SPEARS

ENVIRONMENTAL, SAFETY-RELATED AND ECONOMIC POTENTIAL OF FUSION POWER

MAIN REPORT

by

THE EEF STUDY GROUP

Brussels December 1989

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PREFACE

The Study Group on Environmental, Safety-related and Economic Potential of Fusion Power (EEF) was set up by the Commission of the European Communities Directorate-General XII for Science, Research and Development/Fusion Directorate in order to prepare, by order of the Commission, a technical document on the environmental, safety-related and economic potential of thermonuclear fusion power. The Study Group, whose members have served as individuals, not as representatives of their institutions, has based its findings on research and review work carried out by government-sponsored and private institutions and engineering consultant firms throughout the Community.

The members of the EEF Study Group were: R S PEASE (Chair), Progressive Engineering Consultants, Warrington, United Kingdom; J DARVAS, Commission of the European Communities (CEC), Bruxelles, Belgium; R H FLOWERS, United Kingdom Atomic Energy Authority (UKAEA), Harwell, United Kingdom; L GOUNI, Electricité de France (EdF), Paris, France; G GRIEGER, Max-Planck-Institut für Plasmaphysik (IPP), Garching, Fed. Rep. of Germany; K KÖBERLEIN, Gesellschaft für Reaktorsicherheit (GRS), Garching, Fed. Rep. of Germany; A RONCAGLIA, Universita di Roma, Rome, Italy; J P HOLDREN (Consultant), University of California-Berkeley, Berkeley, United States of America; F COZZANI and K STEINMETZ (Scientific Secretaries), Commission of the European Communities (CEC), Bruxelles, Belgium.

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CHAPTER 1

INTRODUCTION

General aims

1.1 The European Community programme of research into nuclear fusion aims to provide, for the Community countries and their partners, a source of energy which draws on a vast and widespread resource of indigenous fuel, namely the deuterium present in all water and the lithium present throughout the earth's crust.

1.2 The present status of the programme may be characterised as that of basic physics research, but it has reached the stage where, in the Community's largest experiment JET, nuclear fusion power of tens of kilowatts (thermal) is produced in high temperature deuterium gas confined by magnetic fields. In the coming years, this output is to be enhanced several hundred times by using D-T fuel and by other developments. The multi-megawatt (thermal) fusion power will then be close to the heating power delivered to the gas and a net energy output from the gas will be in sight. However the Community's programme has yet to establish firmly the detailed conditions for, and to demonstrate the reality of, an overall net power output from a nuclear fusion plant [1.1,1.2,1.3].

1.3 In adopting the Fusion Research Programme for the period January 1988-March 1992 the Council of Ministers invited the Commission to arrange, before the next programme revision (on 1st January 1991), an independent appraisal of the environmental, safety related and economic potentials of fusion. To prepare a technical document which it would submit for this appraisal, the Commission set up in October 1988 a study group, and has placed study contracts related to the technical issues with research organisations throughout Europe.

1.4 The present report is the outcome of the study group's work and is determined by the terms of reference, namely:

> "The study group shall, on the basis of their own work and of the results of the study contracts, draw up a final report summarizing the results achieved and drawing conclusions on the environmental impact and the economic potential of fusion power".

The Commission's instructions to us are at Annex 1.1; the membership of the study group is at Annex 1.2; the programme of meetings is at Annex 1.3; the studies commissioned and organisations consulted by contract and otherwise are at Annex 1.4; the contract reports received are listed at Annex 1.5; the report published in 1986 by the Commission on fusion economics and environmental potential is at ref. [1.4]; ref. [1.5] is the assessment by the European Parliament in 1988.

1.5 The environmental and economic potential of fusion power have been studied for about 20 years, in Europe, in the U.S.A. and in Japan. The most recent of these is an extensive study made in the USA (the ESECOM study [1.6]). To carry them out it is necessary to hypothesise the strength and shape of the magnetic fields needed and the means for fuelling, heating and exhausting the gas. Then it is necessary to envisage how these might be engineered into a practical electricity generating plant, acceptable to utility companies. On the basis of such conceptual outlines of fusion reactors, which vary considerably in depth of detailed analysis, it is possible to discuss estimates of the potential economic benefits and potential environmental impact. As the physics and engineering research has advanced, so the hypotheses have become more realistic; however, for the reasons given in para. 1.2, such studies today still retain an inherently hypothetical character.

1.6 The potential value to the consumer of a successful outcome of the Community's programme of fusion research is subject to the further uncertainties of the energy market. These include: the required outputs of thermal energy which can be converted to electricity in large central power station units, or which can be used for other industrial purposes, the targets for economic costs set by competing technologies, the effect of various economic assumptions such as interest rates, the plant lifetime, the rate of return and the demands of environmental protection. Furthermore, the economic and social framework for energy is subject to shocks, in which the economics of energy production, or the environmental acceptability of the means of production of energy, are subject to discontinuous quasi-permanent change. Such shocks are unpredictable, but have had a large influence on energy policy of industrialised countries in the past. We have focussed on the Western European energy market within the world-wide context of large-scale energy supply.

<u>Timescale for fusion development</u>

1.7 Large-scale experiments and development plant are needed for fusion reactor development, so that the time needed to conclude a successful programme depends mainly on the time taken to construct, to operate and to assimilate the results of such large plant. It would seem now that probably two such stages in large plant development lie ahead in magnetic fusion, namely: the study of the physics and technology of self-sustained fusion reactions ("ignition") in a high temperature gas and, beyond that, the demonstration of a net electrical power output from a single plant. There does not at present seem to be a compelling need to take risks in shortening or compressing these stages. Consequently we have judged, perhaps conservatively, that for the present analysis and assessment, we should assume that:

(1) the major application of fusion will be the generation of base-load electricity in large central stations;

(2) these stations will begin to contribute to electricity generation in the mid-21st century, i.e. about 60 years hence.

1.8 The fusion reactor concepts used in this report are considered to be prototype systems, where a prototype is defined as the first magnetic fusion reactor to produce electricity for a grid system. We have considered that such a reactor would have to be built about the year 2020 if series-built reactors are to contribute to base-load generation in the mid 21st century. The costs and technology of such a prototype can be forecast with less uncertainty; and the developments subsequent to the prototype are treated herein by means of a generalised learning curve derived from experience with other technologies.

Technological considerations

1.9 The conceptual outlines of fusion power stations considered by us are derived from the Community's research programme and from US studies. In each case they involve a fusion reactor island which generates high temperature steam, which in turn drives the turbo-generator and electrical power systems. The fusion reactors used in this report involve comparatively modest extrapolation of magnetic fusion physics. The parameters of two of the outline reactors provided by the Community's programme (PCSR-E and EEF Reference Reactor) are close to the theoretical and empirical laws based on current experiments. We have also considered the advances both in physics and engineering which may occur as a result of the research, and have taken into account advanced reactor concepts, also provided by the Community's programme, which incorporate examples of possible advance. We have used one of these reactors (AMTR-3) for cost analysis. For studies of environmental potential, the reactor examples used include the above EEF Reference design with conventional engineering materials (ferritic steel), and a variant with a low activation structural material to illustrate what can be achieved with materials designed for use in fusion reactors. We have also drawn on the American studies of the Starfire [1.7] and other reactors, especially for safety analysis.

1.10 Assessing the potential merits of fusion power is done by making comparative studies with other forms of electricity generation. The choices for the comparison are made fairly straightforward by the characteristics of fission power. Like fission, nuclear fusion power:

is primarily for base load electricity generation;

- is insensitive to raw fuel or ore costs;
- is capital intensive;
- uses a steam-raising thermodynamic cycle;
- has the environmental benefit of discharging no "greenhouse" gases into the atmosphere;
- presents problems of radioactivity.

Unlike fission, the fusion reaction does not intrinsically produce radioactive waste, nor does fusion involve the fissile materials U-235 and Pu-239 which have to be used on a large scale in fission and which are essential components of nuclear weapons and are subject to non-proliferation control. From the point of view of economics, fission has rather similar characteristics; large unit size; relatively large capital cost. Fission power is now well established and offers a large body of economic experience. Thus we have compared envisaged fusion reactors with fission counterparts in order to obtain our assessments.

1.11 We have briefly considered the question of alternative uses of fusion. Nuclear fusion will be a source of heat and a source of neutrons and of other radiation. It could provide high grade heat directly to process plant and reject-heat to central heating plant in combined heat and power schemes. However, neither of these issues is a special property of fusion; nor in a fusion context have they been studied in adequate depth to justify including them in our economic and environmental assessments. The neutrons emitted in the D-T fusion reaction have a high energy and could be used to breed fissionable material, or to induce fission in a uranium or thorium blanket. Studies of such potential uses have mainly been carried out in the US and USSR. The reader is referred to the ESECOM report [1.6] for an economic and environmental assessment of their value. In brief, the environmental impact of such a system is dominated by the fission component of the reactor, so that most of the environmental distinction of fusion is lost. The Community's fusion programme has always focussed on pure fusion and its application to electricity generation.

Plan of the report

1.12 The report first sets out in Chapter 2 the energy scene envisaged for Western Europe in the mid-21st century. The demand for fossil fuel and perhaps also for uranium ore, will be affected significantly by developing needs of the third world, especially population giants such as India and China. We have therefore tried to set the European position into a possible world scene. In brief, there is a huge potential demand for base-load electricity generation to which fusion power could contribute. Lastly there is a section which reviews fusion research as a current investment to be set against potential ultimate return.

1.13 Chapter 3 describes the main features of magnetic fusion reactors and the associated technology. It introduces the conceptual reactors used in the assessments. In addition we have drawn on the US conceptual designs used in their environmental and economic studies. For fission reactors we have used a thermal neutron PWR system and a fast neutron breeder reactor. In this chapter we also present some of the areas where major technical advances may take place and outline their potential for economic and environmental benefit. But we have not assessed envisaged reactors based on alternative magnetic confinement systems.

1.14 Chapter 4 reports the outcome of our studies of the economic issues. The report does not provide an answer to the question whether or not fusion will become an economically competitive energy source. Rather, the chapter provides updated information on relevant issues, and some comparative figures based on the above-mentioned technical and societal assumptions. The chapter first deals with methods of comparing electricity generating costs from power stations based on different technologies and operating at widely different times. Secondly, estimates are made of the likely basis of electricity costs in Western Europe in the mid-21st century. In order to allow for uncertainties two main assumptions are offered, namely that electricity generating costs remain unchanged in real terms; and secondly that they are increased by 20% as a consequence of increased fuel prices. Estimates are made of the maximum capital cost of a prototype fusion reactor compatible with subsequently economic competitive series reactors, using two main background assumptions. These estimates are then compared with estimates, provided by the current European fusion programme, of the capital costs of three of the prototype reactor parameter sets presented in Chapter 3.

1.15 Chapter 5 presents the results of the environmental analyses which have been carried out. Neither fusion fuel nor the ultimate fusion products are radioactive, but the plant suffers parasitic radioactivity due to unwanted neutron reactions in the materials of the reactor and from the beta-activity of the intermediate product tritium. The numerical magnitude of the first of these effects is strongly dependent on the development of materials, their purity and isotopic composition. The second is design dependent. We have especially considered those features of fusion which can be compared with the alternative energy sources. These include the size and distribution of the fuel resource, the resource of other materials needed, the potential hazards of operating reactors and the fuel store, the potential hazard in any waste products, the facility for ensuring that there is no production of the fissile materials U-233, U-235 and Pu-239 and the small potential for any chemical or atmospheric pollution.

1.16 Chapter 6 summarises the main points established by our analyses. Our terms of reference invite us to report our general conclusions on the economic and environmental potential of fusion; we do so at the end of Chapter 6.

Acknowledgements

1.17 The timetable for the work of the study group (about one year) is exceptionally compressed and there have been heavy demands placed on those executing the study contracts. Much of the new material from these contracts became available to the study group only in the last few weeks before the completion of this report. The list of study contracts and references to other original material is given in Annexes 1.4 and 1.5. Our warmest thanks go to all those who have contributed to the work in this way. We are especially grateful to the U.S.D.O.E. for making available to us in advance of publication information derived from their ESECOM study [1.6]. We are conscious of the debt we owe to Dr J P Holdren, Chairman of ESECOM for participating in our studies. We have drawn on the IAEA's studies of the safety and potential environmental benefit of fusion, recently updated in an international workshop (Jackson, USA) in April 1989. We are grateful to the International School of Physics, Ettore Majorana for providing an International Workshop (August 1989) at which the subject of our studies was discussed in depth with distinguished experts. Lastly we thank Dr Maisonnier and the Commission staff for their untiring help to us in discharging our task.

References

[1.1] W.M. Stacey. Fusion: an introduction to the physics and technology of magnetic confinement fusion (Wiley, Interscience 1984).

[1.2] B.E. Keen (editor). JET joint undertaking. Progress report 1988. EUR 12323 EN, (Luxembourg, 1988).

[1.3] M. Keilhacker, presented on behalf of the JET Team. Overview of JET Results using a Beryllium First Wall. Bull. Am. Phys. Soc. 34 1912, October 1989.

[1.4] R.Buende et al. Environmental impact and economic prospects of nuclear fusion. Report Number EURFU BRU/X11 – 828/86, (CEC, Bruxelles, 1986).

[1.5] G.J. Lake and D.Holdsworth. Criteria for the assessment of European fusion research (STOA Fusion Project, European Parliament,Luxembourg, Vol 1 EP-STOA-F1, May 1988; Vol 2 EP-STOA-F2, May 1988).

[1.6] Report of the Senior Committee on Environmental, Safety and Economic Aspects of Fusion (J.P. HOLDREN et al). UCRL-53766 of June 1989. (Lawrence Livermore National Laboratory).

[1.7] C.C. Baker et al. STARFIRE - a commercial Tokamak fusion power plant study. Report ANL/FPP-80-1, (Argonne National Laboratory, Chicago, 1980).

ANNEX 1.1

TERMS OF REFERENCE

1. In pursuance of the Research and Training Programme (January 1988 - March 1992) in the field of thermonuclear fusion, adopted by the Council of the European Communities on 25 July 1988, the Commission will arrange before the next programme revision (1.1.1991) for an independent appraisal of the environmental, safety-related and economic potential of fusion.

2. In order to prepare the technical document which it would submit to this appraisal, the Commission will:

a) set up in October 1988, a Study Group of about seven senior professionals,

b) award study contracts to competent bodies on specific topics related to the subject matter of the appraisal mentioned above.

3. The Study Group, under the Chairmanship of Dr R S PEASE, FRS., consultant of Progressive Engineering Consultants (PEC) Ltd., 105 Walton Road, Warrington, WA4 6NR, England, shall receive from PEC the technical and clerical support necessary for the performance of these tasks.

The Study Group shall:

a) develop a preliminary work plan and breakdown of tasks identifying the bodies to which specific tasks could be commissioned and give an estimate of the overall financial volume for the corresponding study contracts (see paragraph 2b) to be placed by the Commission. This work shall be documented by a report to be submitted to the Commission for approval possibly before 24 October 1988;

b) advise the Commission on the need for power reactor conceptual design studies to possibly provide an improved basis for environmental and economic considerations on the longer term; this advice shall be documented in a report to be submitted to the Commission not later than 16 January 1989;

c) supervise the work defined in the plan and carried out under contracts awarded by the Commission;

d) on the basis of the work of the Study Group and of the results of the study contracts referred to in paragraph 2b, draw up a final report summarizing the results achieved and drawing general conclusions on the environmental impact and the economic potential of fusion power.

ANNEX 1.2

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ANNEX 1.3

SCHEDULE OF BUSINESS

Meeting	Date	Business
1	25 Oct.1988	Terms of reference; tentative content of the study, tentative draft work plan and conceptual design studies.
2	21 Nov.1988	Discussion of revised work and contract plan. Support contracts to be launched. Draft opinion on the need of fusion power reactor design studies.
3	21 Dec.1988	Progress on agreed contracts and work. Remaining chapters and contracts. Preparation of the final EEF Report, strategy, distribution of tasks. Discussion of main points of introduction.
4	27 Jan.1989	Progress reports on various items regarding the energy scene in 2050, envisaged fusion reactors. Check of overall schedule. Draft opinion on the need of fusion power reactor design studies (revised paper). Outline of Introduction and Chapter 2.
5	10 Mar.1989	First draft of Introduction and Chapter 2 and outline of Chapters 3 to 5; proposal for annexes to the main report. Preliminary results from contract studies on the energy scene in 2050, tokamak reactors, advances expected, costing issues. Revised and updated schedule of studies and contracts. Comments from J P Holdren.
6	21 Apr.1989	Discussion of draft Introduction, and main problems of the environmental impact and links with energy policies; detailed outline of Chapter 4 and discussion of studies on costing issues. Progress reports on the energy scene, reference reactor, advances expected, fusion R&D expenditure, decommissioning, resources of fuels etc, accident sequences; progress on D-^{3}He issue.

SCHEDULE OF BUSINESS (Contd)

Meeting	Date	Business
7	1Jun.1989	Report on IAEA Technical Committee Meeting on Fusion Reactor Safety. Revised draft of Chapter 2; draft on links to the environment; progress report of contracts. First draft of Chapter 3; progress reports on reference tokamak reactor, advances expected, advantages of spin-polarised nuclei in reactors. Revised outline of Chapter 4. Progress on studies and contracts regarding the environmental and safety-related aspects. Technical arrangements for the preparation of the final EEF Report.
8	6 Jul.1989	Preface and revised draft Introduction. Revised draft of Chapter 2. Draft of Chapter 4. Progress on studies related to Chapter 5. Comments from J P Holdren. Proposals for Conclusions and Recommendations. Methods of production of EEF Report.
9	11 Sep.1989	Discussion of the first complete draft of the EEF Report. Revised draft of Chapter 2. First complete draft of Chapter 3. Revised draft Chapter 4. First draft Chapter 5; results from contracts with Harwell; accident sequences. Discussion of Chapter 6.
10	22 Sep.1989	Discussion of the second (partial) draft of the EEF Report. Chapters 2 and 4; aspects of new materials. Revised draft of Chapter 3. Chapter 5; safety issues. Discussion of Chapter 6.
11	10 Nov.1989	Summary Report to CCFP. Discussion of the third draft of the EEF Report. Discussion of Summary paper.

ANNEX 1.4

COMMISSIONED STUDIES

SUBJECT	STUDY CARRIED OUT BY
The energy frame in 2050.	Institut d'Economie et de Politique de l'Energie, Grenoble.
Main problems of environment and links with energy policy.	Commission of the European Communities, Bruxelles, DG XI/ DG XII.
Review of commercial tokamak reactor designs. A reference model tokamak reactor.	United Kingdom Atomic Energy Authority, Culham.
Advanced model tokamak reactor.	United Kingdom Atomic Energy Authority, Culham.
Model stellarator reactors.	Max-Planck-Institut für Plasmaphysik, Garching.
Model RFP reactors.	United Kingdom Atomic Energy Authority, Culham.
Tokamak advances expected and needed. Advances in exhaust technology for commercial fusion power reactors in mid 21st century.	United Kingdom Atomic Energy Authority, Culham.
Forecast superconducting technology.	Max-Planck-Institut für Plasmaphysik, Garching.
Construction costs for a European PWR plant, structured according to the NET SCAN-2 cost model.	Holinger AG, Baden.
Energy accounting.	Energy Management Centre Europe.
Fusion R&D costs as a European investment.	A Roncaglia, Rome.
Decommissioning of fusion power plants and waste disposal. A comparison with PWR plants.	Studsvik Nuclear, Nykoping.

COMMISSIONED STUDIES (CONTINUED)

SUBJECT	STUDY CARRIED OUT BY
Resources of fuel and other essential materials, low activation elements for fusion.	Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
Advanced fusion fuel cycles.	FOM-Institute for Plasma Physics, Rijnhuizen.
Economic potential and environmental impact of fusion	United Kingdom Atomic Energy Authority, Harwell.
Accident sequences in fusion reactors and estimate of radioactive releases and health hazards.	Gesellschaft für Reaktorsicherheit, Garching.
Safety categorisation and comparison with US studies.	Gesellschaft für Reaktorsicherheit, Köln.
International safeguards issues of fusion reactors.	United Kingdom Atomic Energy Authority, Harwell.
The environmental impact of mining essential raw materials for fusion and fission reactors.	United Kingdom Atomic Energy Authority, Harwell.

