiling on public safety expenditures (\$/person Sv)

$\alpha'=$ overall ceiling on safety expenditures (including occupational and public components) (\$/person Sv)

$\alpha_a=$ ceiling on occupational expenditures for the reduction of accident consequences (\$/person Sv)

$\alpha_a^*=$ ceiling on public expenditures for the reduction of accident consequences (\$/person Sv)

$\alpha_a'=$ overall ceiling on expenditures for the reduction of accident consequences (\$/person Sv)

$A=$ size of an area to be decontaminated (acres)

$\beta=$ additional spending for a dose reduction measure (\$/person Sv)

$\beta_a=$ additional costs for an accident consequence mitigation measure, for a particular accidental occurrence (\$/person Sv)

$C=$ actual capacity factor of the plant had no outage occurred

$C'=$ average capacity factor of the plant, obtained from operating data

$C_a=$ change in accident related costs compared to the case where no accident consequence mitigation measure has been used, or compared to the base case (\$)

$C_{aC}=$ capital cost of an accident consequence mitigation measure (\$)

$C_{AD}=$ cost due to accelerated decommissioning (\$)

C_{al}= average cost of decontamination labor (\$/person yr)

C_{aT}= increase in total costs for an accident consequence mitigation measure over the costs which would be incurred if no consequence reduction scheme was used, or over the costs which would be incurred for the base case (\$)

C_{BV}= book value of the plant or a plant component at the time of a severe accident (\$)

C_{C}= annualized capital cost of a dose reduction action (\$/yr)

C_{cd}= cost of crop disposal (\$)

C_{Ci}= initial capital cost of a dose reduction measure (\$)

C_{CI}= capital investment loss resulting from a severe accident (\$)

C_{d}= cost of land and property decontamination (\$)

C_{dd}= cost of dairy product disposal (\$)

C_{dl}= labor cost for offsite decontamination (\$)

C_{dn}= decontamination cost during phase n of an onsite clean up program (\$)

C_{D}= total cost of an onsite decontamination program (\$)

C_{DW}= change in annual waste disposal costs resulting from the use of a dose reduction measure (\$/yr)

C_{E}= cost of evacuation (\$)

C_{EP}= = emergency phase population relocation cost (\$)

C_{Hi}= total onsite health effects cost (\$)

C_{Hn}= health detriment cost due to radiation exposure during phase n of a decontamination program (\$/yr)

C_{Ho}= total offsite health effects cost (\$)

C_{HP}= total health effects cost due to exposure of the public to radiation (\$)

C_{HR}= health detriment cost due to radiation exposure while performing a repair job (\$/day)

C_{HW}= total health effects cost due to exposure of offsite decontamination workers (\$)

C_{Hx}= change in annual health detriment cost resulting from a dose reduction measure (\$/yr)

C_I= cost of land interdiction (\$)

C_{IP}= intermediate phase relocation cost (\$)

C_j= crew size for a decontamination or repair task (persons)

C_{Ln}= cost of labor to carry out tasks during phase n of a decontamination program (\$)

C_{LR}= labor cost to perform a repair job (\$/day)

C_{Lx}= increase in annual labor costs for all jobs affected due to the implementation of a dose reduction measure (\$/yr)

C_{Mix}= initial additional materials and equipment costs (\$)

C_{Mx}= annualized additional materials and equipment costs for carrying out all tasks affected by a dose reduction measure (\$/yr)

C_{MR}= cost of replacement materials or components (\$)

C_{nj}= new crew size, after implementation of a dose reduction measure, required to complete task j (persons)

C_{NP}= capital investment in new plant components required to replace those destroyed by an accident, or in the new plant built to replace the productive capacity of the shutdown plant ($)

C_{OHx}= increase in annual overhead costs resulting from a dose reduction measure ($/yr)

C_{oj}= old crew size, before using a dose reduction measure, required to complete task j (persons)

C_{On}= cost to operate any equipment required during phase n of a decontamination program ($/yr)

C_P= cost of replacement power during an outage ($)

C_{PM}= change in annual replacement power costs resulting from a dose reduction measure ($/yr)

C_r= cost of relocating a population from an area during an offsite decontamination program ($)

C_R= plant repair costs ($)

C_{sa}= annual cost to maintain a plant in a stable condition subsequent to an accident ($/yr)

C_{st}= plant stabilization costs subsequent to an accident ($)

C_T= annualized cost of a dose reduction measure over the plant lifetime ($/yr)

C_{Tx}= increase in total annual operating, maintenance or waste handling costs resulting from a dose reduction measure ($/yr)

C_{Wn}= cost of radioactive waste removal and disposal during phase n of a decontamination program (\$/yr)

D_{AD}= dose incurred during accelerated decommissioning operations (person Sv)

D_{ao}= occupational dose savings during a given accident scenario when an accident consequence mitigation measure has been used (person Sv)

D_{ap}= public dose savings during a given accident scenario when an accident consequence mitigation measure has been used (person Sv)

D_{aT}= total dose savings during a given accident scenario when an accident consequence mitigation measure has been used (person Sv)

D_c= dose which would be incurred by an individual from constant exposure to surface deposited radionuclides for the entire decontamination period (Sv)

D_D= dose incurred during onsite plant decontamination procedures (person Sv)

D_{Dn}= dose incurred during phase n of a decontamination program (person Sv/yr)

D_{DW}= dose incurred by decontamination workers due to exposure to surface deposited radionuclides (person Sv)

DF_f= cost to decontaminate farmland by a factor of f (\$/acre)

D_o= occupational dose savings resulting from a dose reduction measure (person Sv)

D_p= public dose savings resulting from a dose reduction measure (person Sv)