ANNEX 1.5

LIST OF EEF REPORTS PRODUCED

Copies of these reports can be obtained from
Dr J. Darvas at the address given in Annex 1.2.

1. J.D. Jukes and T.E. James
"Review of commercial Tokamak DT reactor designs"
UKAEA-Culham Laboratory.

2. P.I.H. Cooke, R. Hancox and W.R. Spears
"A reference Tokamak reactor"
UKAEA-Culham Laboratory - August 1989.

3. "Construction costs for a European PWR plant structured according to the Scan-2 cost model"
Holinger AG in association with Colenco AG - July 1989.

4. L. Devell, K. Broden, K. Fagerstrom, A. Hultgren, S. Menon and G. Olsson
"Decommissioning of fusion power plants and waste disposal. A comparison with PWR plants"
Studsvik Nuclear, Nykoping - 1989.

5. F. Barthel, C. Hemmer, H. Schmidt, G. Seidl and H. Wagner
"Resources of fuel and other essential materials (including low activation elements) for fusion"
Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover - July 1989.

6. D.C. Robinson
"Tokamak advances expected and needed and advances in exhaust technology for commercial fusion power reactors in mid 21st century"
UKAEA-Culham Laboratory - 1989.

7. P.I.H. Cooke, M. Cox, R. Hancox and W.R. Spears
"Advanced Model Tokamak Reactors"
UKAEA-Culham Laboratory - August 1989.

8. R.W.B. Best
"Advanced fusion fuel cycles"
Instituut voor Plasmafysica, 'Rijnhuizen', Nieuwegein, Nederland - August 1989.

9. A. Roncaglia
"Research in fusion as a European investment"
University of Rome - August 1989.

10. P.E. Love
"Net energy analysis/energy accounting"
Energy Management Center (Europe) - August 1989.

11. H. Jahn, P. Kafka and H. Löffler
"Accident sequences in fusion reactors and estimate of radioactive release and health hazards"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln - July 1989

12. "Le cadre énergétique des années 2050"
Institut d'Economie et de Politique de l'Energie, Grenoble.

13. H.A.B. Bodin
"Comments on TITAN RFP reactor study (TITAN-I, TITAN-II)"
UKAEA-Culham Laboratory - November 1988.

14. G. Grieger
"Advances in superconductor technology"
Max-Planck Institut für Plasmaphysik, Garching - January 1989.

15. F.J. Walford
"International safeguards issues of fusion reactors"
UKAEA-Harwell Laboratory.

16. J. Bromley
"The environmental impact of mining essential raw materials for fusion and fission reactors"
UKAEA-Harwell Laboratory - August 1989.

17. J.D. Jukes, J.B. Hicks and V.K. Thompson
"Waste generated by fusion reactors"
UKAEA-Culham Laboratory - May 1989.

18. M.J. Sowerby et al
"A contribution to a study on the economic potential and environmental impact of fusion"
UKAEA-Harwell Laboratory - November 1989

19. K. Köberlein
"Accident sequences in fusion reactors and estimates of radioactive releases and health hazards"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln - July 1989.

20. P. Kafka and H. Löffler
"Safety categorization of fusion and comparison with US-studies"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln - December 1989.

Chapter 2

THE EUROPEAN ENERGY SCENE IN 2050

CHAPTER 2

THE EUROPEAN ENERGY SCENE IN 2050

Purpose and methodology

2.1 In this chapter an outline of the European energy scene in the middle of the 21st century is given in order to assess the scope for nuclear fusion. However, it is not possible to do this with precision because of the long timescale involved . What can be done is to discuss the implications of different plausible hypotheses, regarding EC growth rate on Gross Domestic Product (GDP) (para. 2.3 to 2.5) and energy consumption dependence (para. 2.6 to 2.9), total energy consumption and electricity demand (para. 2.10 to 2.12) and the implications of non-repetitive events such as intermittent supply shocks and the effect of economic crises (para. 2.13 to 2.14). On this basis it is possible to discuss the energy scene (para. 2.15 to 2.18), environmental issues (para. 2.19 to 2.24), European energy policy (para. 2.25 to 2.26) and research in fusion as an investment (para. 2.27 to 2.35).

2.2 The European energy scene cannot be dissociated from world energy demands due to the impact of world energy consumption on the environment, on the availability and price of fossil fuels and on the possibility of exporting European know-how, for example, the construction of fusion plants.

Fusion is considered as a technology which might be made available, given sufficient R&D effort, for base-load electricity generation; other potential uses are not considered here.

Footnotes to the text are given in the Annex 2.1. The text is referenced where footnotes apply, the Annex para. ref. is stated.

Basic economic trends

2.3 The first element to be considered in discussing the EC energy demand in the year 2050 is the level of economic activity. Obviously, the result is highly sensitive to the assumptions made regarding the growth rate in real GDP. The following Table 2.1 shows, for different growth rates, the ratio of GDP (year 2050) to GDP (year 1988).

TABLE 2.1. Growth rate and GDP ratio, 2050/1988

Growth Rate	GDP (2050)/GDP (1988)
0%	1.0
1%	1.8
2%	3.4
3%	6.2
4%	11.4
5%	20.6
6%	37.1

The higher growth rate, 6%, is probably implausible.

2.4 The growth rate of economic activity up to 2050 will depend on both supply and demand which interact with each other but, for simplicity, the supply side only is considered here. Three scenarios are identified:

i. An 'intermediate' scenario of 2.5-3% yearly increase in hourly labour productivity, of which 0.5% is absorbed by a reduction in working time. A constant level of employment is assumed. Although there might be a decrease in the EC population of working age, this is off-set by an increase in female employment and immigration into Europe. This leads to an average yearly GDP growth rate of 2-2.5%, and a GDP in Europe in 2050 about four times the 1988 value (Table 2.1).

ii. A 'low' scenario with a reduced productivity growth, say 2%, absorbed partly by a reduction in working time (0.5%), and partly by a reduction in employment (1.5%) arising from changes in age structure, population decline, increase in schooling and a reduction in retirement age. Net immigration into EC countries is assumed to be zero (due to negative labour market conditions and/or to an unfavourable socio-political climate). Supply shocks, aggravated by environmental constraints, provoke temporary declines in activity levels, as in 1975 in the aftermath of the oil crises. Under these conditions GDP levels in Europe would be about the same in 2050 as in 1988.

iii. A 'high' scenario of 4% yearly increase in productivity. The trend in reduction in working time is more than counterbalanced by an increase in overall employment due, for example, to population growth, increased female employment and immigration. The EC overall growth rate could rise to 5%. This would imply a European GDP in 2050 equal to more than 20 times the present level, in real terms (Table 2.1). It is possible that only a scenario of this kind will be consistent with Europe not losing ground in its share in world economic activity.

2.5 In some ways past experience points towards the intermediate scenario. The average GDP growth rate for sixteen industrialised countries over the period 1820-1980 was 2.5%. GDP per man-hour grew in the US at an average yearly rate of 2.3% between 1890 and 1973 (including the years of the Great Depression, 1929-38, when it was equal to 0.7%). However, in 'tranquil' years, without world wars and major economic crises, growth rates can be higher. For the sixteen major industrialised countries, real GDP grew between 1950 and 1973 at an average annual rate of 4.9%. Even though during the post-1973 period there were two oil supply crises, the Italian GDP has grown four-fold in the last forty years.

(See Annex 2.1, para. A2.5 for bibliographical references on these aspects).

The energy problem in Western Europe

2.6 Estimates of total energy consumption in Europe in 2050 may be derived from the estimates of economic growth discussed above, and from estimates of the GDP elasticity of energy consumption (defined as the ratio between the annual percentage change in energy consumption and the annual percentage change in GDP). Other ways of estimating future energy consumption are discussed in Annex 2.1, para. A2.6.

A GDP elasticity of energy consumption greater (less) than one implies a higher (lower) rate of growth for energy consumption than for GDP. The following table considers the three scenarios for GDP growth rates g%, coupled with elasticities e ranging from 0.50 to 1.25 (let us note immediately, more below, that lower elasticities, even negative ones, are technically feasible and may result from higher energy prices and stronger energy conservation policies, so that at low growth rates we may conceive the possibility of a decrease in total energy consumption. Table 2.2 represents perspectives under an implicit 'constant policy' assumption). For a zero net growth scenario we assume constant energy consumption.

TABLE 2.2

Energy consumption, 2050/1988

g% \ e	0.50	0.75	1	1.25
0	1	1	1	1
2.5	2.2	3.2	4.6	6.7
5	4.6	10	21	43

2.7 The main factors affecting the GDP elasticity of energy consumption are changes in technology and in the structure of production and consumption of the economy. These changes may be autonomous or induced by the relative level of energy prices and by policy measures (which may become relevant if conservation strategies are adopted worldwide). High energy prices (inclusive of taxes) tend to reduce consumption as consumers economise on energy (heating, car transport ...). At the same time, high energy prices to the manufacturing sector provide an incentive for R&D on energy-saving technical innovations. This is an example of a 'dynamic substitution process'.

2.8 The impact of energy prices on the GDP elasticity of energy consumption was apparent in the aftermath of the oil crises of 1973-74 and 1979-80. Two aspects of recent experience may be noted. First, the largest effects concern specific energy sources. The GDP elasticity of oil consumption fell after the oil crises, even becoming negative for short periods in some countries, due to the substitution of oil by other energy sources because of the dramatic change in relative price. However, the GDP elasticity of energy consumption from all sources appears to be much more stable. Second, the dynamic substitution process (ie energy-saving resulting from technical progress induced by higher energy prices) gives rise to a reduction in energy consumption per unit of GDP and this does not disappear when energy prices fall. Once the costs for developing new, more energy efficient, technologies are committed, the new technologies continue to be used even though the energy savings are less valuable than when the R&D for the new technology was effected.

(Annex 2.1, para. A2.8 provides information on GDP elasticities).

2.9 Some feedback from GDP growth to GDP elasticity of energy consumption is conceivable: higher rates of economic growth put pressure on exhaustible resources and this favours increased fuel prices and induces the dynamic substitution process resulting in a lower GDP elasticity of energy consumption. Higher growth rates also favour technical progress and a higher proportion of new and more efficient plants. Taking this feedback into account the range of Table 2.2 becomes biased towards the lower values and energy consumption in 2050 is in the range of 2 to about 8 times its present level. Strong energy conservation policies favour the lower end of this range, say 2 to 4, even in the case of sustained economic growth.

The prospects for electricity in Western Europe

2.10 Three salient features characterise electricity. Firstly, its share of total energy consumption is likely to continue to rise, because of its greater flexibility of use compared with other forms of energy, which makes it particularly suitable for automatic control systems and techniques which are likely to play a growing role in the future. Secondly, national electricity production systems are becoming more interdependent since storing electricity is very costly. In order to avoid interruptions of service in the event of a sudden loss of generating capacity European countries are linking their electricity system through an interconnected grid, thus gaining the economies of large scale production while avoiding the risks of service breakdown stemming from a small number of plants (exchange of electricity among European countries amounted in 1987 to 90.7 TWh, i.e. to about 6% of electricity produced: Rapporto sull'energia 1988, p 327 and ff). Thirdly, electricity supply cannot be monolithic: fuel sources and production techniques must be diversified. The more interdependent the energy sectors of the various countries become, the more important is system and operational flexibility.

2.11 The electricity needs in Europe in the middle of the 21st century may be deduced from the estimate of total energy consumption, by attributing to electricity a constant or slightly increased share of the total. This means that electricity consumption in 2050 might be anything from more than twice to less than 10 times its present level (see Annex 2.1, para. A2.11).

2.12 Total electricity production in 1987, in EC-12, was 1659 TWh. The base-load supply to be guaranteed (8760 hours per year) is approximately half the total needs (i.e. at 1987 consumption levels, around 100 GW). The present (1988) installed nuclear generating capacity in the 14 countries of the European fusion programme, is about 100 GW. The corresponding installed base-load capacity in 2050 is estimated to be in the range 250 and 1000 GW (i.e. 250 to 1000-1GW units or 125 to 500-2GW units). In 2050, some 10 to 80-1GW units (or 5 to 40-2GW units) of base-load capacity will need to be built each year. This comprises 5 to 50 GW/a for consumption growth (2% of 250 GW and 5% of 1000 GW) and 5 to 30 GW/a for the replacement of old plant (assuming around 30 year economic plant life).

Fluctuations and shocks

2.13 The energy scenario in 2050 was discussed above by considering conceivable growth rates between 1988 and 2050. However, this kind of reasoning neglects the unavoidable vagaries in the pattern of economic development due to waves of technical change, to changes in economic institutions, in market forms and in governments' economic strategies (see Annex 2.1, para. A2.13). Also, there is the possibility of political upheavals (wars, revolutions) and major economic crises (such as international financial crises due to bankruptcies involving big international debtor countries, or the repetition of 'supply shocks' like the oil crises). Natural catastrophes may also hit areas of the European territory.

Any major crises are likely to provoke sharp declines in economic activity. Such declines, if not compensated by a higher than average growth in the years of reconstruction, would reduce the level of economic activity in 2050. However, these effects are obviously speculative on such a timescale.

2.14 Developments in the rest of the world strongly affect what happens within Europe. This is true both in the political and economic sphere and in the field of technology. The importance and the variety of these influences cannot be exaggerated.

Consider just one example concerning the energy sector. Economic growth in developing countries, bringing their per-capita energy consumption towards the present level of developed countries, would have an explosive impact on world energy sources.

The following data (from World Development Report 1988 pp 240-1) gives an idea of the dimension of this problem. The annual per capita energy consumption (kg oil equivalent) was in 1986: China 532, India 208, Indonesia 213, Nigeria 134, Bangladesh 46.... and USA 7,193. To raise the population of China to the current energy level comparable to the per capita energy use in industrial nations would, by itself, require doubling the world's total current annual supply of coal, oil, gas and nuclear energy. It is clear that either developing countries will never reach the present per capita energy consumption levels of developed countries, or unbearable pressure on non-renewable energy sources will be avoided only by the development of new energy technologies such as fusion.

Different energy sources

2.15 In discussing long-term energy perspectives attention is commonly focused on coal and nuclear (fission) energy, which have a large resource base and rely on established technological knowledge. The suggestion that the world will not be able to rely for more than a few decades on oil and natural gas has been questioned. Oil and gas proven reserves (i.e. reserves the location, size and characteristics of which are already known, and which are economically recoverable with known technology at prevailing price-cost relationships) are now equal to more than forty years of consumption, at the present rate. Estimates of the ultimately available oil and gas resources are much higher, though they differ widely one from another. In addition to the uncertainties of geological estimates, technological developments are possible (e.g. on enhanced recovery ratios, on the exploitability of shale oil and tar sands, and so on) which may add considerably to present estimates (but see para. 2.20 on the 'greenhouse effect' which may severely limit the use of natural gas and oil). A similar uncertainty concerns the share of renewable energy sources in particular solar, biomass, wave, tide and geothermal in the long-term.

2.16 The scarcity of natural resources has two dimensions. First, it is the ultimate scarcity of the stock of any non-renewable natural resource that sooner or later is bound to play a major role (see Annex 2.1, para. A2.16). However, this may require many decades (oil, natural gas) or even centuries (coal). This kind of scarcity is relevant for the policy-maker, who has to prepare well in advance the transition to backstop energy sources. However, due to discounting, i.e. to the low present value attributed by private enterprise to an uncertain event far-off in the future, the 'stock-scarcity' is irrelevant as far as the present-day energy market is concerned.

The second kind of scarcity, which is sometimes confused with the first, refers not to the stock, but to the flow of the natural resource. Oil became scarce in this latter meaning with the Arab embargo in 1973. The risk of 'flow-scarcity', namely shocks due to interruptions of supply, stems not only from the concentration of reserves in a few, often politically unstable, areas of the world, but also from accidents interrupting production and distribution (pipeline interruptions, well fires, mine accidents, and so on). This second kind of scarcity is, by itself, a powerful reason for the diversification of energy sources, even when stock-scarcity is not an issue of immediate concern.

2.17 The current choice among competing energy sources depends on the institutional constraints affecting their utilisation, on their availability and reliability of supply, and on their costs.

Institutional constraints are partly a stratification of decisions taken in the past with a large variety of motivations and only partly the outcome of a policy consciously framed for tackling current and future problems of the energy sector. However this second aspect, which gained importance after the first oil crisis, is likely to become more important with increasing pressure from environmental issues.

The cost of energy conversion using different fuels depends on the technologies used and the price of each fuel. In electricity production the latter is much more relevant for coal, oil and natural gas plants than for nuclear, hydropower and solar-electric plants.

2.18 From past experience, it is clear that, while on occasions flow-scarcity has played a role in determining the price of a natural resource (especially in the case of oil), stock-scarcity is too remote to affect current prices (see Annex 2.1, para. A2.18). This is especially true in the case of coal which will be taken together with nuclear fission plants as the reference point in Chapter 4 for evaluating the economics of fusion. It is possible that oil and natural gas (which have environmental advantages) will play a larger role than at present throughout the 21st century, but it is more likely that coal (considering technical progress in coal mining, new coal fields, etc) will be available as an energy source for much longer than another century, although its use may be curtailed because of the 'greenhouse effect' (para. 2.20).

The long-term price of coal is dependent on production costs and here there are two opposing tendencies to consider: increasing costs due to the exhaustion of the 'more fertile' mines and the necessity to utilize more costly reserves and to decreasing costs, due to technical progress in coal mining and coal utilisation. It is not possible to evaluate these effects separately, but over the next decades it is reasonable to assume they will balance and the price of coal will remain constant (in real terms) at about the average value over the past thirty-five years.

There will be a tendency to move away from old mines, especially within Europe towards a few 'coal provinces' (USSR, South Africa, China and perhaps Australia), with coal travelling long distances from mines to the centres of consumption. Long-distance transportation and concentration on a few external suppliers are negative factors which tend to increase the cost of electricity. A constant long-term price for coal is a trend compatible with past experience even though there have been wide fluctuations during the past thirty-five years (up to 50% above the average value, see Fig. A2.2).

Energy and the environment

2.19 A major factor, possibly the major factor, in shaping the energy sector and energy policies over the next decades, will be the ecological constraint. With economic development and the growth of energy consumption coupled with a better understanding of the environmental effects of various human activities, environmental issues are coming to dominate the choice of competing sources of energy. The reasons for the importance which environmental issues have acquired are easy to understand; what is at stake, in fact, is the very survival of our natural environment.

2.20 One major concern is the "greenhouse effect", i.e. a global climate warming over the next decades due to emissions of "greenhouse gases" such as methane, fluorocarbons, nitrous oxide (N_2O) and, as the most important contributor (about 50%), carbon dioxide (CO_2). About one-third of the present global CO_2 emission is attributed to electric power generation by combustion of fossil fuels, especially coal (the other two-thirds is attributed to industrial users, cement manufacture, food processing, agriculture, transport (internal combustion engine), commercial and domestic users).
(see Annex 2.1, para. A2.20).

The effects of global-climate warming would be very severe in virtually all countries of the world. Unless the emission of greenhouse gases is curbed, the rise in average surface temperature of the Earth could reach 1.5 to 4.5°C before the middle of the next century, with strong local variations, for example, warming at high latitudes may reach more than twice the global average value (see Annex 2.1, para. A2.20). The warming would alter local climates by changing atmospheric and ocean circulation patterns as well as the distribution of rainfall and the frequency, intensity, and duration of temperature extremes. The polar ice-caps would be reduced and the sea level may rise between 0.3 and 1.5m. Inundation of low-lying coastal land and islands, reduction of water resources in some regions, changes in agricultural productivity and impacts on human health may follow from such geoclimatic changes.

Our present poor understanding of global climatology does not allow an exact quantification of this "warming": unknown amounts of greenhouse gases are reabsorbed or biologically stored by natural processes and there may exist other, non man-made contributions to global temperature changes, such as variations in solar activity. However, since the potential effects on human society may be highly disruptive, there is already a serious concern about greenhouse gas emissions and efforts to curb CO_2 discharges will be a major preoccupation of the next century. For power generation, this implies a partial or total substitution of fossil fuelled plants (especially coal) by other power systems (first of all in industrialised countries, including the EC, which are able to make the necessary investment for improvement).

2.21 Though attention has been concentrated on the greenhouse effect, other relevant environmental issues are associated with energy and more specifically, electricity generation. It is not possible to provide even a short survey of all these issues, on which there is a large and growing literature (see Annex 2.1, para. 2.21 for a few references). A simple, incomplete, listing (which does not include nuclear fusion, on which see later Chapter 5) would include:

- for coal: mine accidents, lung illnesses, land subsidence, landscape alterations ; dust and noise in transport; particulate and gaseous emissions due to coal-burning provoking acid rain (with severe effects on forests, vegetable life in general and on fish-life in lakes) and creating or aggravating diseases of the circulatory and respiratory systems;

- for oil: severe risk of sea pollution in off-shore production and during transportation; particulate and gaseous emissions provoking acid rain and public-health impacts;

- for natural gas: risk of catastrophic accidents in transport and storage (Ixhuatepec, Mexico, 1984; Transiberian railway, 1989); particulate and gaseous emissions (though much less than coal or oil, per unit of energy released);

- for nuclear fission: risks connected with radioactivity in normal operations; risks of catastrophic accidents (Chernobyl); the disposal of radioactive waste (including generating plant after closure); risks of nuclear armament proliferation (especially with fast-breeder reactors);

- for all thermal electricity plants: difficulty in meeting cooling water needs and the connected risks of microclimatic changes;

- for solar: landscape alterations (large amounts of territory are needed for installations, at present 25 to 50 MW/km^2); risks of microclimatic changes due to solar radiation not reaching the ground;

- for hydroelectricity: landscape alterations; risks of microclimatic changes (especially in large projects, such as the Aswan dam); risks of catastrophic accidents (flooding due to dam collapses: Vajont, 1963); ecological impacts (e.g. reduced delta fertility, fisheries impact).

2.22 Environmental effects arising from the use of different energy sources are an instance of 'externalities', where the effects from an economic activity of producers (or consumers) do not directly affect costs or earnings specific to each individual producer (or consumer), but may affect a local community or possibly society as a whole. An example of a 'negative externality' would be particulate emissions from a coal burning electricity generating plant where the plant operator has no economic incentive to abate it.

Traditionally, economic theorists require negative externalities to be balanced by the imposition of taxes on individual producers. A commonly adopted second-best solution is compliance with regulatory constraints.

2.23 In practice, the difficulty of assessing the environmental effects of human activities, and specifically of energy production and consumption, led in the past to little or no intervention. It is now clear that the environmental consequences of energy production and consumption have been under-estimated until quite recently.

The growth of scientific knowledge is increasing our understanding of environmental issues. Environmental effects which in the past went completely unnoticed are now at centre stage. In future these issues will be given an increasingly larger weight, when strategic choices within the field of energy production and consumption are considered.

2.24 Environmental concern may affect the energy sector in two distinct ways:

Firstly, if the energy sector as a whole is considered as a source of environmental damage, additional taxes on energy production and consumption and other regulatory measures directed towards energy conservation are likely to be adopted. Under some proposals tax proceeds should be used to fund environmental improvements, research on energy saving and the development of non-polluting energy sources. A strong thrust in this direction may significantly reduce the rate of energy consumption and the estimates for energy consumption in 2050 (para. 2.6).

Secondly, specific regulations and taxes on polluting energy sources, and/or incentives to non-polluting sources, may affect the choice among competing energy sources, and hence the internal structure of the energy sector.

<u>Elements of a European energy policy</u>

2.25 Major targets for EC energy policy are: competitiveness with the rest of the world in energy costs, reliability of supplies and respect for the environment. Non-fulfilment (or insufficient fulfilment) of any of these targets would entail an energy constraint on economic growth, with a loss of potential well-being. The EC countries need to adopt a flexible energy policy capable of meeting the most demanding future situations. To achieve this objective all technological paths need to be explored. It is the energy sector which should adapt to the needs of society, not the other way round.

2.26 To answer the question from which this chapter started: what conditions must a new energy technology satisfy to play a role in the markets of the mid-21st century?

Firstly, a large growth of energy consumption, especially electricity is likely to accompany a many-fold growth of economic activity.

Secondly, in addition to stock-scarcity (ultimate exhaustion of non-renewable resources), the energy sector has to plan for flow-scarcity, i.e. the risk of interruptions of energy supplies. The economic impact of flow-scarcity, which rises with increasing dependence on external energy sources, was made abundantly clear by the oil crises.

Thirdly, environmental issues will increasingly affect the energy sector, constraining its overall growth and its internal structure.

All these considerations clearly demonstrate that Europe has a strong interest in developing a new energy source, such as fusion, which, if successful:

i.   is capable of satisfying the foreseeable demand for electricity, thereby avoiding constraints on economic growth;

ii. may constitute an internal source of energy for Europe and reduce the consequences of being dependent on imported energy sources;

iii. is able to provide energy in an environmentally benign way compared with coal, oil, natural gas and fission.

<u>Research in fusion as a European investment</u>

2.27 Under what conditions is a programme of research expenditure in fusion an economically positive venture? This problem is considered by A. Roncaglia [2.1]. First the report recalls the distinction between commercial and social profitability, and stresses its relevance to the case of fusion R&D. Second it provides a model of cost benefit analysis. Third, using simplifying assumptions, the model is used to illustrate conditions under which fusion R&D is profitable. Fourth, it discusses the coefficients used in this model, including the social rate of discount, and the various assumptions. Finally in drawing conclusions, the limits of the analysis and its possible extension are discussed. Here, the following paragraphs summarise the results.

2.28 The difference between commercial and social profitability depends on the existence of costs and benefits external to the individual economic agent implementing a given project, but internal to society. A typical example of the "external" cost is pollution from a coal/electricity generating plant; a typical example of an "external" benefit is the increase in general well-being stemming from increasing mutual understanding and improved human relations connected with a higher educational level of any given individual. An evaluation of a fusion R&D programme funded by the European Commission and the member states should consider social (or system-wide) profitability, i.e. it should try to take into account not only commercial profitability, but also the foreseeable results of the fusion programme which would not be appropriated under the prevailing rules by a private firm investing in a fusion R&D programme.

Thus a private investor would exclude from the evaluation of commercial profitability all sorts of external benefits which might stem from a fusion R&D programme. For example, improved environmental conditions, increased national security stemming from reduced dependence on imported energy sources, the fall in the prices of primary energy sources which a widespread utilisation of fusion is likely to generate. Thus it cannot be maintained that investment in fusion R&D is socially unprofitable simply because private entrepreneurs do not find it profitable presently to invest in fusion R&D. Nor can a similar conclusion be derived from an analysis limited to commercial profitability, e.g. by comparing fusion R&D expenditure with expected royalty income from a patent on fusion reactors (as is suggested by the STOA Report of May 1988). Again this implies concentrating on commercial profitability alone, ignoring externalities. Furthermore, the computation of royalties involves crucial assumptions (e.g. on the unit value of the royalty, on the timespan of validity of the patent, and on the number of fusion reactors built during that timespan), which are highly uncertain.

2.29 For the evaluation of system-wide profitability, two characteristics of the fusion R&D programme must be stressed. First, the time required to reach (if it can be reached at all) the commercial stage for electricity production with fusion reactors is very long, so that, prima facie, the annual return coming after its completion, if discounted at a positive interest rate, is likely to become small compared to present day research expenditure. The second characteristic, however, is that if fusion reactors are viable, the utilisation of fusion technology for electricity generation may last for centuries.

2.30 Consider a fusion R&D programme which lasts n years and ends successfully with the start of electricity production from fusion reactors in the year n+1. Fusion reactors continue to be used up to year m, where m, as indicated in para. 2.29, is large. To simplify calculation, a smoothly growing economy is assumed with a constant interest rate r and a constant growth rate of electricity consumption g. Then the quantity of electricity consumed in year t is $E_o(1+g)^t$ where E_o is the present-day electricity production. Let the unit cost of this electricity be C_t and let the fusion research expenditure in that year be expressed as a fraction alpha_t of the cost of the electricity consumed. Then the total present-day value K of the cost of the fusion R&D programme is

$$K = \sum_{t=0}^{t=n} \alpha_t C_t E_0 (1 + g)^t / (1 + r)^t$$

2.31 The returns from fusion R&D are equal to the differences between the total (system-wide) electricity production costs in the absence of fusion, and that cost when fusion reactors are utilised. Let this return in year t be expressed as a fraction beta_t of the total electricity cost of that year using the unit cost C_t. Then the total discounted return R is given by

$$R = \sum_{t=n+1}^{t=m} E_0 \beta_t C_t (1 + g)^t / (1 + r)^t$$

2.32 The profitability condition is $R/K>1$. The evaluation is simplified and the main results illustrated by assuming that the coefficients α_t, β_t and C_t can all be replaced by the constant coefficients α, β, C Then, introducing the quantity

$$\gamma \equiv (1 + g)/(1+ r)$$

the formula for R/K becomes

$$R/K = \beta/\alpha \; [(\gamma^{(m-n)} - 1)/(1 - \gamma^{-(n+1)})]$$

This result expresses firstly, the obvious conclusion that the profitability is largest when beta, the "return coefficient", is large, and the "expenditure coefficient" alpha is small. Secondly it illustrates the effects of time and of the rates g and r. If gamma > 1 (the case of large electricity growth rate) then profitability can always be achieved by having a large utilisation period (m-n). The more cautious assumption is gamma < 1 which is essentially adopted in para. 2.11 and chap. 4 (i.e. the electricity growth rate is less than the discount rate). Under this circumstance profitability is obtained provided the research programme is not too long (i.e. n is limited) and not too expensive relative to the hoped-for return (i.e. beta/alpha is large). As an example, [2.1] takes r=5%, g=3% and beta/alpha=2, and the formula gives n<57 for R/K>1, i.e. a programme of R&D of less than 57 years. This also stresses that the growth rate of electricity can be zero, and the research can still be profitable, although the restrictions may be more severe. Thus, the potential for a benefit from fusion research does not necessarily depend on there being a growth of electricity consumption.

2.33 We stress that the ratio alpha, between the Community's annual spend on fusion research and the annual cost of electricity in the Community countries is small. The value estimated in [2.1] is alpha=0.375% and it seems safe to assume that alpha is currently less than 0.01 (let us recall here that EC fusion research expenditure may be estimated as being less than one sixth of European government energy R&D spending: see [2.1]). The value of beta depends not only on the financial considerations of chap. 4 but also on the social elements discussed in reference [2.1], such as regulations on pollution control for fossil-fired power plants and safety in nuclear plants. Thus beta might turn out to be relatively large as stricter pollution abatement regulations are imposed and if fusion turns out to have large advantages over fission in respect of safety. It remains essential however for profitability that the programme of research is successful, i.e. that beta>0.

2.34 These illustrative calculations also serve to highlight the benefits of international cooperation. On a global scale, the value of the electricity generated E_0 is much larger, so that the cost of a given research programme will be represented by a considerably smaller value of alpha: the costs are spread amongst a larger number of beneficiaries. In addition, the effective international collaboration might reduce the duration n of the research phase. Also the larger part of the world is currently anticipating higher growth rates of electricity consumption than the developed countries, and probably for longer times. Thus the global benefits of a successful fusion research programme could be represented by considerably more favourable coefficients in the above illustrative calculations. The efforts that have been and are being made by the European Community and its member states to secure effective international cooperation in fusion research will, if successful, greatly increase the overall profitability of a successful outcome of the research. In addition, the widespread use of fusion in place of fossil-fuel power plants will be much more effective in reducing global pollution of the atmosphere. We thus strongly support the efforts of the European Community to secure effective global cooperation in fusion research; however, international cooperation, though very valuable, is not a necessary prerequisite for achieving profitability in Europe.

2.35 In conclusion, let us summarise the scheme of reasoning. The aim of the European fusion R&D programme is electricity generation through fusion reactors. When, and if, this programme is successfully completed, we will have at our disposal a new and unlimited energy source. The costs of the research programme, stretching over a long timespan, thus have to be compared with a potentially crucial advantage which, though distant in the future, might accompany the development of human societies for an indefinitely long period. These advantages are captured, in the simple model presented above, in the form of reduced electricity generating costs, thus allowing for the comparison (after discounting) of research benefits with research costs, so as to establish the boundary conditions for the "social profitability" of the fusion R&D programme.

Reference

[2.1] A. Roncaglia. Research in fusion as a European investment, EEF Report (see Annex 1.5).

ANNEX 2.1

(Notes on individual paragraphs)

This Annex consists of short footnotes to the text. Footnote numbers point to corresponding paragraphs in the text.

A2.5 The data are all drawn from A. Maddison (Phases of capitalist development, Oxford University Press, Oxford 1982), except the last one, which is drawn from the Bank of Italy, Relazione annuale per il 1988 - Considerazioni finali, Roma, 31 maggio 1989.

The magnitude of long-term economic changes is illustrated by the following quote: "In the past 160 years, the total product of the [advanced capitalist] countries has increased sixty-fold, their population more than four-fold, and their per capita product thirteen-fold. Annual working hours were cut from around 3,000 to less than 1,700, which means that labour productivity increased about twenty-fold. Life expectation doubled, from about thirty-five to over seventy years". (A. Maddison, op.cit, p.4).

On the perspectives of population up to year 2025, the most reliable estimates are presented in United Nations, World Population Prospects, New York 1986. Longer-term forecasts are generally considered too uncertain; see however K.C. Zachariah, M.T. Vu, World Population Projections, 1987-88 edition, published for the World Bank by the Johns Hopkins University Press, Baltimore 1988.

A2.6 Long-term scenarios of energy consumption can also be obtained in other ways. Equivalent to the one adopted in the text is the method based on the forecast of future GDP levels and average energy consumption per unit of GDP. The method adopted in the text however has the advantage of showing explicitly, through the growth rates and the income elasticity of energy consumption, the link between the present and the future situation. This is implicit in the forecast of future energy consumption levels. Another method relies on the forecast of the population size and the per capita energy consumption. This is in fact an approximation of the previous method, since it is clear that per capita energy consumption depends on per capita income and on the average propensity to energy consumption. An advantage of this method is that population forecasts are reasonably reliable (at least for time-spans of up to forty years). A more questionable claim made in its support is that errors in forecasting the per capita income may be compensated by errors in the average per capita energy consumed.

A survey of some forecasts of energy and electricity consumptions is provided by a paper commissioned by the EEF Study Group (Instut d'Economie et de Politique de l'Energie, Le cadre énergétique des années 2050).

Another brief survey is provided by the Brundtland Report (World Commission on Environment and Development, Our Common Future, Oxford University Press, Oxford 1987, especially p.171), which concentrates attention on rather optimistic scenarios connected to very strong energy conservation policies. Other estimates were kindly provided by DGX XVII experts.

A new method has recently been proposed by M. Silvestri (Il futuro dell'energia, Bollati-Boringhieri, Torino 1988), who starts from an approximate mathematical relationship expressing energy requirements (E) in terms of a demographic factor (N), a geographic-climatic factor (C), a social factor (F), a technical factor (k), and a dominant per capita economic factor (g). Then, $E = N\ C\ f\ k\ g$.

Considering a set of hypotheses for the independent variables (op. cit., pp. 64-69), Silvestri arrives at a forecast of world energy consumption in 2088 equal to 5.6 times the world energy consumption in 1988.

A2.8 A thorough detailed analysis of long-term GDP elasticities of energy demand, or the demand for different energy sources, considering the influence on elasticities of price changes, economic cycles, etc., would be very useful, but (to our knowledge) this is not available. For a survey of researches on GDP and price elasticities of demand for energy and energy sources, see G. Pireddu, L'energia nell'analisi economica, mimeo 1989, pp. 36-8; GDP elasticities for energy demand for OECD countries range from 0.83 to 1.01; but these are mainly short-term elasticities concerning recent experience. P. Sylos Labini ("Effetto prezzo", Dimensione energia n.3, 1985; and "Effetto prezzo", mimeo, Roma 1989) finds short-term GDP elasticities of energy consumption to be strongly affected by energy prices, with GDP elasticities of oil consumption in OECD countries ranging from 1.07 in 1970-73 to negative values in 1979-85. However, GDP elasticities of electricity consumption are higher and relatively more stable, as shown in the following Table 2.3:

Table 2.3. GDP elasticities of electricity consumption.

years	OECD	USA	Italy
1970-73	1.56	1.67	1.85
1973-79	1.53	1.21	1.44
1979-85	1.00	1.10	0.25
1985-87			1.43

A2.11 Electricity production and consumption has grown very rapidly over the past decades. Extrapolations of past trends into the future would give results around or above the maximum of the range suggested in the text for electricity production levels in 2050. Table 2.4 shows electricity production (P) and consumption (C) in Italy (data from ENEL, in TWh):

Table 2.4. Electricity production and consumption, Italy.

year	P	C
1938	15.5	13.3
1958	45.5	38.3
1983	203.4	220.4

A2.13 Among the elements which can affect in a major way the behaviour of the economy between now and 2050, we may single out the following; cycles of technical change, changes in economic institutions, changes in market forms, changes in governments' economic strategies.

a) According to a line of reasoning developed by Schumpeter, major technical innovations determine both major long-term cycles of economic activity and major modifications in the productive structure of the economy.

This line of reasoning has recently been revived with reference to the 'microelectronic revolution'. Schumpeterian economists maintain that this revolution is bringing with it an acceleration in economic growth (up to now concealed by the oil crises) and a change in the structure of the economy (e.g. with the spreading of 'flexible production', with an acceleration of induced technical progress, and so on) affecting the requirements of means of production, the sectoral proportions of the economy, the qualifications required in the labour force, and so on. A large scope for energy savings is foreseen, thanks to the use of microelectronics in the automation of productive processes; this should be accompanied by an increase in the share of electricity, which is considered the most flexible form of energy.

b) A major change in economic institutions, as far as European countries are concerned, is about to occur: the new steps towards unified Europe scheduled before 1992. It is not possible to discuss here the effects of these changes, but it is clear that they will be far-reaching and it is hoped that they will produce both a higher pace of economic activity and a rationalisation of the productive structure.

c) Changes in market forms are generally slow, being connected with changes in institutions, in the nature of the commodities produced, the productive process, and the needs satisfied by those commodities. But such changes under specific circumstances may be precipitated in a relatively short time-span, as seen by the restructuring of the international oil market with the shift of leadership from the 'Seven Sisters' to OPEC.

Changes in market forms play an important role in determining the relative prices and the availability (and reliability of supply) of different energy sources. Shocks on this side not only cannot be ruled out, but are in fact likely over such a long time-span as the next 6 decades.

d) Changes in governments' economic strategies may be due to shifts in the balance of power within each of the EC countries, and/or to a change in 'mainstream' economic thinking. Any opinion here is debatable. For instance Keynesian economists maintain that the growth of international trade and the relatively quick pace of economic development in the '50s and '60s has something to do with the dominance of Keynesian ideas among economic policy-makers, while the relative stagnation of the '70s and '80s has something to do with the shift towards 'monetary orthodoxy'. On the other side, monetarists and 'new classicals' maintain that Keynesian policy receipts precipitated the world economy into inflation and disarray, and that now these problems are being slowly overcome by a reduction of State interference in the free operations of the markets. Whichever opinion is held, it is difficult to deny that long-term changes in economic strategies affect both the path of economic activity and the very structure of the economy. (Similarly, in the field of energy a radical shift of policy from a target of minimising the prices of energy inputs in production and consumption to a target of energy conservation induced by higher prices may affect in a very strong way future energy consumption levels).