D_{pop}= projected long term dose to the population affected by an accident (person Sv)

D_R= dose incurred during plant repair (person Sv/day)

DR_f= cost to decontaminate residential, business and public property by a factor of f (\$/person)

D_T= total dose saving (including occupational and public components) resulting from the use of a dose reduction measure (person Sv)

D_{Tx}= total dose savings during plant operation, maintenance or waste handling due to the use of a dose reduction measure (person Sv/yr)

D_{xo}= occupational dose savings during plant operation, maintenance or waste handling due to the use of a dose reduction measure (person Sv/yr)

D_{xp}= public dose savings during plant operation, maintenance or waste handling due to the use of a dose reduction measure (person Sv/yr)

E= cost of food, lodging and transportation for an evacuee (\$/person day)

E_{LIM}= occupational exposure limit (Sv/yr)

E^*_{LIM}= public exposure limit (Sv/yr)

f= decontamination factor

F= power production cost increase due to the purchase of replacement power (\$/MWe)

F_0= power production cost increase (due to the purchase of replacement power) at time zero (\$/MWe)

f_c= fraction of farmland sales from crops

F_f= fraction of a region to be decontaminated which is farmland

f_j= frequency of carrying out task j during plant repair (days^{-1})

f_{jn}= frequency of carrying out task j during phase n of a plant decontamination program (yr^{-1})

tion factor, which is estimated to be paid labor

f_{nj}= new frequency of carrying out task j, after implementation of a dose reduction measure (yr^{-1})

f_{oj}= old frequency of carrying out task j, before implementation of a dose reduction measure (yr^{-1})

F_P= average annual farm production (sales) for an area to be decontaminated (\$/acre)

F_V= average national market value of farmland and structures in an area to be decontaminated (\$/acre)

g= rate of cost escalation (yr^{-1})

G= electrical generation rating of the shutdown reactor (MWe)

H= estimate of somatic plus genetic societal detriment attributable to radiation exposure (3,800 \$/person Sv)

I= national average per capita and corporate income (\$/person day)

I_f= fraction of farmland wealth in improvements in an affected area

I_o= initial capital investment in plant components destroyed during an accident (\$)

I_r= fraction of non-farmland wealth in improvements in an affected area

j= identification number for tasks carried out during normal plant operation, maintenance or waste handling, or during plant repair or decontamination subsequent to an accident

k= useful life of depreciating assets (yrs)

L_c= replacement labor cost (\$/person yr)

L_c^*= per capita income in region where the power plant is located ($/person yr)

m= total number of phases required to complete an onsite decontamination program

m_j= rate of worker remuneration for task j of a repair job ($/person day)

m_{nj}= new rate of worker remuneration for task j, after implementation of a dose reduction measure ($/person hr)

m_{oj}= old rate of worker remuneration for task j, before implementation of a dose reduction measure ($/person hr)

n= identification number for phases of onsite decontamination program

N= exponent expressing harm induced by radiation (0.5)

N_W= number of decontamination workers required to complete an offsite decontamination program within a specified amount of time (persons)

p= probability, over the plant lifetime, of a given accident occurring

P= size of the population affected by a dose reduction measure (persons)

P_d= population of an area affected by a decontamination program (persons)

P_E= size of initially evacuated population (persons)

P_{EP}= number of persons which must be relocated in addition to those previously evacuated (persons)

P_i= total number of persons affected by a reactor accident (persons)

P_{IP}= size of the population affected by intermediate phase relocation (persons)

P_r= size of population to be relocated during offsite decontamination operations (persons)

r= real societal discount rate

R= occupational exposure rate before implementation of a dose reduction measure (Sv/yr)

R^*= public exposure rate before implementation of a dose reduction measure (Sv/yr)

R_a= maximum occupational exposure rate after the occurrence of an accident (Sv/yr)

R_a^*= maximum public exposure rate after the occurrence of an accident (Sv/yr)

$R_j(t)$= function describing how the dose rate varies with time while carrying out task j of a repair job (Sv/hr)

$R_{jn}(t)$= function describing how the dose rate varies with time while carrying out task j of phase n of a decontamination program (Sv/hr)

RL_f= fraction of the residential, business and public decontamination cost, for the appropriate decontamination factor, which is estimated to be paid labor

$R_{nj}(t)$= new function describing how the occupational dose rate varies with time while carrying out task j, after implementing a dose reduction measure (Sv/hr)

$R_{np}(t)$= new function describing how the public dose rate varies with time while carrying out task j, after implementing a dose reduction measure (Sv/hr)

$R_{oj}(t)$= old function describing how the occupational dose rate varies with time while carrying out task j, before implementing a dose reduction measure (Sv/hr)

$R_{op}(t)$= old function describing how the public dose rate varies with time while carrying out task j, before implementing a dose reduction measure (Sv/hr)

R_P= plant repair during an outage (1,250 $/hr)

R_{ri}= ratio of region specific to national average personal incomes

R_V= average national per capita tangible wealth in an area (\$/person)

RV_f= ratio of region specific to national average market value of farmland and structures in an area

RV_r= ratio of region specific to national average personal incomes in an area

s= sinking fund depreciation factor

S= end of life decommissioning cost (\$)

t_a= time of occurrence of severe accident (years after initial plant startup)

t_c= duration of contact maintenance period (hr)

t_E= duration of evacuation (days)

t_{1EP}= time at the start of the emergency phase relocation period in areas where no evacuation has occurred (days from accident occurrence)

t_{2EP}= time at the end of the emergency phase relocation period in areas where no evacuation has ocurred (days from accident occurrence)

t_d= outage duration (yrs)

t_D= specified amount of time to complete an offsite decontamination effort (yrs)

t_{fj}= time after an event occurrence at which task j of a decontamination program is completed (hr)

t_I= duration of interdiction period (yrs)

t_{1IP}= time at the start of the intermediate phase relocation period (days from accident occurrence)

t_{2IP}= time at the end of the intermediate phase relocation period (days from accident occurrence)

t_j= time required to complete task j of a repair job (hr)

t_l= expected plant lifetime remaining after a dose reduction measure is implemented (yrs)