A2.16 In evaluating the scarcity of exhaustible natural resources, the growth of energy consumption over time must be taken into account. Measuring reserves in terms of years of consumption, at the present rate of consumption, may be

PREFACE

The Study Group on Environmental, Safety-related and Economic Potential of Fusion Power (EEF) was set up by the Commission of the European Communities Directorate-General XII for Science, Research and Development/Fusion Directorate in order to prepare, by order of the Commission, a technical document on the environmental, safety-related and economic potential of thermonuclear fusion power. The Study Group, whose members have served as individuals, not as representatives of their institutions, has based its findings on research and review work carried out by government-sponsored and private institutions and engineering consultant firms throughout the Community.

The members of the EEF Study Group were: R S PEASE (Chair), Progressive Engineering Consultants, Warrington, United Kingdom; J DARVAS, Commission of the European Communities (CEC), Bruxelles, Belgium; R H FLOWERS, United Kingdom Atomic Energy Authority (UKAEA), Harwell, United Kingdom; L GOUNI, Electricité de France (EdF), Paris, France; G GRIEGER, Max-Planck-Institut für Plasmaphysik (IPP), Garching, Fed. Rep. of Germany; K KÖBERLEIN, Gesellschaft für Reaktorsicherheit (GRS), Garching, Fed. Rep. of Germany; A RONCAGLIA, Universita di Roma, Rome, Italy; J P HOLDREN (Consultant), University of California-Berkeley, Berkeley, United States of America; F COZZANI and K STEINMETZ (Scientific Secretaries), Commission of the European Communities (CEC), Bruxelles, Belgium.

CONTENTS

Chapter 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

General aims

1.1 The European Community programme of research into nuclear fusion aims to provide, for the Community countries and their partners, a source of energy which draws on a vast and widespread resource of indigenous fuel, namely the deuterium present in all water and the lithium present throughout the earth's crust.

1.2 The present status of the programme may be characterised as that of basic physics research, but it has reached the stage where, in the Community's largest experiment JET, nuclear fusion power of tens of kilowatts (thermal) is produced in high temperature deuterium gas confined by magnetic fields. In the coming years, this output is to be enhanced several hundred times by using D-T fuel and by other developments. The multi-megawatt (thermal) fusion power will then be close to the heating power delivered to the gas and a net energy output from the gas will be in sight. However the Community's programme has yet to establish firmly the detailed conditions for, and to demonstrate the reality of, an overall net power output from a nuclear fusion plant [1.1,1.2,1.3].

1.3 In adopting the Fusion Research Programme for the period January 1988-March 1992 the Council of Ministers invited the Commission to arrange, before the next programme revision (on 1st January 1991), an independent appraisal of the environmental, safety related and economic potentials of fusion. To prepare a technical document which it would submit for this appraisal, the Commission set up in October 1988 a study group, and has placed study contracts related to the technical issues with research organisations throughout Europe.

1.4 The present report is the outcome of the study group's work and is determined by the terms of reference, namely:

> "The study group shall, on the basis of their own work and of the results of the study contracts, draw up a final report summarizing the results achieved and drawing conclusions on the environmental impact and the economic potential of fusion power".

The Commission's instructions to us are at Annex 1.1; the membership of the study group is at Annex 1.2; the programme of meetings is at Annex 1.3; the studies commissioned and organisations consulted by contract and otherwise are at Annex 1.4; the contract reports received are listed at Annex 1.5; the report published in 1986 by the Commission on fusion economics and environmental potential is at ref. [1.4]; ref. [1.5] is the assessment by the European Parliament in 1988.

1.5 The environmental and economic potential of fusion power have been studied for about 20 years, in Europe, in the U.S.A. and in Japan. The most recent of these is an extensive study made in the USA (the ESECOM study [1.6]). To carry them out it is necessary to hypothesise the strength and shape of the magnetic fields needed and the means for fuelling, heating and exhausting the gas. Then it is necessary to envisage how these might be engineered into a practical electricity generating plant, acceptable to utility companies. On the basis of such conceptual outlines of fusion reactors, which vary considerably in depth of detailed analysis, it is possible to discuss estimates of the potential economic benefits and potential environmental impact. As the physics and engineering research has advanced, so the hypotheses have become more realistic; however, for the reasons given in para. 1.2, such studies today still retain an inherently hypothetical character.

1.6 The potential value to the consumer of a successful outcome of the Community's programme of fusion research is subject to the further uncertainties of the energy market. These include: the required outputs of thermal energy which can be converted to electricity in large central power station units, or which can be used for other industrial purposes, the targets for economic costs set by competing technologies, the effect of various economic assumptions such as interest rates, the plant lifetime, the rate of return and the demands of environmental protection. Furthermore, the economic and social framework for energy is subject to shocks, in which the economics of energy production, or the environmental acceptability of the means of production of energy, are subject to discontinuous quasi-permanent change. Such shocks are unpredictable, but have had a large influence on energy policy of industrialised countries in the past. We have focussed on the Western European energy market within the world-wide context of large-scale energy supply.

Timescale for fusion development

1.7 Large-scale experiments and development plant are needed for fusion reactor development, so that the time needed to conclude a successful programme depends mainly on the time taken to construct, to operate and to assimilate the results of such large plant. It would seem now that probably two such stages in large plant development lie ahead in magnetic fusion, namely: the study of the physics and technology of self-sustained fusion reactions ("ignition") in a high temperature gas and, beyond that, the demonstration of a net electrical power output from a single plant. There does not at present seem to be a compelling need to take risks in shortening or compressing these stages. Consequently we have judged, perhaps conservatively, that for the present analysis and assessment, we should assume that:

(1) the major application of fusion will be the generation of base-load electricity in large central stations;

(2) these stations will begin to contribute to electricity generation in the mid-21st century, i.e. about 60 years hence.

1.8 The fusion reactor concepts used in this report are considered to be prototype systems, where a prototype is defined as the first magnetic fusion reactor to produce electricity for a grid system. We have considered that such a reactor would have to be built about the year 2020 if series-built reactors are to contribute to base-load generation in the mid 21st century. The costs and technology of such a prototype can be forecast with less uncertainty; and the developments subsequent to the prototype are treated herein by means of a generalised learning curve derived from experience with other technologies.

Technological considerations

1.9 The conceptual outlines of fusion power stations considered by us are derived from the Community's research programme and from US studies. In each case they involve a fusion reactor island which generates high temperature steam, which in turn drives the turbo-generator and electrical power systems. The fusion reactors used in this report involve comparatively modest extrapolation of magnetic fusion physics. The parameters of two of the outline reactors provided by the Community's programme (PCSR-E and EEF Reference Reactor) are close to the theoretical and empirical laws based on current experiments. We have also considered the advances both in physics and engineering which may occur as a result of the research, and have taken into account advanced reactor concepts, also provided by the Community's programme, which incorporate examples of possible advance. We have used one of these reactors (AMTR-3) for cost analysis. For studies of environmental potential, the reactor examples used include the above EEF Reference design with conventional engineering materials (ferritic steel), and a variant with a low activation structural material to illustrate what can be achieved with materials designed for use in fusion reactors. We have also drawn on the American studies of the Starfire [1.7] and other reactors, especially for safety analysis.

1.10 Assessing the potential merits of fusion power is done by making comparative studies with other forms of electricity generation. The choices for the comparison are made fairly straightforward by the characteristics of fission power. Like fission, nuclear fusion power:

is primarily for base load electricity generation;

- is insensitive to raw fuel or ore costs;

- is capital intensive;

- uses a steam-raising thermodynamic cycle;

- has the environmental benefit of discharging no "greenhouse" gases into the atmosphere;

- presents problems of radioactivity.

Unlike fission, the fusion reaction does not intrinsically produce radioactive waste, nor does fusion involve the fissile materials U-235 and Pu-239 which have to be used on a large scale in fission and which are essential components of nuclear weapons and are subject to non-proliferation control. From the point of view of economics, fission has rather similar characteristics; large unit size; relatively large capital cost. Fission power is now well established and offers a large body of economic experience. Thus we have compared envisaged fusion reactors with fission counterparts in order to obtain our assessments.

1.11 We have briefly considered the question of alternative uses of fusion. Nuclear fusion will be a source of heat and a source of neutrons and of other radiation. It could provide high grade heat directly to process plant and reject-heat to central heating plant in combined heat and power schemes. However, neither of these issues is a special property of fusion; nor in a fusion context have they been studied in adequate depth to justify including them in our economic and environmental assessments. The neutrons emitted in the D-T fusion reaction have a high energy and could be used to breed fissionable material, or to induce fission in a uranium or thorium blanket. Studies of such potential uses have mainly been carried out in the US and USSR. The reader is referred to the ESECOM report [1.6] for an economic and environmental assessment of their value. In brief, the environmental impact of such a system is dominated by the fission component of the reactor, so that most of the environmental distinction of fusion is lost. The Community's fusion programme has always focussed on pure fusion and its application to electricity generation.

Plan of the report

1.12 The report first sets out in Chapter 2 the energy scene envisaged for Western Europe in the mid-21st century. The demand for fossil fuel and perhaps also for uranium ore, will be affected significantly by developing needs of the third world, especially population giants such as India and China. We have therefore tried to set the European position into a possible world scene. In brief, there is a huge potential demand for base-load electricity generation to which fusion power could contribute. Lastly there is a section which reviews fusion research as a current investment to be set against potential ultimate return.

1.13 Chapter 3 describes the main features of magnetic fusion reactors and the associated technology. It introduces the conceptual reactors used in the assessments. In addition we have drawn on the US conceptual designs used in their environmental and economic studies. For fission reactors we have used a thermal neutron PWR system and a fast neutron breeder reactor. In this chapter we also present some of the areas where major technical advances may take place and outline their potential for economic and environmental benefit. But we have not assessed envisaged reactors based on alternative magnetic confinement systems.

1.14 Chapter 4 reports the outcome of our studies of the economic issues. The report does not provide an answer to the question whether or not fusion will become an economically competitive energy source. Rather, the chapter provides updated information on relevant issues, and some comparative figures based on the above-mentioned technical and societal assumptions. The chapter first deals with methods of comparing electricity generating costs from power stations based on different technologies and operating at widely different times. Secondly, estimates are made of the likely basis of electricity costs in Western Europe in the mid-21st century. In order to allow for uncertainties two main assumptions are offered, namely that electricity generating costs remain unchanged in real terms; and secondly that they are increased by 20% as a consequence of increased fuel prices. Estimates are made of the maximum capital cost of a prototype fusion reactor compatible with subsequently economic competitive series reactors, using two main background assumptions. These estimates are then compared with estimates, provided by the current European fusion programme, of the capital costs of three of the prototype reactor parameter sets presented in Chapter 3.

1.15 Chapter 5 presents the results of the environmental analyses which have been carried out. Neither fusion fuel nor the ultimate fusion products are radioactive, but the plant suffers parasitic radioactivity due to unwanted neutron reactions in the materials of the reactor and from the beta-activity of the intermediate product tritium. The numerical magnitude of the first of these effects is strongly dependent on the development of materials, their purity and isotopic composition. The second is design dependent. We have especially considered those features of fusion which can be compared with the alternative energy sources. These include the size and distribution of the fuel resource, the resource of other materials needed, the potential hazards of operating reactors and the fuel store, the potential hazard in any waste products, the facility for ensuring that there is no production of the fissile materials U-233, U-235 and Pu-239 and the small potential for any chemical or atmospheric pollution.

1.16 Chapter 6 summarises the main points established by our analyses. Our terms of reference invite us to report our general conclusions on the economic and environmental potential of fusion; we do so at the end of Chapter 6.

Acknowledgements

1.17 The timetable for the work of the study group (about one year) is exceptionally compressed and there have been heavy demands placed on those executing the study contracts. Much of the new material from these contracts became available to the study group only in the last few weeks before the completion of this report. The list of study contracts and references to other original material is given in Annexes 1.4 and 1.5. Our warmest thanks go to all those who have contributed to the work in this way. We are especially grateful to the U.S.D.O.E. for making available to us in advance of publication information derived from their ESECOM study [1.6]. We are conscious of the debt we owe to Dr J P Holdren, Chairman of ESECOM for participating in our studies. We have drawn on the IAEA's studies of the safety and potential environmental benefit of fusion, recently updated in an international workshop (Jackson, USA) in April 1989. We are grateful to the International School of Physics, Ettore Majorana for providing an International Workshop (August 1989) at which the subject of our studies was discussed in depth with distinguished experts. Lastly we thank Dr Maisonnier and the Commission staff for their untiring help to us in discharging our task.

References

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[1.2] B.E. Keen (editor). JET joint undertaking. Progress report 1988. EUR 12323 EN, (Luxembourg, 1988).

[1.3] M. Keilhacker, presented on behalf of the JET Team. Overview of JET Results using a Beryllium First Wall. Bull. Am. Phys. Soc. 34 1912, October 1989.

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[1.6] Report of the Senior Committee on Environmental, Safety and Economic Aspects of Fusion (J.P. HOLDREN et al). UCRL-53766 of June 1989. (Lawrence Livermore National Laboratory).

[1.7] C.C. Baker et al. STARFIRE - a commercial Tokamak fusion power plant study. Report ANL/FPP-80-1, (Argonne National Laboratory, Chicago, 1980).

ANNEX 1.1

TERMS OF REFERENCE

1. In pursuance of the Research and Training Programme (January 1988 - March 1992) in the field of thermonuclear fusion, adopted by the Council of the European Communities on 25 July 1988, the Commission will arrange before the next programme revision (1.1.1991) for an independent appraisal of the environmental, safety-related and economic potential of fusion.

2. In order to prepare the technical document which it would submit to this appraisal, the Commission will:

a) set up in October 1988, a Study Group of about seven senior professionals,

b) award study contracts to competent bodies on specific topics related to the subject matter of the appraisal mentioned above.

3. The Study Group, under the Chairmanship of Dr R S PEASE, FRS., consultant of Progressive Engineering Consultants (PEC) Ltd., 105 Walton Road, Warrington, WA4 6NR, England, shall receive from PEC the technical and clerical support necessary for the performance of these tasks.

The Study Group shall:

a) develop a preliminary work plan and breakdown of tasks identifying the bodies to which specific tasks could be commissioned and give an estimate of the overall financial volume for the corresponding study contracts (see paragraph 2b) to be placed by the Commission. This work shall be documented by a report to be submitted to the Commission for approval possibly before 24 October 1988;

b) advise the Commission on the need for power reactor conceptual design studies to possibly provide an improved basis for environmental and economic considerations on the longer term; this advice shall be documented in a report to be submitted to the Commission not later than 16 January 1989;

c) supervise the work defined in the plan and carried out under contracts awarded by the Commission;

d) on the basis of the work of the Study Group and of the results of the study contracts referred to in paragraph 2b, draw up a final report summarizing the results achieved and drawing general conclusions on the environmental impact and the economic potential of fusion power.

ANNEX 1.2

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ANNEX 1.3

SCHEDULE OF BUSINESS

Meeting	Date	Business
1	25 Oct.1988	Terms of reference; tentative content of the study, tentative draft work plan and conceptual design studies.
2	21 Nov.1988	Discussion of revised work and contract plan. Support contracts to be launched. Draft opinion on the need of fusion power reactor design studies.
3	21 Dec.1988	Progress on agreed contracts and work. Remaining chapters and contracts. Preparation of the final EEF Report, strategy, distribution of tasks. Discussion of main points of introduction.
4	27 Jan.1989	Progress reports on various items regarding the energy scene in 2050, envisaged fusion reactors. Check of overall schedule. Draft opinion on the need of fusion power reactor design studies (revised paper). Outline of Introduction and Chapter 2.
5	10 Mar.1989	First draft of Introduction and Chapter 2 and outline of Chapters 3 to 5; proposal for annexes to the main report. Preliminary results from contract studies on the energy scene in 2050, tokamak reactors, advances expected, costing issues. Revised and updated schedule of studies and contracts. Comments from J P Holdren.
6	21 Apr.1989	Discussion of draft Introduction, and main problems of the environmental impact and links with energy policies; detailed outline of Chapter 4 and discussion of studies on costing issues. Progress reports on the energy scene, reference reactor, advances expected, fusion R&D expenditure, decommissioning, resources of fuels etc, accident sequences; progress on D-^{3}He issue.

SCHEDULE OF BUSINESS (Contd)

Meeting	Date	Business
7	1Jun.1989	Report on IAEA Technical Committee Meeting on Fusion Reactor Safety. Revised draft of Chapter 2; draft on links to the environment; progress report of contracts. First draft of Chapter 3; progress reports on reference tokamak reactor, advances expected, advantages of spin-polarised nuclei in reactors. Revised outline of Chapter 4. Progress on studies and contracts regarding the environmental and safety-related aspects. Technical arrangements for the preparation of the final EEF Report.
8	6 Jul.1989	Preface and revised draft Introduction. Revised draft of Chapter 2. Draft of Chapter 4. Progress on studies related to Chapter 5. Comments from J P Holdren. Proposals for Conclusions and Recommendations. Methods of production of EEF Report.
9	11 Sep.1989	Discussion of the first complete draft of the EEF Report. Revised draft of Chapter 2. First complete draft of Chapter 3. Revised draft Chapter 4. First draft Chapter 5; results from contracts with Harwell; accident sequences. Discussion of Chapter 6.
10	22 Sep.1989	Discussion of the second (partial) draft of the EEF Report. Chapters 2 and 4; aspects of new materials. Revised draft of Chapter 3. Chapter 5; safety issues. Discussion of Chapter 6.
11	10 Nov.1989	Summary Report to CCFP. Discussion of the third draft of the EEF Report. Discussion of Summary paper.

ANNEX 1.4

COMMISSIONED STUDIES

SUBJECT	STUDY CARRIED OUT BY
The energy frame in 2050.	Institut d'Economie et de Politique de l'Energie, Grenoble.
Main problems of environment and links with energy policy.	Commission of the European Communities, Bruxelles, DG XI/ DG XII.
Review of commercial tokamak reactor designs. A reference model tokamak reactor.	United Kingdom Atomic Energy Authority, Culham.
Advanced model tokamak reactor.	United Kingdom Atomic Energy Authority, Culham.
Model stellarator reactors.	Max-Planck-Institut für Plasmaphysik, Garching.
Model RFP reactors.	United Kingdom Atomic Energy Authority, Culham.
Tokamak advances expected and needed. Advances in exhaust technology for commercial fusion power reactors in mid 21st century.	United Kingdom Atomic Energy Authority, Culham.
Forecast superconducting technology.	Max-Planck-Institut für Plasmaphysik, Garching.
Construction costs for a European PWR plant, structured according to the NET SCAN-2 cost model.	Holinger AG, Baden.
Energy accounting.	Energy Management Centre Europe.
Fusion R&D costs as a European investment.	A Roncaglia, Rome.
Decommissioning of fusion power plants and waste disposal. A comparison with PWR plants.	Studsvik Nuclear, Nykoping.

COMMISSIONED STUDIES (CONTINUED)

SUBJECT	STUDY CARRIED OUT BY
Resources of fuel and other essential materials, low activation elements for fusion.	Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
Advanced fusion fuel cycles.	FOM-Institute for Plasma Physics, Rijnhuizen.
Economic potential and environmental impact of fusion	United Kingdom Atomic Energy Authority, Harwell.
Accident sequences in fusion reactors and estimate of radioactive releases and health hazards.	Gesellschaft für Reaktorsicherheit, Garching.
Safety categorisation and comparison with US studies.	Gesellschaft für Reaktorsicherheit, Köln.
International safeguards issues of fusion reactors.	United Kingdom Atomic Energy Authority, Harwell.
The environmental impact of mining essential raw materials for fusion and fission reactors.	United Kingdom Atomic Energy Authority, Harwell.

ANNEX 1.5

LIST OF EEF REPORTS PRODUCED

Copies of these reports can be obtained from
Dr J. Darvas at the address given in Annex 1.2.