T_{my}= total person-years of effort required to decontaminate an area (person yrs)

t_n= duration of phase n of an onsite decontamination program (yrs)

t_{nj}= new time to complete task j, after implementation of a dose reduction measure (hr)

t_{oj}= old time to complete task j, before implementation of a dose reduction measure (hr)

t_{pn}= time after an event occurrence at which phase n of a decontamination program begins (yrs)

t_{pl}= expected plant lifetime (yrs)

t_r= duration of remote maintenance period (hr)

t_R= time to complete an entire repair job (days)

t_{sj}= time after an event occurrence at which task j of a decontamination program begins (hr)

t_x= duration of public exposure resulting from normal operation, maintenance or waste handling activities (yrs)

U= fraction of total dose savings, due to a dose reduction measure, affecting plant workers

$U_a =$ fraction of total dose savings, due to an accident consequence mitigation measure, for a given accident scenario, affecting plant workers

$V =$ fraction of total dose savings, due to a dose reduction measure, affecting the public

$V_a =$ fraction of total dose savings, due to an accident consequence mitigation measure, for a given accident scenario, affecting the public

$W_f =$ total farm wealth (prior to reactor accident) in an area from farmland and structures ($)

$WF_f =$ ratio of decontamination worker dose, for an appropriate level of decontamination effort, in farm areas, to the dose which would be incurred by an individual from constant exposure during the decontamination period

$WR_f =$ ratio of decontamination worker dose, for an appropriate level of decontamination effort, in residential, business and public areas, to the dose which would be incurred by an individual from constant exposure during the decontamination period

$x =$ subscript indicating either operation (O), maintenance (M) or waste handling (W) costs

$Z =$ seasonal factor

Appendix A

A.1 Discount Rate Used In Cost Estimations

The discount rate is used as a means of incorporating the time value of money into financial analyses. It represents the earning power of money or the cost of capital. The rate used in evaluating public projects, such as a fusion power plant, is often referred to as the societal discount rate. Estimates of discount rates can be obtained from interest rates charged in capital markets. These interest rates include a component which allows for the general inflation in the economy. The real interest rate, which does not include an inflationary component, can be estimated from the observed market rate using:

$$r = \left(\frac{1 + r_m}{1 + i}\right) - 1 \tag{A.1}$$

where

$r =$ the real interest rate

$r_m =$ the market interest rate or apparent interest rate observed in the economy

$i =$ the inflation rate in the economy

To avoid projecting future inflation rates, analyses of future cash flows should employ real discount rates. Furthermore, the analysis will be subject to less error since real cash flows and discount rates show less variation than observed cash flows and discount rates.

The societal discount rate can be interpreted as representing the cost to society of capital based on the level of risk associated with a particular investment. It is a reflection of society's judgement of expending capital at the current point in time versus expending it at some point in the future. The real societal discount rate is arrived at by correcting the prime rate, or the interest rate charged by large money lenders to their best business borrowers, for inflation. A real discount rate of 5 % is recommended for use in present value calculations. It has been projected that the inflation rate will gradually decline over the next few years. Reduced inflation will reduce the inflation premium in nominal interest rates. Real interest rates are also expected to decline, approaching 5 %, which prevailed prior to the onset of the inflationary 1970's [A.1]. It is also recommended that continuous compounding be employed in calculations. The result of this is to increase the effect of interest on the time value of money. The assumption of continuous compounding also simplifies the form of mathematical models.

A.2 References

(A.1) Economic Report of the President to Congress, Washington D.C., February 1984.

Appendix B

B.1 Health Effects And Health Care Costs

Studies have been carried out which estimate the costs and risks of radiation exposure [B.1, B.2]. These values have been used to estimate the cost to society attributable to radiation exposure [B.3].

Assuming that the number of non-fatal cancers of all types induced by radiation exposures is as large as the number of fatal cancers, a risk factor for cancer incidence is approximately 2×10^{-2} $(\text{personSv})^{-1}$. If the average (of all types) cost of one case of cancer (including medical care and lost income) is $75,000 , then an estimate of the cost due to somatic effects would be 1,500 $/person Sv.

The risk factor for hereditary effects has been estimated at 8×10^{-3} $(\text{personSv})^{-1}$ [B.4]. It has been suggested by the BEIR Committee, that 16 % of genetic disorders resulting from radiation exposure would produce congenital disabilities while 84 % of the effects would be "irregularly inherited". These effects include congenital malformations, latent anomalies and degenerative diseases resulting in a serious handicap at some point in an affected individual's life. The cost of congenital disabilities has been estimated as $700,000 by assuming the cost of these effects to be equivalent to the cost per case of cancer of the nervous system. Considering lost earnings and institutional care, the cost of "irregularly inherited" effects is estimated as $210,000 (from [B.3], adjusted using price indexes [B.5]). The cost to society due to radiation induced genetic effects is then 2,300 $/person Sv.

An estimate of the total societal detriment attributable to radiation exposure (H) can be found by summing the costs due to somatic and genetic effects. A cautious estimate would be 3,800 $/person Sv. The ICRP has suggested that it may be appropriate to arbitrarily increase the cost factor by a factor of ten to provide further impetus for dose reduction actions when individual doses are near the dose limit [B.3].