1. J.D. Jukes and T.E. James
   "Review of commercial Tokamak DT reactor designs"
   UKAEA-Culham Laboratory.

2. P.I.H. Cooke, R. Hancox and W.R. Spears
   "A reference Tokamak reactor"
   UKAEA-Culham Laboratory - August 1989.

3. "Construction costs for a European PWR plant structured according to the Scan-2 cost model"
   Holinger AG in association with Colenco AG - July 1989.

4. L. Devell, K. Broden, K. Fagerstrom, A. Hultgren, S. Menon and G. Olsson
   "Decommissioning of fusion power plants and waste disposal. A comparison with PWR plants"
   Studsvik Nuclear, Nykoping - 1989.

5. F. Barthel, C. Hemmer, H. Schmidt, G. Seidl and H. Wagner
   "Resources of fuel and other essential materials (including low activation elements) for fusion"
   Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover - July 1989.

6. D.C. Robinson
   "Tokamak advances expected and needed and advances in exhaust technology for commercial fusion power reactors in mid 21st century"
   UKAEA-Culham Laboratory - 1989.

7. P.I.H. Cooke, M. Cox, R. Hancox and W.R. Spears
   "Advanced Model Tokamak Reactors"
   UKAEA-Culham Laboratory - August 1989.

8. R.W.B. Best
   "Advanced fusion fuel cycles"
   Instituut voor Plasmafysica, 'Rijnhuizen', Nieuwegein, Nederland - August 1989.

9. A. Roncaglia
   "Research in fusion as a European investment"
   University of Rome - August 1989.

10. P.E. Love
"Net energy analysis/energy accounting"
Energy Management Center (Europe) - August 1989.

11. H. Jahn, P. Kafka and H. Löffler
"Accident sequences in fusion reactors and estimate of radioactive release and health hazards"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln
- July 1989

12. "Le cadre énergétique des années 2050"
Institut d'Economie et de Politique de l'Energie, Grenoble.

13. H.A.B. Bodin
"Comments on TITAN RFP reactor study (TITAN-I, TITAN-II)"
UKAEA-Culham Laboratory - November 1988.

14. G. Grieger
"Advances in superconductor technology"
Max-Planck Institut für Plasmaphysik, Garching
- January 1989.

15. F.J. Walford
"International safeguards issues of fusion reactors"
UKAEA-Harwell Laboratory.

16. J. Bromley
"The environmental impact of mining essential raw materials for fusion and fission reactors"
UKAEA-Harwell Laboratory - August 1989.

17. J.D. Jukes, J.B. Hicks and V.K. Thompson
"Waste generated by fusion reactors"
UKAEA-Culham Laboratory - May 1989.

18. M.J. Sowerby et al
"A contribution to a study on the economic potential and environmental impact of fusion"
UKAEA-Harwell Laboratory - November 1989

19. K. Köberlein
"Accident sequences in fusion reactors and estimates of radioactive releases and health hazards"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln
- July 1989.

20. P. Kafka and H. Löffler
"Safety categorization of fusion and comparison with US-studies"
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln
- December 1989.

Chapter 2

THE EUROPEAN ENERGY SCENE IN 2050

CHAPTER 2

THE EUROPEAN ENERGY SCENE IN 2050

Purpose and methodology

2.1 In this chapter an outline of the European energy scene in the middle of the 21st century is given in order to assess the scope for nuclear fusion. However, it is not possible to do this with precision because of the long timescale involved . What can be done is to discuss the implications of different plausible hypotheses, regarding EC growth rate on Gross Domestic Product (GDP) (para. 2.3 to 2.5) and energy consumption dependence (para. 2.6 to 2.9), total energy consumption and electricity demand (para. 2.10 to 2.12) and the implications of non-repetitive events such as intermittent supply shocks and the effect of economic crises (para. 2.13 to 2.14). On this basis it is possible to discuss the energy scene (para. 2.15 to 2.18), environmental issues (para. 2.19 to 2.24), European energy policy (para. 2.25 to 2.26) and research in fusion as an investment (para. 2.27 to 2.35).

2.2 The European energy scene cannot be dissociated from world energy demands due to the impact of world energy consumption on the environment, on the availability and price of fossil fuels and on the possibility of exporting European know-how, for example, the construction of fusion plants.

Fusion is considered as a technology which might be made available, given sufficient R&D effort, for base-load electricity generation; other potential uses are not considered here.

Footnotes to the text are given in the Annex 2.1. The text is referenced where footnotes apply, the Annex para. ref. is stated.

Basic economic trends

2.3 The first element to be considered in discussing the EC energy demand in the year 2050 is the level of economic activity. Obviously, the result is highly sensitive to the assumptions made regarding the growth rate in real GDP. The following Table 2.1 shows, for different growth rates, the ratio of GDP (year 2050) to GDP (year 1988).

TABLE 2.1. Growth rate and GDP ratio, 2050/1988

Growth Rate	GDP (2050)/GDP (1988)
0%	1.0
1%	1.8
2%	3.4
3%	6.2
4%	11.4
5%	20.6
6%	37.1

The higher growth rate, 6%, is probably implausible.

2.4 The growth rate of economic activity up to 2050 will depend on both supply and demand which interact with each other but, for simplicity, the supply side only is considered here. Three scenarios are identified:

i. An 'intermediate' scenario of 2.5-3% yearly increase in hourly labour productivity, of which 0.5% is absorbed by a reduction in working time. A constant level of employment is assumed. Although there might be a decrease in the EC population of working age, this is off-set by an increase in female employment and immigration into Europe. This leads to an average yearly GDP growth rate of 2-2.5%, and a GDP in Europe in 2050 about four times the 1988 value (Table 2.1).

ii. A 'low' scenario with a reduced productivity growth, say 2%, absorbed partly by a reduction in working time (0.5%), and partly by a reduction in employment (1.5%) arising from changes in age structure, population decline, increase in schooling and a reduction in retirement age. Net immigration into EC countries is assumed to be zero (due to negative labour market conditions and/or to an unfavourable socio-political climate). Supply shocks, aggravated by environmental constraints, provoke temporary declines in activity levels, as in 1975 in the aftermath of the oil crises. Under these conditions GDP levels in Europe would be about the same in 2050 as in 1988.

iii. A 'high' scenario of 4% yearly increase in productivity. The trend in reduction in working time is more than counterbalanced by an increase in overall employment due, for example, to population growth, increased female employment and immigration. The EC overall growth rate could rise to 5%. This would imply a European GDP in 2050 equal to more than 20 times the present level, in real terms (Table 2.1). It is possible that only a scenario of this kind will be consistent with Europe not losing ground in its share in world economic activity.

2.5 In some ways past experience points towards the intermediate scenario. The average GDP growth rate for sixteen industrialised countries over the period 1820-1980 was 2.5%. GDP per man-hour grew in the US at an average yearly rate of 2.3% between 1890 and 1973 (including the years of the Great Depression, 1929-38, when it was equal to 0.7%). However, in 'tranquil' years, without world wars and major economic crises, growth rates can be higher. For the sixteen major industrialised countries, real GDP grew between 1950 and 1973 at an average annual rate of 4.9%. Even though during the post-1973 period there were two oil supply crises, the Italian GDP has grown four-fold in the last forty years.

(See Annex 2.1, para. A2.5 for bibliographical references on these aspects).

The energy problem in Western Europe

2.6 Estimates of total energy consumption in Europe in 2050 may be derived from the estimates of economic growth discussed above, and from estimates of the GDP elasticity of energy consumption (defined as the ratio between the annual percentage change in energy consumption and the annual percentage change in GDP). Other ways of estimating future energy consumption are discussed in Annex 2.1, para. A2.6.

A GDP elasticity of energy consumption greater (less) than one implies a higher (lower) rate of growth for energy consumption than for GDP. The following table considers the three scenarios for GDP growth rates g%, coupled with elasticities e ranging from 0.50 to 1.25 (let us note immediately, more below, that lower elasticities, even negative ones, are technically feasible and may result from higher energy prices and stronger energy conservation policies, so that at low growth rates we may conceive the possibility of a decrease in total energy consumption. Table 2.2 represents perspectives under an implicit 'constant policy' assumption). For a zero net growth scenario we assume constant energy consumption.

TABLE 2.2

Energy consumption, 2050/1988

g% \ e	0.50	0.75	1	1.25
0	1	1	1	1
2.5	2.2	3.2	4.6	6.7
5	4.6	10	21	43

2.7 The main factors affecting the GDP elasticity of energy consumption are changes in technology and in the structure of production and consumption of the economy. These changes may be autonomous or induced by the relative level of energy prices and by policy measures (which may become relevant if conservation strategies are adopted worldwide). High energy prices (inclusive of taxes) tend to reduce consumption as consumers economise on energy (heating, car transport ...). At the same time, high energy prices to the manufacturing sector provide an incentive for R&D on energy-saving technical innovations. This is an example of a 'dynamic substitution process'.

2.8 The impact of energy prices on the GDP elasticity of energy consumption was apparent in the aftermath of the oil crises of 1973-74 and 1979-80. Two aspects of recent experience may be noted. First, the largest effects concern specific energy sources. The GDP elasticity of oil consumption fell after the oil crises, even becoming negative for short periods in some countries, due to the substitution of oil by other energy sources because of the dramatic change in relative price. However, the GDP elasticity of energy consumption from all sources appears to be much more stable. Second, the dynamic substitution process (ie energy-saving resulting from technical progress induced by higher energy prices) gives rise to a reduction in energy consumption per unit of GDP and this does not disappear when energy prices fall. Once the costs for developing new, more energy efficient, technologies are committed, the new technologies continue to be used even though the energy savings are less valuable than when the R&D for the new technology was effected.

(Annex 2.1, para. A2.8 provides information on GDP elasticities).

2.9 Some feedback from GDP growth to GDP elasticity of energy consumption is conceivable: higher rates of economic growth put pressure on exhaustible resources and this favours increased fuel prices and induces the dynamic substitution process resulting in a lower GDP elasticity of energy consumption. Higher growth rates also favour technical progress and a higher proportion of new and more efficient plants. Taking this feedback into account the range of Table 2.2 becomes biased towards the lower values and energy consumption in 2050 is in the range of 2 to about 8 times its present level. Strong energy conservation policies favour the lower end of this range, say 2 to 4, even in the case of sustained economic growth.

The prospects for electricity in Western Europe

2.10 Three salient features characterise electricity. Firstly, its share of total energy consumption is likely to continue to rise, because of its greater flexibility of use compared with other forms of energy, which makes it particularly suitable for automatic control systems and techniques which are likely to play a growing role in the future. Secondly, national electricity production systems are becoming more interdependent since storing electricity is very costly. In order to avoid interruptions of service in the event of a sudden loss of generating capacity European countries are linking their electricity system through an interconnected grid, thus gaining the economies of large scale production while avoiding the risks of service breakdown stemming from a small number of plants (exchange of electricity among European countries amounted in 1987 to 90.7 TWh, i.e. to about 6% of electricity produced: Rapporto sull'energia 1988, p 327 and ff). Thirdly, electricity supply cannot be monolithic: fuel sources and production techniques must be diversified. The more interdependent the energy sectors of the various countries become, the more important is system and operational flexibility.

2.11 The electricity needs in Europe in the middle of the 21st century may be deduced from the estimate of total energy consumption, by attributing to electricity a constant or slightly increased share of the total. This means that electricity consumption in 2050 might be anything from more than twice to less than 10 times its present level (see Annex 2.1, para. A2.11).

2.12 Total electricity production in 1987, in EC-12, was 1659 TWh. The base-load supply to be guaranteed (8760 hours per year) is approximately half the total needs (i.e. at 1987 consumption levels, around 100 GW). The present (1988) installed nuclear generating capacity in the 14 countries of the European fusion programme, is about 100 GW. The corresponding installed base-load capacity in 2050 is estimated to be in the range 250 and 1000 GW (i.e. 250 to 1000-1GW units or 125 to 500-2GW units). In 2050, some 10 to 80-1GW units (or 5 to 40-2GW units) of base-load capacity will need to be built each year. This comprises 5 to 50 GW/a for consumption growth (2% of 250 GW and 5% of 1000 GW) and 5 to 30 GW/a for the replacement of old plant (assuming around 30 year economic plant life).

Fluctuations and shocks

2.13 The energy scenario in 2050 was discussed above by considering conceivable growth rates between 1988 and 2050. However, this kind of reasoning neglects the unavoidable vagaries in the pattern of economic development due to waves of technical change, to changes in economic institutions, in market forms and in governments' economic strategies (see Annex 2.1, para. A2.13). Also, there is the possibility of political upheavals (wars, revolutions) and major economic crises (such as international financial crises due to bankruptcies involving big international debtor countries, or the repetition of 'supply shocks' like the oil crises). Natural catastrophes may also hit areas of the European territory.

Any major crises are likely to provoke sharp declines in economic activity. Such declines, if not compensated by a higher than average growth in the years of reconstruction, would reduce the level of economic activity in 2050. However, these effects are obviously speculative on such a timescale.

2.14 Developments in the rest of the world strongly affect what happens within Europe. This is true both in the political and economic sphere and in the field of technology. The importance and the variety of these influences cannot be exaggerated.

Consider just one example concerning the energy sector. Economic growth in developing countries, bringing their per-capita energy consumption towards the present level of developed countries, would have an explosive impact on world energy sources.

The following data (from World Development Report 1988 pp 240-1) gives an idea of the dimension of this problem. The annual per capita energy consumption (kg oil equivalent) was in 1986: China 532, India 208, Indonesia 213, Nigeria 134, Bangladesh 46.... and USA 7,193. To raise the population of China to the current energy level comparable to the per capita energy use in industrial nations would, by itself, require doubling the world's total current annual supply of coal, oil, gas and nuclear energy. It is clear that either developing countries will never reach the present per capita energy consumption levels of developed countries, or unbearable pressure on non-renewable energy sources will be avoided only by the development of new energy technologies such as fusion.

Different energy sources

2.15 In discussing long-term energy perspectives attention is commonly focused on coal and nuclear (fission) energy, which have a large resource base and rely on established technological knowledge. The suggestion that the world will not be able to rely for more than a few decades on oil and natural gas has been questioned. Oil and gas proven reserves (i.e. reserves the location, size and characteristics of which are already known, and which are economically recoverable with known technology at prevailing price-cost relationships) are now equal to more than forty years of consumption, at the present rate. Estimates of the ultimately available oil and gas resources are much higher, though they differ widely one from another. In addition to the uncertainties of geological estimates, technological developments are possible (e.g. on enhanced recovery ratios, on the exploitability of shale oil and tar sands, and so on) which may add considerably to present estimates (but see para. 2.20 on the 'greenhouse effect' which may severely limit the use of natural gas and oil). A similar uncertainty concerns the share of renewable energy sources in particular solar, biomass, wave, tide and geothermal in the long-term.

2.16 The scarcity of natural resources has two dimensions. First, it is the ultimate scarcity of the stock of any non-renewable natural resource that sooner or later is bound to play a major role (see Annex 2.1, para. A2.16). However, this may require many decades (oil, natural gas) or even centuries (coal). This kind of scarcity is relevant for the policy-maker, who has to prepare well in advance the transition to backstop energy sources. However, due to discounting, i.e. to the low present value attributed by private enterprise to an uncertain event far-off in the future, the 'stock-scarcity' is irrelevant as far as the present-day energy market is concerned.

The second kind of scarcity, which is sometimes confused with the first, refers not to the stock, but to the flow of the natural resource. Oil became scarce in this latter meaning with the Arab embargo in 1973. The risk of 'flow-scarcity', namely shocks due to interruptions of supply, stems not only from the concentration of reserves in a few, often politically unstable, areas of the world, but also from accidents interrupting production and distribution (pipeline interruptions, well fires, mine accidents, and so on). This second kind of scarcity is, by itself, a powerful reason for the diversification of energy sources, even when stock-scarcity is not an issue of immediate concern.

2.17 The current choice among competing energy sources depends on the institutional constraints affecting their utilisation, on their availability and reliability of supply, and on their costs.

Institutional constraints are partly a stratification of decisions taken in the past with a large variety of motivations and only partly the outcome of a policy consciously framed for tackling current and future problems of the energy sector. However this second aspect, which gained importance after the first oil crisis, is likely to become more important with increasing pressure from environmental issues.

The cost of energy conversion using different fuels depends on the technologies used and the price of each fuel. In electricity production the latter is much more relevant for coal, oil and natural gas plants than for nuclear, hydropower and solar-electric plants.

2.18 From past experience, it is clear that, while on occasions flow-scarcity has played a role in determining the price of a natural resource (especially in the case of oil), stock-scarcity is too remote to affect current prices (see Annex 2.1, para. A2.18). This is especially true in the case of coal which will be taken together with nuclear fission plants as the reference point in Chapter 4 for evaluating the economics of fusion. It is possible that oil and natural gas (which have environmental advantages) will play a larger role than at present throughout the 21st century, but it is more likely that coal (considering technical progress in coal mining, new coal fields, etc) will be available as an energy source for much longer than another century, although its use may be curtailed because of the 'greenhouse effect' (para. 2.20).

The long-term price of coal is dependent on production costs and here there are two opposing tendencies to consider: increasing costs due to the exhaustion of the 'more fertile' mines and the necessity to utilize more costly reserves and to decreasing costs, due to technical progress in coal mining and coal utilisation. It is not possible to evaluate these effects separately, but over the next decades it is reasonable to assume they will balance and the price of coal will remain constant (in real terms) at about the average value over the past thirty-five years.

There will be a tendency to move away from old mines, especially within Europe towards a few 'coal provinces' (USSR, South Africa, China and perhaps Australia), with coal travelling long distances from mines to the centres of consumption. Long-distance transportation and concentration on a few external suppliers are negative factors which tend to increase the cost of electricity. A constant long-term price for coal is a trend compatible with past experience even though there have been wide fluctuations during the past thirty-five years (up to 50% above the average value, see Fig. A2.2).

Energy and the environment

2.19 A major factor, possibly the major factor, in shaping the energy sector and energy policies over the next decades, will be the ecological constraint. With economic development and the growth of energy consumption coupled with a better understanding of the environmental effects of various human activities, environmental issues are coming to dominate the choice of competing sources of energy. The reasons for the importance which environmental issues have acquired are easy to understand; what is at stake, in fact, is the very survival of our natural environment.

2.20 One major concern is the "greenhouse effect", i.e. a global climate warming over the next decades due to emissions of "greenhouse gases" such as methane, fluorocarbons, nitrous oxide (N_2O) and, as the most important contributor (about 50%), carbon dioxide (CO_2). About one-third of the present global CO_2 emission is attributed to electric power generation by combustion of fossil fuels, especially coal (the other two-thirds is attributed to industrial users, cement manufacture, food processing, agriculture, transport (internal combustion engine), commercial and domestic users).
(see Annex 2.1, para. A2.20).

The effects of global-climate warming would be very severe in virtually all countries of the world. Unless the emission of greenhouse gases is curbed, the rise in average surface temperature of the Earth could reach 1.5 to 4.5°C before the middle of the next century, with strong local variations, for example, warming at high latitudes may reach more than twice the global average value (see Annex 2.1, para. A2.20). The warming would alter local climates by changing atmospheric and ocean circulation patterns as well as the distribution of rainfall and the frequency, intensity, and duration of temperature extremes. The polar ice-caps would be reduced and the sea level may rise between 0.3 and 1.5m. Inundation of low-lying coastal land and islands, reduction of water resources in some regions, changes in agricultural productivity and impacts on human health may follow from such geoclimatic changes.

Our present poor understanding of global climatology does not allow an exact quantification of this "warming": unknown amounts of greenhouse gases are reabsorbed or biologically stored by natural processes and there may exist other, non man-made contributions to global temperature changes, such as variations in solar activity. However, since the potential effects on human society may be highly disruptive, there is already a serious concern about greenhouse gas emissions and efforts to curb CO_2 discharges will be a major preoccupation of the next century. For power generation, this implies a partial or total substitution of fossil fuelled plants (especially coal) by other power systems (first of all in industrialised countries, including the EC, which are able to make the necessary investment for improvement).