B.2 References

(B.1) N.X. Hartunian, C.N. Smart and M.S. Thompson, The Incidence and Economic Costs of Cancer, Motor Vehicle Injuries, Coronary Heart Disease and Stroke: A Comparative Analysis, American Journal of Public Health, 70, p. 1249, 1980.

(B.2) T. Straume and R.L. Dobson, Leukemia and Cancer Risk Estimates from Recalculated Hiroshima and Nagasaki Doses, Proceedings of the 26th Annual Meeting of the Health Physics Society, Louisville, Kentucky, 1981.

(B.3) P.G. Voilleque and R.A. Pavlick, Societal Cost of Radiation Exposure, Health Physics, 43, No. 3, p. 405, 1982.

(B.4) International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Oxford, Pergammon Press, 1977.

(B.5) United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States: 1984, 104th edition, Washington D.C., 1984.

Appendix C

C.1 Replacement Power Costs

A major cost component during plant outages is that of replacement power. Societal costs for replacing power can be quite substantial. These costs will arise because the power previously produced by an operating fusion reactor must be replaced by power generated by a more expensive source.

Short duration outages may not require the purchase of replacement power. Short term generation increases and load management schemes may allow the utility to meet the needs of its service area. Some possible emergency procedures for short term outages are given in table C.1.

Longer term power plant outages or permanent plant shutdowns require a different set of options to compensate for the loss in generating capacity. Included in these alternatives are load management schemes, load conservation programs, long term purchase agreements with neighboring utilities, additional interconnections in the power grid, restructuring of electricity usage rates, deferment of planned power plant decommissionings, acceleration of existing construction schedules and addition of new capacity to the construction schedule. All options for compensating for lost power production have associated costs. These costs will result because by the time fusion power is commercially available, it is expected to be competitive with fission [C.2], which has a very low operating and fuel cycle cost relative to fossil fueled units. Lower marginal cost power is normally employed in base load electricity generation, while higher marginal cost generating units are used to handle daily or seasonal variations in power requirements. The loss of power generation from a fusion plant would require that higher cost generating units be used. A net cost is incurred as a result of using a more expensive energy source.

Table C.1: Typical Utility Operating Procedures For Short Duration Outages [C.1]

Utility Action[*]	Typical Effect
Bypass plant pollution control equipment	Increase available generating capacity by a small amount
Switch from economic dispatch to critical fuel conservation dispatch	Prolong time before more serious emergency actions are necessary
Purchase excess industrial generation	Add generating capacity
Purchase emergency power from other utilities	Often makes substantial power available, but at high cost
Reduce standby reserves	Increase generating capacity by 50-100% of the capacity of a large unit
Direct load control (customer load management)	Reduce load
Reduce voltage by 5%	Reduce load by 3%
Appeal to industry	Reduce load by 1-2%
Appeal to public	Reduce load by 1-2%
Interrupt interruptible service	Reduce load
Run generating units at extreme outputs	Increase generating capacity by 1-3%
Reduce spinning reserve to zero	Increase generating capacity by the capacity of a large unit
Reduce voltage by 8% (an additional 3%)	Reduce load by 1%
Shed load (rotating blackouts)	Reduce load by amount necessary to balance with supply

---

[*] Actions are listed in the approximate order in which they would be implemented.

Different methods and fuels are used to generate replacement power in different regions of the United States. To estimate costs arising from a fusion plant outage, the plant location and resulting mix of units used to generate the replacement power must be considered. Furthermore, the availability of excess capacity to generate the replacement power must exist.

The cost incurred as a result of purchasing replacement power during a fusion plant outage can be estimated from a simplified model developed for fission plant outages [C.1]. Since fusion is expected to be competitive with fission, the model can also be applied to estimate replacement power costs for fusion power plant outages.

The model relates power production cost increases during the first year of the outage to the fraction of replacement power obtained from oil fired and non-economy power sources (i.e. higher marginal cost fuel sources such as gas turbines). Figure C.1 shows the relationship between oil fired and non-economy replacement power fraction and the power production cost increase due to one full year of reactor outage time. These costs were obtained from a study carried out in 1982 [C.1] and have been updated to current values using price indexes found in the Statistical Abstract of the United States [C.3]. The importance of the fraction of replacement power from non economy sources in determining production cost increases is evident. The simplified model was derived from detailed loss of benefits case studies. The range of results from these studies is also indicated in the figure. Beyond the first year of outage time, the annual power production cost increases can be modified for cost escalation to provide an estimate of the total power production cost increase for longer duration outages.

As stated previously, the fraction of non-economy power purchases will vary with location in the United States. The average fraction of replacement power from non-economy purchases within each of the National Electric Reliability Council (NERC) regions can be employed. These fractions are given in table C.2 and the corresponding regions are shown in figure C.2.

Figure C.1: Relationship Between Power Production Cost Increase and Non-Economy Power Fraction [C.1]

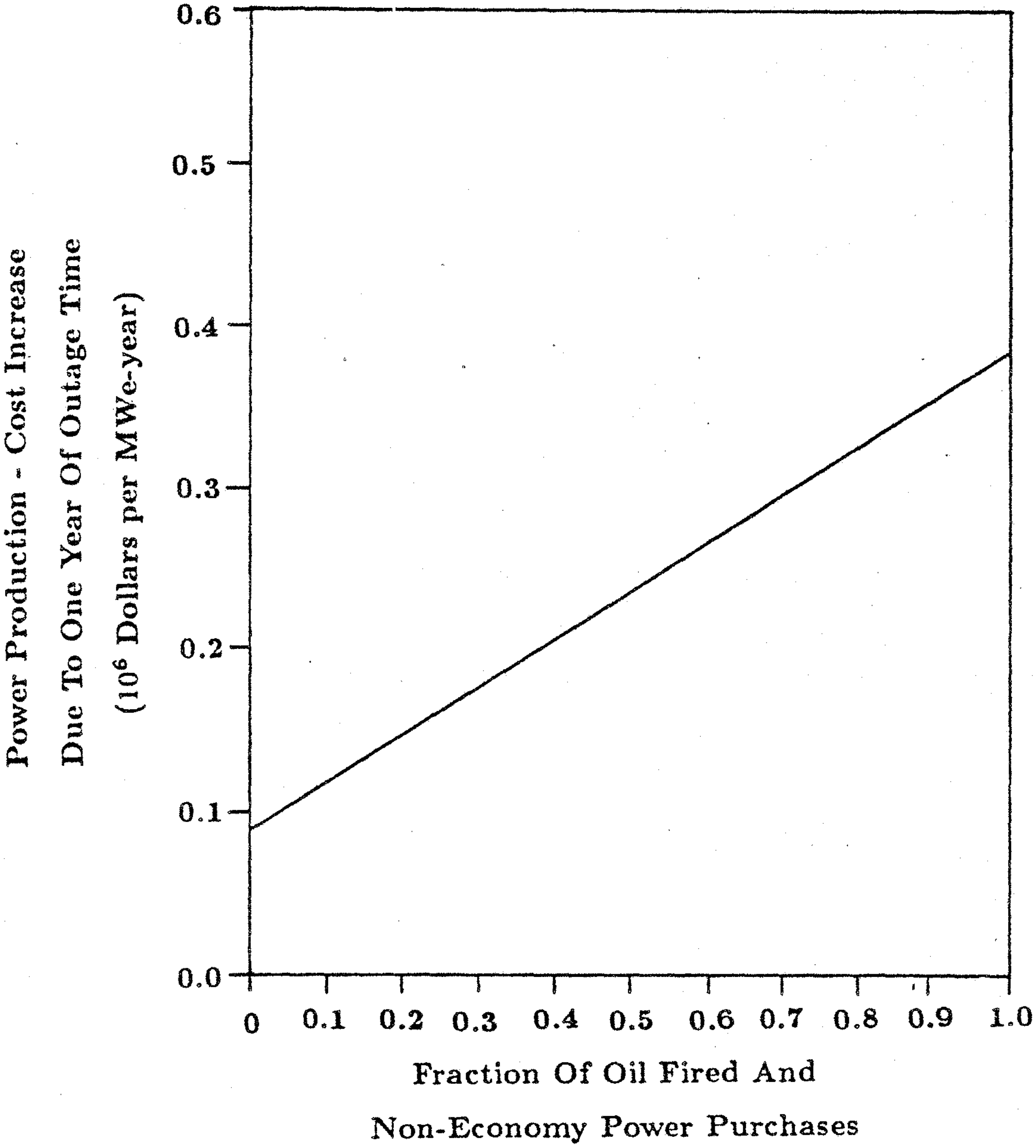
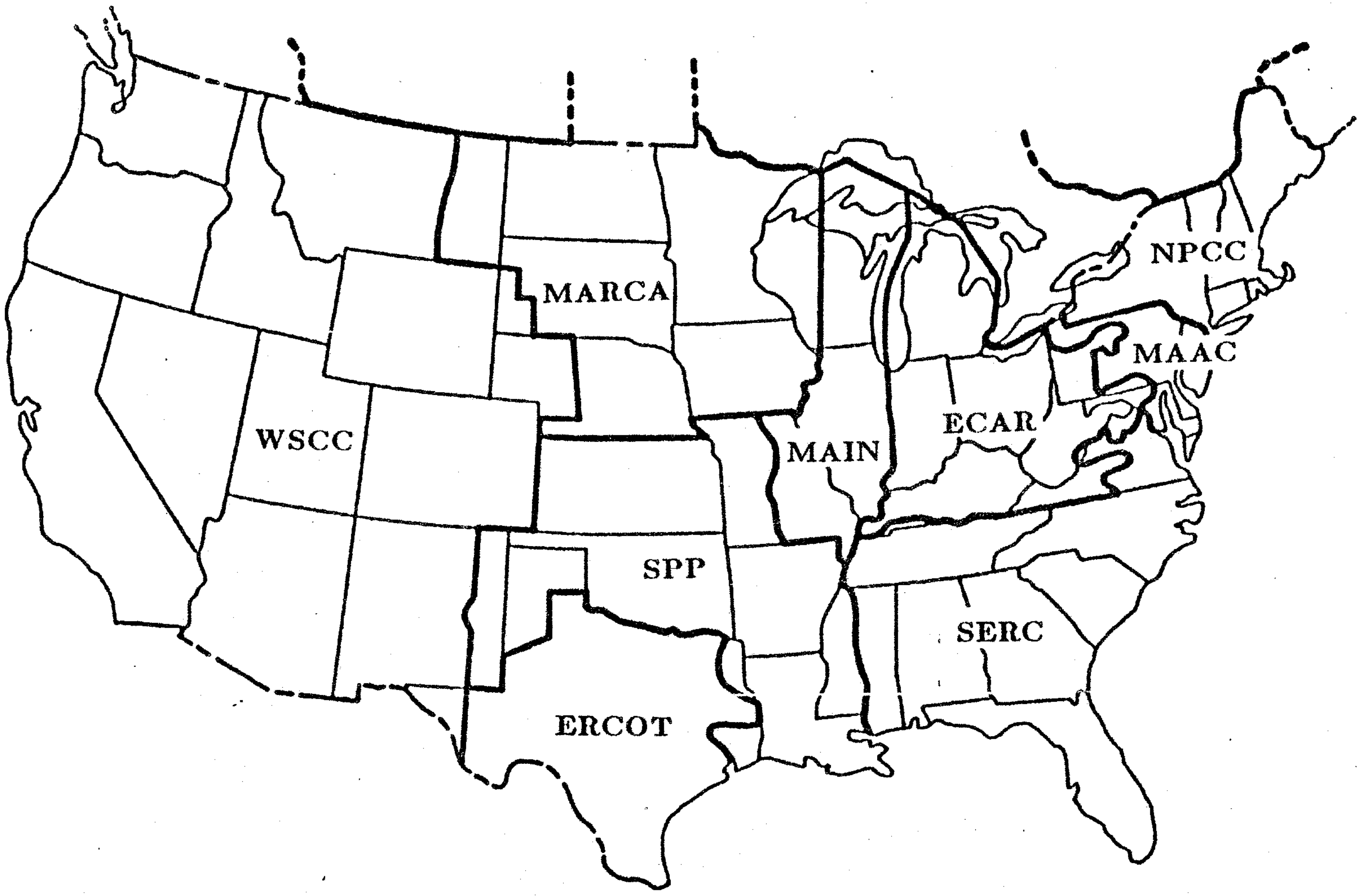