2.21 Though attention has been concentrated on the greenhouse effect, other relevant environmental issues are associated with energy and more specifically, electricity generation. It is not possible to provide even a short survey of all these issues, on which there is a large and growing literature (see Annex 2.1, para. 2.21 for a few references). A simple, incomplete, listing (which does not include nuclear fusion, on which see later Chapter 5) would include:

- for coal: mine accidents, lung illnesses, land subsidence, landscape alterations ; dust and noise in transport; particulate and gaseous emissions due to coal-burning provoking acid rain (with severe effects on forests, vegetable life in general and on fish-life in lakes) and creating or aggravating diseases of the circulatory and respiratory systems;

- for oil: severe risk of sea pollution in off-shore production and during transportation; particulate and gaseous emissions provoking acid rain and public-health impacts;

- for natural gas: risk of catastrophic accidents in transport and storage (Ixhuatepec, Mexico, 1984; Transiberian railway, 1989); particulate and gaseous emissions (though much less than coal or oil, per unit of energy released);

- for nuclear fission: risks connected with radioactivity in normal operations; risks of catastrophic accidents (Chernobyl); the disposal of radioactive waste (including generating plant after closure); risks of nuclear armament proliferation (especially with fast-breeder reactors);

- for all thermal electricity plants: difficulty in meeting cooling water needs and the connected risks of microclimatic changes;

- for solar: landscape alterations (large amounts of territory are needed for installations, at present 25 to 50 MW/km^2); risks of microclimatic changes due to solar radiation not reaching the ground;

- for hydroelectricity: landscape alterations; risks of microclimatic changes (especially in large projects, such as the Aswan dam); risks of catastrophic accidents (flooding due to dam collapses: Vajont, 1963); ecological impacts (e.g. reduced delta fertility, fisheries impact).

2.22 Environmental effects arising from the use of different energy sources are an instance of 'externalities', where the effects from an economic activity of producers (or consumers) do not directly affect costs or earnings specific to each individual producer (or consumer), but may affect a local community or possibly society as a whole. An example of a 'negative externality' would be particulate emissions from a coal burning electricity generating plant where the plant operator has no economic incentive to abate it.

Traditionally, economic theorists require negative externalities to be balanced by the imposition of taxes on individual producers. A commonly adopted second-best solution is compliance with regulatory constraints.

2.23 In practice, the difficulty of assessing the environmental effects of human activities, and specifically of energy production and consumption, led in the past to little or no intervention. It is now clear that the environmental consequences of energy production and consumption have been under-estimated until quite recently.

The growth of scientific knowledge is increasing our understanding of environmental issues. Environmental effects which in the past went completely unnoticed are now at centre stage. In future these issues will be given an increasingly larger weight, when strategic choices within the field of energy production and consumption are considered.

2.24 Environmental concern may affect the energy sector in two distinct ways:

Firstly, if the energy sector as a whole is considered as a source of environmental damage, additional taxes on energy production and consumption and other regulatory measures directed towards energy conservation are likely to be adopted. Under some proposals tax proceeds should be used to fund environmental improvements, research on energy saving and the development of non-polluting energy sources. A strong thrust in this direction may significantly reduce the rate of energy consumption and the estimates for energy consumption in 2050 (para. 2.6).

Secondly, specific regulations and taxes on polluting energy sources, and/or incentives to non-polluting sources, may affect the choice among competing energy sources, and hence the internal structure of the energy sector.

Elements of a European energy policy

2.25 Major targets for EC energy policy are: competitiveness with the rest of the world in energy costs, reliability of supplies and respect for the environment. Non-fulfilment (or insufficient fulfilment) of any of these targets would entail an energy constraint on economic growth, with a loss of potential well-being. The EC countries need to adopt a flexible energy policy capable of meeting the most demanding future situations. To achieve this objective all technological paths need to be explored. It is the energy sector which should adapt to the needs of society, not the other way round.

2.26 To answer the question from which this chapter started: what conditions must a new energy technology satisfy to play a role in the markets of the mid-21st century?

Firstly, a large growth of energy consumption, especially electricity is likely to accompany a many-fold growth of economic activity.

Secondly, in addition to stock-scarcity (ultimate exhaustion of non-renewable resources), the energy sector has to plan for flow-scarcity, i.e. the risk of interruptions of energy supplies. The economic impact of flow-scarcity, which rises with increasing dependence on external energy sources, was made abundantly clear by the oil crises.

Thirdly, environmental issues will increasingly affect the energy sector, constraining its overall growth and its internal structure.

All these considerations clearly demonstrate that Europe has a strong interest in developing a new energy source, such as fusion, which, if successful:

i. is capable of satisfying the foreseeable demand for electricity, thereby avoiding constraints on economic growth;

ii. may constitute an internal source of energy for Europe and reduce the consequences of being dependent on imported energy sources;

iii. is able to provide energy in an environmentally benign way compared with coal, oil, natural gas and fission.

Research in fusion as a European investment

2.27 Under what conditions is a programme of research expenditure in fusion an economically positive venture? This problem is considered by A. Roncaglia [2.1]. First the report recalls the distinction between commercial and social profitability, and stresses its relevance to the case of fusion R&D. Second it provides a model of cost benefit analysis. Third, using simplifying assumptions, the model is used to illustrate conditions under which fusion R&D is profitable. Fourth, it discusses the coefficients used in this model, including the social rate of discount, and the various assumptions. Finally in drawing conclusions, the limits of the analysis and its possible extension are discussed. Here, the following paragraphs summarise the results.

2.28 The difference between commercial and social profitability depends on the existence of costs and benefits external to the individual economic agent implementing a given project, but internal to society. A typical example of the "external" cost is pollution from a coal/electricity generating plant; a typical example of an "external" benefit is the increase in general well-being stemming from increasing mutual understanding and improved human relations connected with a higher educational level of any given individual. An evaluation of a fusion R&D programme funded by the European Commission and the member states should consider social (or system-wide) profitability, i.e. it should try to take into account not only commercial profitability, but also the foreseeable results of the fusion programme which would not be appropriated under the prevailing rules by a private firm investing in a fusion R&D programme.

Thus a private investor would exclude from the evaluation of commercial profitability all sorts of external benefits which might stem from a fusion R&D programme. For example, improved environmental conditions, increased national security stemming from reduced dependence on imported energy sources, the fall in the prices of primary energy sources which a widespread utilisation of fusion is likely to generate. Thus it cannot be maintained that investment in fusion R&D is socially unprofitable simply because private entrepreneurs do not find it profitable presently to invest in fusion R&D. Nor can a similar conclusion be derived from an analysis limited to commercial profitability, e.g. by comparing fusion R&D expenditure with expected royalty income from a patent on fusion reactors (as is suggested by the STOA Report of May 1988). Again this implies concentrating on commercial profitability alone, ignoring externalities. Furthermore, the computation of royalties involves crucial assumptions (e.g. on the unit value of the royalty, on the timespan of validity of the patent, and on the number of fusion reactors built during that timespan), which are highly uncertain.

2.29 For the evaluation of system-wide profitability, two characteristics of the fusion R&D programme must be stressed. First, the time required to reach (if it can be reached at all) the commercial stage for electricity production with fusion reactors is very long, so that, prima facie, the annual return coming after its completion, if discounted at a positive interest rate, is likely to become small compared to present day research expenditure. The second characteristic, however, is that if fusion reactors are viable, the utilisation of fusion technology for electricity generation may last for centuries.

2.30 Consider a fusion R&D programme which lasts n years and ends successfully with the start of electricity production from fusion reactors in the year n+1. Fusion reactors continue to be used up to year m, where m, as indicated in para. 2.29, is large. To simplify calculation, a smoothly growing economy is assumed with a constant interest rate r and a constant growth rate of electricity consumption g. Then the quantity of electricity consumed in year t is $E_o(1+g)^t$ where E_o is the present-day electricity production. Let the unit cost of this electricity be C_t and let the fusion research expenditure in that year be expressed as a fraction $alpha_t$ of the cost of the electricity consumed. Then the total present-day value K of the cost of the fusion R&D programme is

$$K = \sum_{t=0}^{t=n} \alpha_t C_t E_0 (1 + g)^t / (1 + r)^t$$

2.31 The returns from fusion R&D are equal to the differences between the total (system-wide) electricity production costs in the absence of fusion, and that cost when fusion reactors are utilised. Let this return in year t be expressed as a fraction $beta_t$ of the total electricity cost of that year using the unit cost C_t. Then the total discounted return R is given by

$$R = \sum_{t=n+1}^{t=m} E_0 \beta_t C_t (1 + g)^t / (1 + r)^t$$

2.32 The profitability condition is $R/K>1$. The evaluation is simplified and the main results illustrated by assuming that the coefficients α_t, β_t and C_t can all be replaced by the constant coefficients α, β, C Then, introducing the quantity

$$\gamma \equiv (1 + g)/(1+ r)$$

the formula for R/K becomes

$$R/K = \beta/\alpha \, [(\gamma^{(m-n)} - 1)/(1 - \gamma^{-(n+1)})]$$

This result expresses firstly, the obvious conclusion that the profitability is largest when beta, the "return coefficient", is large, and the "expenditure coefficient" alpha is small. Secondly it illustrates the effects of time and of the rates g and r. If gamma > 1 (the case of large electricity growth rate) then profitability can always be achieved by having a large utilisation period (m-n). The more cautious assumption is gamma < 1 which is essentially adopted in para. 2.11 and chap. 4 (i.e. the electricity growth rate is less than the discount rate). Under this circumstance profitability is obtained provided the research programme is not too long (i.e. n is limited) and not too expensive relative to the hoped-for return (i.e. beta/alpha is large). As an example, [2.1] takes r=5%, g=3% and beta/alpha=2, and the formula gives n<57 for R/K>1, i.e. a programme of R&D of less than 57 years. This also stresses that the growth rate of electricity can be zero, and the research can still be profitable, although the restrictions may be more severe. Thus, the potential for a benefit from fusion research does not necessarily depend on there being a growth of electricity consumption.

2.33 We stress that the ratio alpha, between the Community's annual spend on fusion research and the annual cost of electricity in the Community countries is small. The value estimated in [2.1] is alpha=0.375% and it seems safe to assume that alpha is currently less than 0.01 (let us recall here that EC fusion research expenditure may be estimated as being less than one sixth of European government energy R&D spending: see [2.1]). The value of beta depends not only on the financial considerations of chap. 4 but also on the social elements discussed in reference [2.1], such as regulations on pollution control for fossil-fired power plants and safety in nuclear plants. Thus beta might turn out to be relatively large as stricter pollution abatement regulations are imposed and if fusion turns out to have large advantages over fission in respect of safety. It remains essential however for profitability that the programme of research is successful, i.e. that beta>0.

2.34 These illustrative calculations also serve to highlight the benefits of international cooperation. On a global scale, the value of the electricity generated E_0 is much larger, so that the cost of a given research programme will be represented by a considerably smaller value of alpha: the costs are spread amongst a larger number of beneficiaries. In addition, the effective international collaboration might reduce the duration n of the research phase. Also the larger part of the world is currently anticipating higher growth rates of electricity consumption than the developed countries, and probably for longer times. Thus the global benefits of a successful fusion research programme could be represented by considerably more favourable coefficients in the above illustrative calculations. The efforts that have been and are being made by the European Community and its member states to secure effective international cooperation in fusion research will, if successful, greatly increase the overall profitability of a successful outcome of the research. In addition, the widespread use of fusion in place of fossil-fuel power plants will be much more effective in reducing global pollution of the atmosphere. We thus strongly support the efforts of the European Community to secure effective global cooperation in fusion research; however, international cooperation, though very valuable, is not a necessary prerequisite for achieving profitability in Europe.

2.35 In conclusion, let us summarise the scheme of reasoning. The aim of the European fusion R&D programme is electricity generation through fusion reactors. When, and if, this programme is successfully completed, we will have at our disposal a new and unlimited energy source. The costs of the research programme, stretching over a long timespan, thus have to be compared with a potentially crucial advantage which, though distant in the future, might accompany the development of human societies for an indefinitely long period. These advantages are captured, in the simple model presented above, in the form of reduced electricity generating costs, thus allowing for the comparison (after discounting) of research benefits with research costs, so as to establish the boundary conditions for the "social profitability" of the fusion R&D programme.

Reference

[2.1] A. Roncaglia. Research in fusion as a European investment, EEF Report (see Annex 1.5).

ANNEX 2.1

(Notes on individual paragraphs)

This Annex consists of short footnotes to the text. Footnote numbers point to corresponding paragraphs in the text.

A2.5 The data are all drawn from A. Maddison (Phases of capitalist development, Oxford University Press, Oxford 1982), except the last one, which is drawn from the Bank of Italy, Relazione annuale per il 1988 - Considerazioni finali, Roma, 31 maggio 1989.

The magnitude of long-term economic changes is illustrated by the following quote: "In the past 160 years, the total product of the [advanced capitalist] countries has increased sixty-fold, their population more than four-fold, and their per capita product thirteen-fold. Annual working hours were cut from around 3,000 to less than 1,700, which means that labour productivity increased about twenty-fold. Life expectation doubled, from about thirty-five to over seventy years". (A. Maddison, op.cit, p.4).

On the perspectives of population up to year 2025, the most reliable estimates are presented in United Nations, World Population Prospects, New York 1986. Longer-term forecasts are generally considered too uncertain; see however K.C. Zachariah, M.T. Vu, World Population Projections, 1987-88 edition, published for the World Bank by the Johns Hopkins University Press, Baltimore 1988.

A2.6 Long-term scenarios of energy consumption can also be obtained in other ways. Equivalent to the one adopted in the text is the method based on the forecast of future GDP levels and average energy consumption per unit of GDP. The method adopted in the text however has the advantage of showing explicitly, through the growth rates and the income elasticity of energy consumption, the link between the present and the future situation. This is implicit in the forecast of future energy consumption levels. Another method relies on the forecast of the population size and the per capita energy consumption. This is in fact an approximation of the previous method, since it is clear that per capita energy consumption depends on per capita income and on the average propensity to energy consumption. An advantage of this method is that population forecasts are reasonably reliable (at least for time-spans of up to forty years). A more questionable claim made in its support is that errors in forecasting the per capita income may be compensated by errors in the average per capita energy consumed.

A survey of some forecasts of energy and electricity consumptions is provided by a paper commissioned by the EEF Study Group (Instut d'Economie et de Politique de l'Energie, Le cadre énergétique des années 2050).

Another brief survey is provided by the Brundtland Report (World Commission on Environment and Development, Our Common Future, Oxford University Press, Oxford 1987, especially p.171), which concentrates attention on rather optimistic scenarios connected to very strong energy conservation policies. Other estimates were kindly provided by DGX XVII experts.

A new method has recently been proposed by M. Silvestri (Il futuro dell'energia, Bollati-Boringhieri, Torino 1988), who starts from an approximate mathematical relationship expressing energy requirements (E) in terms of a demographic factor (N), a geographic-climatic factor (C), a social factor (F), a technical factor (k), and a dominant per capita economic factor (g). Then, $E = N\ C\ f\ k\ g$.

Considering a set of hypotheses for the independent variables (op. cit., pp. 64-69), Silvestri arrives at a forecast of world energy consumption in 2088 equal to 5.6 times the world energy consumption in 1988.

A2.8 A thorough detailed analysis of long-term GDP elasticities of energy demand, or the demand for different energy sources, considering the influence on elasticities of price changes, economic cycles, etc., would be very useful, but (to our knowledge) this is not available. For a survey of researches on GDP and price elasticities of demand for energy and energy sources, see G. Pireddu, L'energia nell'analisi economica, mimeo 1989, pp. 36-8; GDP elasticities for energy demand for OECD countries range from 0.83 to 1.01; but these are mainly short-term elasticities concerning recent experience. P. Sylos Labini ("Effetto prezzo", Dimensione energia n.3, 1985; and "Effetto prezzo", mimeo, Roma 1989) finds short-term GDP elasticities of energy consumption to be strongly affected by energy prices, with GDP elasticities of oil consumption in OECD countries ranging from 1.07 in 1970-73 to negative values in 1979-85. However, GDP elasticities of electricity consumption are higher and relatively more stable, as shown in the following Table 2.3:

Table 2.3. GDP elasticities of electricity consumption.

years	OECD	USA	Italy
1970-73	1.56	1.67	1.85
1973-79	1.53	1.21	1.44
1979-85	1.00	1.10	0.25
1985-87			1.43

A2.11 Electricity production and consumption has grown very rapidly over the past decades. Extrapolations of past trends into the future would give results around or above the maximum of the range suggested in the text for electricity production levels in 2050. Table 2.4 shows electricity production (P) and consumption (C) in Italy (data from ENEL, in TWh):

Table 2.4. Electricity production and consumption, Italy.

year	P	C
1938	15.5	13.3
1958	45.5	38.3
1983	203.4	220.4

A2.13 Among the elements which can affect in a major way the behaviour of the economy between now and 2050, we may single out the following; cycles of technical change, changes in economic institutions, changes in market forms, changes in governments' economic strategies.

a) According to a line of reasoning developed by Schumpeter, major technical innovations determine both major long-term cycles of economic activity and major modifications in the productive structure of the economy.

This line of reasoning has recently been revived with reference to the 'microelectronic revolution'. Schumpeterian economists maintain that this revolution is bringing with it an acceleration in economic growth (up to now concealed by the oil crises) and a change in the structure of the economy (e.g. with the spreading of 'flexible production', with an acceleration of induced technical progress, and so on) affecting the requirements of means of production, the sectoral proportions of the economy, the qualifications required in the labour force, and so on. A large scope for energy savings is foreseen, thanks to the use of microelectronics in the automation of productive processes; this should be accompanied by an increase in the share of electricity, which is considered the most flexible form of energy.

b) A major change in economic institutions, as far as European countries are concerned, is about to occur: the new steps towards unified Europe scheduled before 1992. It is not possible to discuss here the effects of these changes, but it is clear that they will be far-reaching and it is hoped that they will produce both a higher pace of economic activity and a rationalisation of the productive structure.

c) Changes in market forms are generally slow, being connected with changes in institutions, in the nature of the commodities produced, the productive process, and the needs satisfied by those commodities. But such changes under specific circumstances may be precipitated in a relatively short time-span, as seen by the restructuring of the international oil market with the shift of leadership from the 'Seven Sisters' to OPEC.

Changes in market forms play an important role in determining the relative prices and the availability (and reliability of supply) of different energy sources. Shocks on this side not only cannot be ruled out, but are in fact likely over such a long time-span as the next 6 decades.

d) Changes in governments' economic strategies may be due to shifts in the balance of power within each of the EC countries, and/or to a change in 'mainstream' economic thinking. Any opinion here is debatable. For instance Keynesian economists maintain that the growth of international trade and the relatively quick pace of economic development in the '50s and '60s has something to do with the dominance of Keynesian ideas among economic policy-makers, while the relative stagnation of the '70s and '80s has something to do with the shift towards 'monetary orthodoxy'. On the other side, monetarists and 'new classicals' maintain that Keynesian policy receipts precipitated the world economy into inflation and disarray, and that now these problems are being slowly overcome by a reduction of State interference in the free operations of the markets. Whichever opinion is held, it is difficult to deny that long-term changes in economic strategies affect both the path of economic activity and the very structure of the economy. (Similarly, in the field of energy a radical shift of policy from a target of minimising the prices of energy inputs in production and consumption to a target of energy conservation induced by higher prices may affect in a very strong way future energy consumption levels).

A2.16 In evaluating the scarcity of exhaustible natural resources, the growth of energy consumption over time must be taken into account. Measuring reserves in terms of years of consumption, at the present rate of consumption, may be misleading. An exercise, the results of which are presented in the following table, consists in computing N, the cumulative consumption between 1988 and 2050 of an exhaustible natural resource in terms of years of present consumption, for different annual growth rates of consumption, g.

$$N = \sum_{t=0}^{n-1} X_0(1+g)^t / X_0 = \sum_{t=0}^{n-1} (1+g)^t = [(1+g)^n - 1]/g$$

(where X_0= present consumption, and n = 62). Thus:

Table 2.5. Cumulative consumption factor, 1988 to 2050.

g	N
0	62
0.01	85
0.02	121
0.03	175
0.04	259
0.05	392

Computational exercises of this kind are occasionally used by 'neomalthusian' economists, stressing the natural constraints on economic growth. The experience of the past two centuries however shows that such natural constraints did not materialise in industrialised countries. Since the times in which Robert Malthus (Essay on the Principle of Population, 1798), thought that the natural constraint resided in the availability of food and the times in which W. S. Jevons (The Coal Question, 1865) feared the proximate exhaustion of coal, human ingenuity - i.e. technical progress - consistently proved to be capable of circumventing the constraints set by nature on economic growth.