Table C.2: Average Fraction of Oil Fired and Non-Economy Replacement Energy by NERC Region [C.4]

National Electric Reliability Council Region	Per cent of Replacement Energy from Oil Fired Power Plants and Non-Economy Power Purchases
MARCA	20
NPCC	95
MAAC	50
MAIN	15
ERCOT	50
SPP	40
WSSS (California)	95
WSSS (non-California)	25
SERC	15
ECAR	5

Figure C.2: Regional Electric Reliability Councils of the National Electric Reliability Council [C.4]



Knowing the estimated fraction of non-economy replacement power purchases for an outage, the present value of the production cost increase can be calculated. The model presented here was developed by Buehring and Peerenboom [C.1] and was also used by Burke [C.4]. The cost of replacement power is given by:

$$C_P = \left(\frac{GC}{C'}\right) \int_0^{t_{out}} F(t) \cdot e^{-rt} dt \tag{C.1}$$

where

C_P= present value of the replacement power cost over the outage period (\$)

G= electrical generation rating of the reactor (MWe)

C= actual capacity factor of the plant had the outage not occurred

C'= average capacity factor of the plant, obtained from operating data

t_{out}= outage duration (yrs)

$F(t)$= unit production cost increase of outage versus time (\$/MWe yr)

r= real discount rate

The unit production cost increase function, $F(t)$, can be specified. It can be taken as constant, representing zero growth in real power production costs. It can also be taken to escalate at a real rate. In this case,

$$F(t) = F_0 \cdot e^{gt} \tag{C.2}$$

where

F_0= power production cost increase at time zero, obtained from figure C.1 (\$/MWe)

g= real escalation rate of replacement power costs (yr^{-1})

Using this form for the unit production cost increase, equation C.1 can be integrated to give the replacement power cost for the outage.

$$C_P = \left(\frac{GCF_0}{C'}\right)\left[\frac{1 - e^{-(r-g)t_{out}}}{r-g}\right] \tag{C.3}$$

The limitations and assumptions involved in this simplified model for replacement power cost should be outlined. These are:

(1) The model was derived to estimate the power production cost increases for long duration outages.

(2) Utility specific characteristics including fuel mix, excess capacity, load curves and alternative options which might be implemented during the outage are not accounted for.

(3) The average fraction of non-economy replacement power purchases for the NERC regions are used, as opposed to those for a specific utility.

(4) The fraction of replacement energy from non-economy purchases is correlated to the production cost increase in the first year of the outage based on detailed case studies.

(5) Fossil fuel prices are assumed to be high relative to fusion power generation costs.

(6) Costs due to environmental effects resulting from the use of alternate energy

sources are not considered.

(7) Although the model was not intended to be used for outages of less than one year, it was assumed to be possible to extend it for use in short duration outages.

(8) Daily or seasonal effects or alternative measures to alleviate the need for replacement power purchases are not accounted for in the model. Hence, costs for very short duration outages may be overestimated.

C.2 References

(C.1) W.A. Buehring and J.P. Peerenboom, Loss of Benefits Resulting from Nuclear Power Plant Outages, Argonne National Laboratory, NUREG/CR-3045 (ANL/AA-28), Vols 1 & 2, March 1982.

(C.2) C.C. Baker et al., STARFIRE - A Commercial Fusion Tokamak Power Plant Study, Argonne National Laboratory, ANL/FPP-80-1, 1980.

(C.3) United States Department of Commerce, Bureau of the Census, Statistical Abstract of the United States: 1984, 104th edition, Washington D.C., 1984.

(C.4) R.P. Burke, Economic Risks of Nuclear Power Reactor Accidents, Doctoral Thesis, Department of Nuclear Engineering, Massachusetts Institute of Technology, October 1983.