However, technical progress cannot be considered a manna falling from heaven. The much higher complexity of present-day technology compared with that of one or two centuries ago requires that faith in technical progress be accompanied by a systematic and sustained R&D effort in the fields where the 'natural constraints' are more to be feared, such as in the energy sector.

The following Tables 2.6, 2.7, 2.8 give an idea of the relative size and geographical distribution of fossil fuel reserves:

Table 2.6.

WORLD RESERVES OF FOSSIL FUEL RESOURCES (1)

Country or Group of Countries	Solid Fuel (2)	Coal (3) > 5,700 kcal/kg	Coal (3) < 5,700 kcal/kg	Oil (4)	Natural Gas (4)
		G Tonnes of coal equivalent			
Soviet Union	3,456	109	62	12.0	56.1
China	1,526	99	-	3.6	1.2
North America	1,311	127	96	7.5	10.9
Australia	645	27	14	2.9	11.9
Western Europe	466	77	13	4.4	7.5
Africa	254	65	-	11.1	9.8
India	115	12	2	0.9	0.7
Latin America	48	3	12	24.2	9.6
Middle East	6	-	-	114.7	40.8
Rest of the World	230	41	17	0.3	1.1
TOTAL	8,057	560	216	181.4	149.6
		Composition %			
Soviet Union	42.9	19	28.7	6.6	37.5
China	18.9	17.7	-	2.0	0.8
North America	16.3	22.7	44.4	4.1	7.3
Australia	8.0	4.8	6.5	1.6	8.0
Western Europe	5.8	13.8	6.0	2.4	5.0
Africa	3.2	11.6	-	6.1	6.6
India	1.4	2.1	0.9	0.5	0.5
Latin America	0.6	0.5	5.6	13.3	6.4
Middle East	0.1	-	-	63.2	27.3
Rest of the World	2.9	7.3	7.9	0.2	0.7

(1) Economically recoverable reserves; 1 billion tonnes of coal
- 740 billion cubic meters of gas
- 0.7 billion tonns of oil

(2) Existing resources;

(3) Data from World Energy Conference 1986

(4) Data from BP Statistical Review of World Energy 1988

Source: Rapporto sull'energia 1988, p.245

PROVEN RESERVES OF OIL (1.1.89)

COUNTRY	10^9 toe	Percentage of World Total	Duration[(1)] (Years)
Asia	2906	2.3	
- India	864	0.7	
- Indonesia	1122	0.9	18
- Malesia	311	0.3	
Western Europe	2523	2.0	13
- Norway	1419	1.1	25
- England	703	0.6	6
Middle East	77726	63.0	109
- Iran	12627	10.2	111
- Iraq	13600	11.0	106
- Kuwait	12501	10.1	266
- Saudi Arabia	23115	18.7	92
Africa	7747	6.3	31
- Algeria	1142	0.9	
- Libia	2292	2.4	61
- Nigeria	2176	1.8	31
America	21112	17.1	
- Argentina	308	0.2	
- Brazil	346	0.3	
- Canada	922	0.7	10
- Columbia	275	0.2	
- Mexico	7359	6.0	51
- Venezuela	7899	6.4	85
- United States	3604	2.9	8
TOTAL	112015		
Countries with Planned Economies	11396	9.3	15
- China	3202	2.6	24
- USSR	7956	6.5	13
WORLD TOTAL	123412	100.0	41

1) ENEA estimates based on data from Petroleum Economist, December 1988

Source: ENEA Rapporto congiunturale energia 1988

Table 2.8.

PROVEN RESERVES OF NATURAL GAS (1.1.89)

COUNTRY	10^9 m^3	Percentage of World Total	Duration[1] (Years)
Asia	6810	6.1	59
- India	670	0.6	
- Indonesia	2365	2.1	68
- Malesia	1463	1.3	
Western Europe	5663	5.0	31
- Norway	2419	2.2	86
- England	643	0.6	14
- Holland	1750	1.6	26
Middle East	33454	29.9	429
- Iran	13991	12.5	777
- Iraq	2688	2.4	
- Kuwait	1202	1.1	266
- Saudi Arabia	4127	3.7	188
Africa	7168	6.4	119
- Algeria	2948	2.6	68
- Libia	727	0.6	104
- Nigeria	1405	2.1	800
America	14671	13.1	21
- Argentina	755	0.7	
- Brazil	104	0.1	
- Canada	2691	2.4	23
- Columbia	111	0.1	
- Mexico	2117	1.9	57
- Venezuela	2893	2.6	
- United States	5297	4.7	11
TOTAL	67768		59
Countries with Planned Economics	44167	39.0	52
- China	897	0.8	45
- USSR	42450	38.0	56
WORLD TOTAL . .	111936	100.0	56

(1) Based on actual production.

Source: ENEA Rapporto congiunturale energia 1988

Estimates of remaining ultimately recoverable resources (RURR) are generally much higher than estimates for proven reserves, but also much more uncertain. For oil see e.g. M.Colitti, "Size and Distribution of Known and Undiscovered Petroleum Resources in the World, with an Estimate of Future Exploration, OPEC Review, 1981, n.3, pp. 9-65.

Professor Holdren suggests the following globally aggregated RURR figures:

conventional oil and gas	-	1,000 TWy (combined)
coal	-	5,000 TWy
heavy oils and tar sands	-	500 TWy
oil shale	-	30,000 TWy
uranium (in LWRs)	-	2,500 TWy
uranium (in breeders)	-	3,000,000 TWy

1 TWy = 1 terawatt-year = 31.5 billion gigajoules
= 31.5×10^{18} J
= ca. 1 billion tonnes of coal,

The range of informed opinion about the best estimates for RURR is perhaps plus or minus 50% from the figures given.

A2.18 Some economists consider the prices of natural resources to be determined by the interplay between demand and supply, assumed to be autonomous from each other: supply being constrained by the ultimate scarcity of the natural resource and demand being determined by the pattern of income and by price-induced substitution with competing energy sources. A long-run specification of this theory is the Hotelling theorem, which says that the price of exhaustible resources grows over time at a rate equal to the interest rate, finally reaching a level sufficient to bring forth the complete substitution of the resource under consideration before its final exhaustion. Thus, real prices will increase for all energy sources and the pace of increase will be quicker for oil and natural gas than for coal, due to the much greater availability of the latter. Oil and gas will thus be priced out of the energy market, to be reserved for 'nobler' uses, while coal will acquire increasing importance over the next decades, competing with nuclear energy. The Hotelling theorem assumes perfect completion and perfect knowledge, both of the quantity ultimately available of the exhaustible natural resource and of the factors determining its demand and that for competing resources.

A2.19 Other economists criticise the idea, developed in the Hotelling theorem, that stock-scarcity determines the current prices of natural resources. These economists stress the large uncertainty generally surrounding both the ultimate availability of the resource and the technologies of use which will prevail in future. Up to the moment in which ultimate exhaustion appears to be really proximate, when stock-scarcity becomes relevant, medium to long run price movements are mainly determined by production costs, inclusive of a profit margin depending on the 'degree of monopoly' of the sector. (Of course there is also a differential rent, accruing to lower-cost reserves compared to the 'marginal' reserve currently exploited). Short-run disequilibria between supply and demand may affect short-run prices, but over the longer run, when market forms do not experience dramatic changes, current production costs rule the price. Thus, in order to determine the long-run trends in the prices of the different energy sources, we can concentrate on the long-run trends in their production costs. These are subjected to two contrasting forces: on the one hand, the necessity of exploiting more and more difficult reserves, and on the other hand technological improvements reducing the cost of exploitation of each given reserve.

The past history of oil and coal prices is presented in the following Table 2.9 and Figures A2.1 and A2.2 (drawn from Institut d'Economie et de Politique de l'Energie, Le cadre énergétique des années 2050, paper prepared for the EEF Study Group, mimeo, 1989).

A2.20 In considering the "greenhouse effect", the EC Commission has concluded that, in the long term, new non-carbon based energy systems could give a significant contribution to curbing CO_2 emissions. Therefore, the Commission decided to study the policy options for limiting greenhouse gas emissions and proposed to sustain vigorous research programmes on new energy technologies having the potential to limit CO_2 emissions. ("The Greenhouse Effect and the Community", Communication to the Council COM(88) 656 final, 16.11.88).

The European Council of Ministers, in a resolution of 8 June 1989, stated that available scientific data showed that "the atmosphere is being significantly modified by human activities", and that "according to available climate models this could bring about, by the so called 'greenhouse effect', climatic modifications having a serious impact on the environment, on human beings and their activity".

The Council invited the Commission and the Member States to take several urgent actions, among these "to promote the development and use of energy sources, such as non-fossil fuels, which will not contribute to the greenhouse effect and to give high priority to the development and introduction in the Member States of innovative commercially viable technologies in these fields", taking due account of "safety aspects, security of supply, environmental impact, public health and economic considerations".

(Para. 2.20 and Annex para. A2.20 are a slightly modified version of a draft kindly provided by DG XI).

Table 2.9.

The Changing Price of Coal for base-load stations between 1950-87
(in Centimes per thermal unit at 1984 prices)

1950	4.8
1951	5.0
1952	5.1
1953	5.1
1954	5.1
1955	5.1
1956	5.1
1957	5.2
1958	5.1
1959	5.2
1960	5.4
1961	5.2
1962	5.1
1963	4.9
1964	4.8
1965	4.7
1966	4.6
1967	4.4
1968	4.2
1969	4.0
1970	3.8
1971	4.4
1972	4.2
1973	3.6
1974	6.2
1975	7.2
1976	6.2
1977	5.9
1978	5.4
1979	5.3
1980	6.1
1981	8.0
1982	7.9
1983	7.3
1984	6.7
1985	6.1
1986	5.8
1987	5.8

Source: 1950-1965 - INSEE, wholesale price, PIB deflation in accord with standard 66-87.

1966-1985 - EDF, scaled down price of coal PIB deflation.

1986-1987 - INSEE, whole price, PIB deflation in accord with standard 66-87.

FIGURE A2·1

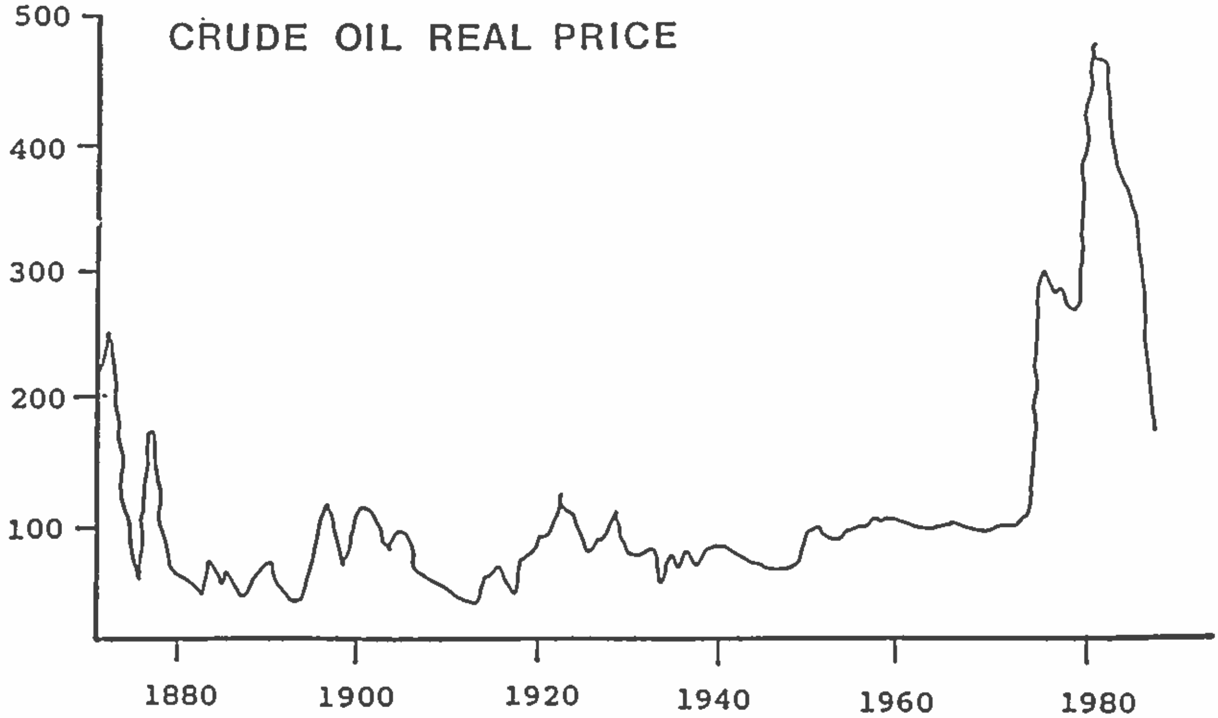
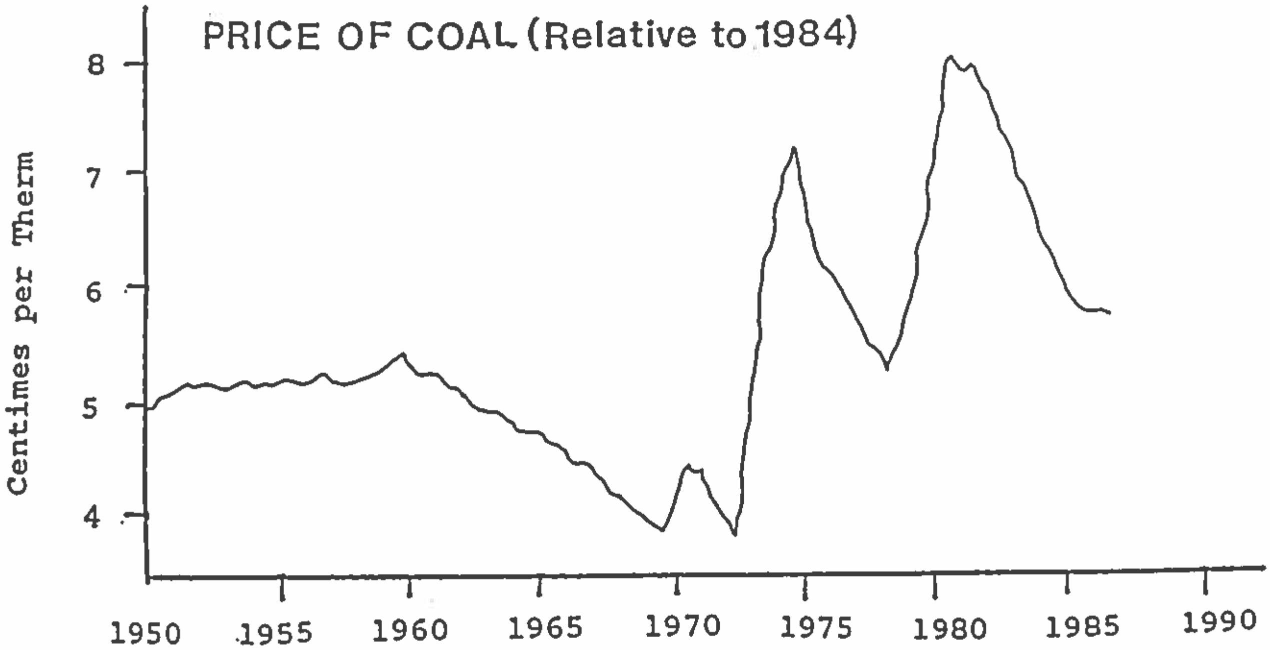

CRUDE OIL REAL PRICE
500
400
300
200
100
1880
1900
1920
1940
1960
1980

FIGURE A2·2


PRICE OF COAL (Relative to 1984)
Centimes per Therm
8
7
6
5
4
1950
1955
1960
1965
1970
1975
1980
1985
1990

A2.21 The debate on environmental issues is continuously offering new fact-finding analyses and new suggestions for action. Among the many contributions, we may refer for useful surveys to the Brundtland Report (The World Commission on Environment and Development, Our Common Future, Oxford University Press, Oxford, 1987); to M. Silvestri (op.cit, p.A2.6); and to M. Dall'Aglio, G. Frigessi, D.Merluzzi, "Energy and Environment: Limits and Conflicts", paper presented to the XIII Congress of the World Energy Conference, Cannes, 5-11 October 1986.

Chapter 3

ENVISAGED FUSION REACTORS

CHAPTER 3

ENVISAGED FUSION REACTORS

Introduction

3.1 In this chapter the reactor concepts will be established which will form the basis for the critical assessments made in this report. A complete fusion power station consists of several parts. The core is the fusion nuclear island (Fig. 3.1) positioned in the reactor hall designed to provide the third protective barrier against tritium losses. It is this fusion island part for which the assessment is made in this report. The other parts, the balance of plant containing the turbo-alternator, the electricity control plant, etc. are assumed to be conventional and of a design compatible with the tritium breeding blanket operating temperatures mentioned in reference [3.1]. This allows easier comparison of the various power sources as done in Chapter 4. The nuclear island is further described in para. 3.8

Within the nuclear island, the Tokamak concept is used as a basic reference. Although the European Fusion Programme lacks a modern and fully self-consistent European reactor design which could be used in this respect, such designs have been produced by other Fusion Programmes and are available in the literature. Europe however, has deep and extensive experience from its intense studies on the Next Step (NET) designs, whose characteristics are close to those of future power producing reactors. It is thus possible to establish the EEF Reference Reactor concept by reviewing the Tokamak reactor designs published world-wide, applying European criteria to them by utilizing the European experience on Next Step designs and to assume some, but plausible improvements above the state of the art. This is justified, because the Fusion Programmes will undoubtedly produce a continuous flow of improvements and the amount of improvement expected is much larger than that assumed in establishing the Reference Reactor concept.

3.2 Thus the "EEF Reference Reactor concept" can be considered as a rather reliable projection of present knowledge to later reactors. Very probably, however, the development potential of fusion is much larger than that embodied in the EEF Reference Reactor system. To get a measure on this potential two "Advanced Reactor systems" are also defined. They rest on the assumption that the fusion programme will be very successful in demonstrating that the advanced ideas already existing can be developed into feasible concepts. In this context also Stellarators and Reversed Field Pinches will be considered.

3.3 In para. 3.4 to 3.7 the review of published Tokamak reactor designs is described and, in para. 3.8 to 3.11 the reactors used in this report are defined and described. Para. 3.12 to 3.16 provide an analysis of what Tokamak advances would be needed to arrive at the desired end product, an attractive fusion reactor. These desired advances are then compared with the advances expected from successfully running fusion programmes. This is done in para. 3.17 to 3.21. Para. 3.22 to 3.24 analyse the properties of Stellarator and Reversed Field Pinch reactors which were selected a long time ago for deeper studies in the European Fusion Programme, because of their expected favourable reactor properties. Para. 3.25 to 3.26 investigate the potential impact of advanced structural materials still to be developed, and para. 3.27 to 3.30 the possible influence of new superconducting materials. Para. 3.31 to 3.34 deals with alternate fuels.

Review of published Tokamak reactor designs

3.4 As a basis for establishing the EEF Reference Reactor concept a review is made of the more recent designs of commercial Tokamak D-T fusion reactors (reference [3.1]), beginning with STARFIRE (1980). The main purpose of this work is to provide tables of data, definitions, formulae and references, relating to the engineering design, economics and physics assumptions in a comparative form ready for use in this report. Some preliminary comments are made on how this data base is founded and appears to be changing in the light of more recent studies. The full information can be found in reference [3.1], here only the essentials are extracted.