Appendix D

D.1 Low Activation Maintenance Downtime Estimates

Table D.1: Low Activation Scheduled Downtime Estimates for Reactor Plant Equipment Maintenance

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0 x $10^{-8\dagger}$ Sv/h	Days Per Year at 2.1 x $10^{-4\ddagger}$ Sv/h
First wall/blanket system				
13.7° Sector	0.16	8.8	-	0.34
16.3° Sector	0.167	10.3	-	0.40
Blanket coating	1.0	2.5	-	-
Shield				
Shield door	0.167	*	-	0.04
Cooling line shields	0.167	*	-	0.01
RF & ECRH duct shield	0.167	*	-	0.01
RF heating & current drive				
Cross field amplifiers	1.0	20.0	20.0	-
Wave guide (blkt)	0.167	*	-	0.34
Wave guide (bdle B)	0.167	*	-	0.01
Phase shifter	1.0	4.7	4.7	-
Window Assembly	0.167	*	-	0.01
Grill	0.167	*	-	0.01

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0×10^{-8} Sv/h	Days Per Year at 2.1×10^{-4} Sv/h
Reactor vacuum system				
Plasma chamber system:				
Cryosorption pumps	0.5	16.3	-	1.88
Cryo. regen. valves	0.5	13.1	-	3.02
Cryo. isol. valves	1.0	1.1	-	0.25
Roughing pumps/motors	0.2	1.3	-	0.32
Roughing regen. valves	1.0	1.1	-	0.25
Equip. isol. valves	1.0	2.4	-	0.55
Traps	1.0	1.3	-	0.32
Magnet dewar system:				
Roughing pumps/motors	0.2	1.3	-	0.32
Equip. isol. valves	1.0	1.6	-	0.38
Traps	1.0	1.3	-	0.32
Power supply and switching				
ECRH plasma breakdown:				
High volt. switch gear	1.0	0.2	0.2	-
Crowbar	1.0	0.2	0.2	-
Regulator	1.0	0.2	0.2	-
Low volt. switch gear	1.0	1.8	1.8	-
Controls	1.0	1.8	1.8	-
RF heating & current drive:				
Power supply system	1.0	1.5	1.5	-

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0 x 10^{-8} Sv/h	Days Per Year at 2.1 x 10^{-4} Sv/h
TF magnets:				
Power supply system	1.0	0.2	0.2	-
Dump resistor system	1.0	0.6	0.6	-
EF magnets:				
Power supply system	1.0	0.2	0.2	-
Dump resistor system	1.0	0.4	0.4	-
OH magnets:				
Power supply system	1.0	0.2	0.2	-
Dump resistor system	1.0	0.3	0.3	-
CF magnets:				
Power supply system	1.0	0.4	0.4	-
Switch gear sets	1.0	0.2	0.2	-
ECRH plasma breakdown				
Gyrotrons	1.0	1.8	1.8	-
Gry. mount assemblies	1.0	1.2	1.2	-

Total for scheduled maintenance: 65.60 days per year
(considering effect of task frequency)

Notes:

- * The maintenance action is conducted in parallel with first wall/blanket sector replacement on a non-interference basis so that the time required to complete the task does not lengthen the outage duration. However, the task does contribute to the total dose incurred.
- † Dose rate behind the shield
- ‡ Dose rate just behind the blanket

Table D.2: Low Activation Unscheduled Downtime Estimates for Reactor Plant Equipment Maintenance

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0 x 10^{-8} Sv/h	Days Per Year at 2.1 x 10^{-4} Sv/h
First wall/blanket system				
13.7° Sector	0.04	8.8	-	0.081
16.3° Sector	0.04	9.7	-	0.090
Blanket coating	0.10	13.5	-	-
Shield				
Shield door	0.04	8.6	-	0.080
Vacuum pump shield	0.01	1.8	-	0.004
Vacuum duct shield	0.005	5.5	-	0.006
RF & ECRH duct shield	0.005	1.3	-	0.001
Cooling line shields	0.005	1.3	-	0.001
Fuel injection shield	0.005	1.3	-	0.001
Magnets				
TF coils	0.0005	261	-	0.030
EF coils/OH coils (u/e)	0.004	97.4	-	0.090
EF coils/OH coils (l/e)	0.004	138	-	0.128
CF coils (l/i)	0.0005	192	-	0.022
OH coils/EF coils (core)	0.004	95.6	-	0.088
RF heating & current drive				
Cross field amplifiers	0.10	0.4	0.04	-
Wave guide (blkt)	0.005	10.0	-	0.012
Wave guide (bdle B)	0.03	2.0	-	0.014

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0×10^{-8} Sv/h	Days Per Year at 2.1×10^{-4} Sv/h
Wave guide (dist'n)	0.0001	0.9	-	0.0001
Phase shifter	0.10	0.4	0.04	-
Circulator/dir'l cplr	0.0001	0.9	-	0.0001
Window Assembly	0.003	2.0	-	0.001
Grill	0.01	2.0	-	0.005
SF6 supply lines/valves	0.0003	0.2	-	-
Primary structure support				
Antitorque panels	0.0002	5.9	-	0.0003
Equip. support str.	0.0001	54.6	0.003	0.001
Centerpost sup. str.	0.0001	54.6	0.003	0.001
Reactor vacuum system				
Plasma Chamber System:				
Cryosorption pumps	0.02	2.5	-	0.011
Cryo. regen. valves	0.15	1.5	-	0.050
Cryo. isol. valves	0.0003	2.5	-	0.0002
Roughing pumps/motors	0.14	1.7	-	0.056
Roughing regen. valves	0.15	1.5	-	0.050
Equip. isol. valves	0.0003	1.5	-	0.0001
Roughing vacuum lines	0.003	1.5	-	0.001
Traps	0.01	1.5	-	0.003
Magnet dewar system:				
Roughing pumps/motors	0.14	1.7	-	0.056
Equip. isol. valves	0.15	1.5	-	0.050
Roughing vacuum lines	0.003	1.5	-	0.001

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0 x 10^{-8} Sv/h	Days Per Year at 2.1 x 10^{-4} Sv/h
Traps	0.01	1.5	-	0.003
Power supply and switching				
ECRH plasma breakdown:				
High volt. switch gr	0.006	1.8	0.01	-
High voltage trans.	0.004	2.0	0.008	-
High voltage rect.	0.004	2.0	0.008	-
Crowbar	0.006	1.8	0.01	-
Regulator	0.20	2.0	0.4	-
Low voltage dist'n	0.0000127	2.0	-	-
Low volt. switch gear	0.006	1.8	0.01	-
Controls	0.09	1.8	0.16	-
RF heating & current drive:				
Power supply system	0.04	1.8	0.07	-
TF magnets:				
Power supply system	0.04	1.8	0.07	-
Dump resistor system	0.04	1.8	0.07	-
EF magnets:				
Power supply system	0.04	1.8	0.07	-
Dump resistor system	0.04	1.8	0.07	-
OH magnets:				
Power supply system	0.04	1.8	0.07	-
Dump resistor system	0.04	1.8	0.07	-
CF magnets:				
Power supply system	0.04	1.8	0.07	-

Component or Subassembly	Frequency (yr^{-1})	Downtime per Maintenance Action (days)	Days Per Year at 1.0×10^{-8} Sv/h	Days Per Year at 2.1×10^{-4} Sv/h
Switch gear sets	0.006	1.8	0.011	-
Uninter. pwr sys	0.33	1.0	0.33	-
ECRH plasma breakdown				
Gyrotrons	5.0	0.8	4.0	-
Gry. mount assemblies	0.1	1.0	0.1	-
Wave guides (bdle B)	0.003	2.0	-	0.001

Total for unscheduled maintenance: 11.15 days per year

D.3 Downtime Savings For The Low Activation STARFIRE Design

The total time spent for maintenance activities on reactor plant equipment for the reference STARFIRE design is estimated at 80 days (68.45 days scheduled plus 11.55 days unscheduled) [D.1]. Comparing this to the total time for scheduled and unscheduled maintenance for the low activation design (76.75 days), it can be seen that there is a time savings of 3.25 days. The low activation reactor would operate for 277.2 days each year, resulting in an availabiltiy of 76 %.

D.4 References

(D.1) C.C. Baker et al., STARFIRE - A Commercial Tokamak Fusion Power Plant Study, Argonne National Laboratory, ANL/FPP-80-1, September 1980.

Appendix E

E.1 Tritium Dose Calculations

A simple linear first order differential equation can be developed to describe the tritium activity concentration in the reactor building subsequent to the release of 25 g of tritium from the cryopumps. The concentration in the reactor building at any time was assumed uniform and the detritiation system was assumed to operate at an efficiency ot 90 %. The normal operation detritiation system was assumed to be operable subsequent to the accident, removing tritium at a rate sufficient to balance the steady state leakage rate. Hence, leakage from any reactor components does not place an additional load on the emergency system. Since the chemical form of tritium is important in assessing the dose, both HT and HTO activity concentrations must be described.

From simple mass balance considerations, the following equations were obtained:

$$C_{HT}(t) = C_0 \cdot e^{-kt} \tag{E.1}$$

$$k = 0.9 \left(\frac{q}{V}\right) + \lambda_d + \lambda_c \tag{E.2}$$

$$C_{HTO}(t) = C_0 \left(e^{-mt} - e^{-kt}\right) \tag{E.3}$$

$$m = 0.9 \left(\frac{q}{V}\right) + \lambda_d \tag{E.4}$$

$$C_{TOT}(t) = C_0 \cdot e^{-mt} \tag{E.5}$$

where

C_{HT}= activity concentration of elemental tritium (Ci/m^3)

C_0= initial elemental tritium concentration evaluated immediately after the release (Ci/m^3)

q= detritiation system volumetric flow rate (m^3/min)

V= reactor building volume (m^3)

λ_c= conversion constant from elemental tritium to tritiated water vapor

= 2.2075×10^{-7} min^{-1}

λ_d= decay constant for tritium

= 1.714×10^{-7} min^{-1}

C_{HTO}= activity concentration of tritiated water vapor (Ci/m^3)

C_{TOT}= total tritium activity level (Ci/m^3)

The flow rate (q) for a given option was dependent on the number of detritiation units employed. For option A, no emergency detritiation units were used and $q = 0$. For option B, one unit was used with $q = 140$ m^3/min. For options C and D, using two and three detritiation units respectively, the flow rates used were 280 m^3/min and 420 m^3/min.

The time at which manual clean up can begin was found by setting the total tritium activity concentration equal to 500 μCi/m^3. It was assumed that clean up was "complete" once the total activity concentration was within 5 % of 50 μCi/m^3 (the steady state level).

The dose rate due to HT or HTO at any time can be obtained by multiplying each concentration by its appropriate dose conversion factor. The total dose rate at any time is given by the sum of the HT, HTO and dose rates:

$$R(t) = R_{HT}(t) + R_{HTO}(t) + R \tag{E.6}$$

$$= 7.717\text{x}10^{-7}\mathrm{C_{HT}(t)} + 1.893\text{x}10^{-2}\mathrm{C_{HTO}(t)} + 2.5\text{x}10^{-5}\ \mathrm{Sv/min} \tag{E.7}$$

The dose incurred per individual was evaluated by integrating the time varying dose rate over the duration of manual clean up.

The crew entering the reactor building subsequent to the accident was assumed to consist of five persons. These workers would enter the building at a concentration of 500 μCi/m^3 and would begin to repair the damage resulting from the accident and carry out any other necessary maintenance. Workers would remain in the building until the outage was over, at which time a tritium level of 52.5 μCi/m^3 would exist. If the contact period exceeded eight hours, a new crew of five workers was assumed to take over. No allowance was made for lost time due to shift changes or breaks during a shift. The total cumulative dose was assessed by summing the individual doses and by assuming that five workers were present at all times during the contact period of the outage.