3.5 In Table 3.1 are listed the reactor studies with which the review is concerned. The USA's STARFIRE design is by far the most detailed and comprehensive commercial Tokamak reactor study available and, in spite of its age, it embodies several concepts which remain of topical concern, e.g. safety, low activation, ease of maintenance, steady-state operation.

TABLE 3.1

PUBLISHED COMMERCIAL TOKAMAK REACTOR DESIGNS INCLUDED IN THE REVIEW

Reactor	Description
STARFIRE	Commercial Tokamak fusion power plant study (Argonne National Laboratory, USA, 1980)
FCTR	First commercial Tokamak reactor (Euratom-NET, 1985)
PCSR	Prototype commercial-sized reactor (Euratom-NET, 1986)
ESECOM	Exploring the competitive potential of magnetic fusion energy. (Senior Committee on Environmental, Safety and Economic Aspects of Magnetic Fusion Energy, USA, 1989)
SSR	Second Stability Power Reactor (Argonne National Laboratory, USA 1988)

In Euratom, most effort has concentrated on design issues and technology for next step devices, i.e. the closely related NET/INTOR/ITER Tokamaks and otherwise on demonstration-stage reactors (DEMO's). The work directly relevant to commercial-stage Tokamak reactors has been a direct extrapolation from NET along what is widely regarded as the conventional Tokamak line. This has led to the determination of sets of design parameters defining the size and geometrical properties of first-of-a-kind (since the NET-orientated computer codes used for this purpose consider the device as the only one of its kind) or prototype commercial size reactors called FCTR and PCSR (PCSR is a later and slightly more compact version of FCTR). The results of this study are, however, not to be regarded as fully integrated conceptual reactor designs nor as embodying recent more advanced concepts in physics and technology of the type described further below. They are parameter sets characterized by the assumed values of crucial plasma physics parameters such as beta, the plasma pressure divided by the energy density of the confining magnetic field. Thus earlier studies refer to the set of values assumed in the INTOR studies and later ones to certain later, experimentally obtained values, which sustain a higher level of confidence. Particularly, when quoting the evaluated cost of such reactors in reference [3.1], it has to be kept in mind that no "cost-saving experience" like a "learning-curve" has been applied to these reactor studies. Cost evaluation is the task of Chapter 4.

3.6 In the USA, STARFIRE has been followed by two different reactor oriented studies:

(i) Blanket Comparison and Selection Study (BCSS) (1984) and
(ii) Tokamak Power Systems Study (TPSS) (1985).

The BCSS was concerned with issues relating to the reactor blanket, such as tritium and heat generation and their removal; particularly emphasising reliable engineering, economics and safety. The main objective of the BCSS was to identify and rank a limited number of blanket concepts from initially a very wide range to provide a focus for reactor designs and further R&D. The TPSS explored innovative design concepts with the potential for making substantial improvement in the Tokamak as a commercially attractive reactor, as compared to STARFIRE. One direction singled out was to reduce the plant size and TPSS activities concentrated on plasma engineering and impurity control and blanket/first wall/shielding technology. It should be mentioned that this work was in parallel with a world-wide activity on Tokamak Concept Innovations running within the INTOR frame-work and to which the European fusion programme made a large number of essential contributions. The improvements and new concepts identified in BCSS and TPSS have been embodied in a range of outline commercial Tokamak designs (reference cases) summarised by Holdren et al in their ESECOM report. In addition, a more detailed design study of a power reactor (SSR) operating in the second stability region of high beta has become available.

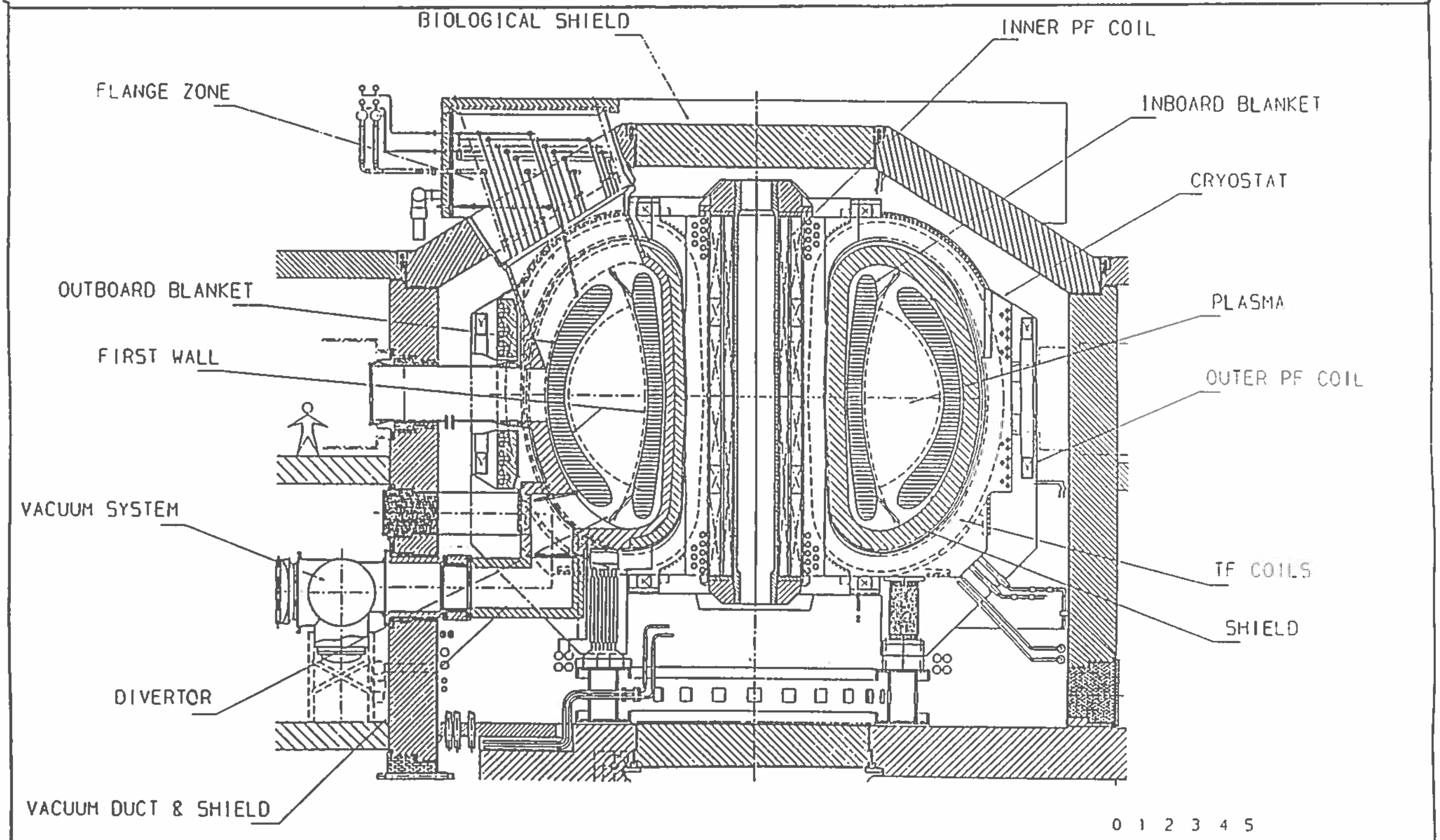
TABLE 3.2 MAIN FEATURES OF PUBLISHED COMMERCIAL REACTOR DESIGNS

REACTOR	FEATURES
STARFIRE (USA-ANL) 1980	Detailed conceptual study of complete power plant; needs reviewing in view of present experimental results. Steady-state operation; non-inductive current drive; impurity control by limiter. Ceramic breeder; stainless steel structure; water cooled. Safety and environmental basis; full remote maintenance.
FCTR-I (EUR-NET) 1985	Extrapolation of NET technology and assumptions to a power reactor; INTOR plasma parameters; optimised for minimum capital cost. Pulsed operation; inductively driven current; single-null divertor. Liquid breeder (Li-Pb); stainless steel structure; water cooled; full remote maintenance.
PCSR-I (EUR-NET) 1986	As FCTR-I with INTOR plasma parameters, but with modifications to increase compactness.
PCSR-E (EUR-NET) 1986	As PCSR-I but based on 1986 experimental plasma parameters.
ESECOM (USA) 1988	Reference cases based on STARFIRE with alternative blanket designs and improved plasma parameters. Assessment of economic, environment and safety aspects.
Case 1: V-Li/Tok	"Base case"; vanadium alloy structure; liquid-Li breeder and coolant.
Case 2: RAF-He/Tok	"Reduced activation" ferritic steel (RAF) structure; solid Li_2O breeder; helium cooled.
Case 5: SiC-He/Tok	"Low activation" silicon carbide (SiC) structure; solid Li_2O breeder; helium cooled.
Case 6:	"Pool" type design with vanadium structure; molten salt (Flibe) breeder and coolant.
SSR (ANL-LANL) 1987/88	High beta (20%) based on operation in "second stability region". Large aspect ratio; low plasma current and current drive power.

3.7 This review therefore includes some of those ESECOM reference cases which seem closest to the Euratom and ITER programmes of experiment, technology and design. In particular, reference cases (1), (2) considered in ESECOM are advances on STARFIRE technology using the two leading candidate blankets from BCSS. They are advanced versions of the blanket/breeder/coolant combinations considered for the technology phases of NET and ITER. The main features are listed in Table 3.2. SSR is included because of the importance of high beta for Tokamak economics.

Definition and description of the reactors used in this report

3.8 On the basis of the studies described in para. 3.4 to 3.7 the EEF Reference Reactor Tokamak concept has been defined (reference [3.2]) by exploiting the SUPERCOIL code which has been extensively used for the NET design. A fusion power plant consists of a nuclear fusion island and a thermal energy conversion cycle based on conventional technologies of converting steam into electricity. It is therefore possible to use this conventional non-nuclear part of the plant to normalise the relative capital cost of electrical power stations based on coal, fission and fusion (see Chapter 4). Fig. 3.1 provides a sketch of the nuclear fusion island which (without needing a pressurised containment as in the case of a PWR) is assumed to be positioned in the reactor hall designed to provide the third protective barrier against release of radioactive material. Inside, it is surrounded by several concrete containments as described in Chapter 5. The core of the nuclear island is the doughnut-shaped Tokamak plasma which is surrounded by a blanket which has to convert the neutron energy into steam and to breed the fuel component tritium. Around the blanket is a shield to attenuate the neutron flux to values small enough to be acceptable to the superconducting coils. Servicing of the blanket and shield is conceived to be done from the top of the reactor, through the gaps between the coils. There are two independent sets of coils. One will provide the magnetic confinement field (TF-coils) and the other the initial ohmic heating (PF-coils) by inducing a current to flow through the plasma. Although they would be much more effective if closer to the plasma, the PF-coils are arranged outside the TF-coils for maintenance reasons. For reasons of economy the magnet has to be superconducting, which makes a cryostat necessary around the magnet to shield it from excessive heat flux. Plasma energy and particle exhaust is foreseen via special divertors from which the exhaust gas will be pumped.



VERTICAL SECTION OF THE NUCLEAR ISLAND OF A FUSION DEVICE

FIG 3.1

3.9 For the blanket and shield materials, there exists a wide variety of combinations. They range from liquid metal to ceramic blanket materials, from water to gas cooling and the use of various neutron multipliers, etc. To find the optimum combination is the task of current R&D programmes. Only one example of possible blanket and shield design parameters is used for the EEF Reference Reactor to determine the dimensions and to estimate the cost of the reactor. This is described in Table 3.3. This one example is considered sufficient for the purpose of this study. The properties of other blanket concepts to reduce the radiological inventory are dealt with separately in Chapter 5.

3.10 Optimization of the EEF Reference Reactor was done by minimising the generating cost of electricity, as estimated by the SCAN-2 cost model. Its main parameters so obtained [3.2] are listed in Table 3.4 together with three other reactors, for comparison. One, the NET/ITER-like PCSR-E (reference [3.1]), extrapolates NET/ITER physics and technology to reactor dimensions and thus contains a considerable number of safety factors to cover the still existing uncertainties in the predictions. The EEF Reference Reactor (Reactor 2 of reference [3.2]), is also based on present knowledge, but with some plausible improvements above the state of the art and without containing the safety factors mentioned above. These safety factors will not be needed any more once the experimental results from a NET/ITER device are available. Reactors AMTR-1, AMTR-2 and AMTR-3 are advanced model tokamak reactors which incorporate the advances expected by the year 2020 from a successful fusion research programme. Compared with the EEF Reference Reactor described in reference [3.2], AMTR-1 of reference [3.3] is of smaller dimensions, operates at a somewhat higher beta, has a lower plasma current and has a higher steam cycle thermal conversion efficiency. Reactor AMTR-3 of reference [3.3a] is very similar to the AMTR-2 reactor of reference [3.3], but is slightly modified to allow for the already attained steam cycle thermal conversion efficiency of 40%. As can be seen from Table 3.4, it is a more advanced reactor than AMTR-1 in that the beta is still further increased, the plasma current is almost completely driven by the bootstrap effect rather than by external means and the tolerable stress level for the support structure is increased. The result is a reactor which is more compact than the EEF Reference Reactor, but with a higher first wall neutron load. Further details can be found in references [3.1], [3.2], [3.3] and [3.3a].

TABLE 3.3 BLANKET DESIGN PARAMETERS
(for PCSR-E and EEF Reference Reactors)

Component	Material	Volume Fraction	Density [t/m³]
First wall	ferritic steel structure lead multiplier water coolant	0.667 0.176 0.157	7.9 9.4 1.0
Main blanket zone	ferritic steel structure lithium lead breeder water coolant void	0.117 0.487 0.081 0.315	7.9 9.4 1.0 0.0
Blanket flange zone	ferritic steel structure lithium lead breeder water coolant void	0.28 0.12 0.12 0.48	7.9 9.4 1.0 0.0
Shield	austenitic steel structure water coolant	0.79 0.21	7.9 1.0

3.11 For NET/ITER-like, next-step devices the structural material used will very probably be stainless steel, 316L or a similar steel. This is a steel developed for fission application and its properties and handling technologies are well known. It also tolerates the low operating temperatures chosen for next-step-devices in order to cope with the problem of tritium permeation. This steel, however, is by no means optimised for the neutron energy spectra of later fusion reactors. Next-step-devices cannot wait for the development of special fusion-optimised materials which might require a lead-time of twenty or perhaps even thirty years.

However, in order to study the potential impact of the advanced materials expected to be available later, the EEF Reference Reactor is considered in two versions: one using conventional, and the other one using vanadium as an example of more advanced materials which are specified in Chapter 5. In this chapter it is only assumed that the advanced materials will be more expensive and, if at all, would lead to only very small changes in the reactor parameters. The main impacts of the advanced materials are on reactor safety, activation, waste management, maintenance periods etc. These will be discussed in Chapter 5.

TABLE 3.4

MAIN REACTOR PARAMETERS

Parameter	Reactor	PCSR-E	EEF Reference	AMTR-1	AMTR-3
Plasma configuration		SN	DN	DN	DN
Effective plasma elongation		1.7	2.25	2.25	2.5
Null-point elongation		1.57	2.5	2.5	2.78
Plasma triangularity		0.2/0.6	0.6	0.6	0.6
Scrape-off layer thickness	m	0.2/0.1	0.15	0.15	0.15
Plasma major radius	m	9.3	5.31	4.51	3.81
Plasma half width	m	2.39	1.40	0.98	0.83
Aspect ratio		3.89	3.78	4.60	4.58
Plasma current	MA	16.6	16.6	8.96	7.49
Total volume averaged beta	%	3.83	7.62	9.39	18.59
Toroidal field (on minor axis)	T	6.36	6.22	5.84	4.84
Peak field on TF coil	T	11.3	14.9	14.4	14.74
Peak-to-peak toroidal field ripple	%	1.7	0.25	0.08	0.05
Vertical bore of TF coil	m	12.5	12.4	10.3	10.1
Stored energy in TF coils	GJ	115	58	34	20
Number of TF coils		22	22	22	22
Maximum tensile stress in TF coil	MPa	160	250	250	500
Mean electron density	$10^{20}/m^3$	1.57	1.45	1.58	2.14
Mean fuel density	$10^{20}/m^3$	1.43	1.23	1.36	1.67
Mean plasma temperature	keV	10	20	20	20
Alpha density fraction	%	5.0	5.3	5.3	5.3
Z (effective)		1.14	1.54	1.54	1.54
Troyon coefficient	%Tm/MA	3.5	4.0	6.0	10
Ratio of useful to total beta		0.75	0.67	0.67	0.67
Plasma safety factor	q_I	2.22	2.17	2.17	2.17
<u>Current drive</u>					
Method		Induction	NBI	NBI	BS
Power efficiency	$10^{20}m^{-2}A/W$	-	0.7	2.0	oo
"Wall plug" efficiency		-	0.7	0.7	0.7
Drive power	MW	-	91	16	0
Bootstrap current fraction		0	0.5	0.5	1.0
Burn time	s	5×10^3	10^6	10^6	10^6

TABLE 3.4 (Contd)

Parameter	Reactor	PCSR-E	EEF Reference	AMTR-1	AMTR-3
Enhancement factor for burn					
Rebut-Lallia		0.57	0.65	1.19	1.32
Kaye-Big		2.4	2.27	3.05	3.67
Kaye-Goldston		1.4	1.27	1.55	1.76
JAERI		1.4	1.54	2.04	2.02
Mean first wall neutron load	MW/m^2	2.22	4.15	5.04	7.99
Shield thickness, inboard	m	0.79	0.83	0.84	0.88
Shield thickness, outboard	m	0.69	0.74	0.75	0.78
Blanket thickness, inboard	m	0.55	0.55	0.55	0.55
Blanket thickness, outboard	m	0.85	0.85	0.85	0.85
Blanket energy multiplication factor		1.22	1.25	1.25	1.25
Blanket structure lifetime	MWa/m^2	10	10	10	10
Divertor neutron fluence limit	MWa/m^2	2	2	2	2
Fusion power	MW	3580	3050	2250	2815
Total thermal power	MW	4170	3780	2730	3402
Gross electrical power output	MW	1460	1510	1370	1360
Recirculating power fraction		0.15	0.20	0.11	0.11
Net electrical power output	MW	1250	1200	1200	1200
Steam cycle thermal conversion efficiency	%	35	40	50	40
Reactor design lifetime	a	25	25	25	25
Availability (target)	%	75	75	75	75

Abbreviations:

SN – Single-null divertor, DN – Double-null divertor
NBI – Neutral beam injection, BS – Bootstrap current

In Table 3.4, apart from the obvious ones, the most important technical terms have the following meaning:

Plasma configuration: shape of the plasma cross-section

Scrape-off layer: thickness of the boundary layer directly outside the plasma confinement region, needed for exhaust purposes

Total volume averaged beta: total volume averaged plasma pressure devided by the energy density of the confining magnetic field

Alpha density fraction: fractional contribution of the reaction product helium to the plasma density

Z (effective):	measure of the contribution of impurities to the total plasma density
Troyon coefficient:	coefficient determining the achievable beta value (see above)
Plasma safety factor:	factor describing the twist of the magnetic field which is determined by the ratio of the strength of the magnetic field and the amount of the plasma current
Current drive:	Method of driving the required plasma current
Bootstrap current:	plasma current internally driven by the plasma pressure
Burn time:	duration of burn during one cycle
Enhancement factor for burn:	improvement needed with respect to various scaling laws to achieve burn conditions
Blanket energy multiplication factor:	energy multiplication in the blanket by exothermal reactions

Tokamak advances needed

3.12 The required advances in Tokamak performance fall into three categories:

i). Improvements in plasma physics performance and/or reactor technology may become necessary to arrive at an end product which, with the then available technology, can be built without excessive difficulty and be operated with sufficiently high availability.

ii). Improvements in plasma physics performance and/or reactor technology may also be requested for reducing the production cost of fusion power in order to arrive at a cost level which will be competitive with other power sources or, in general, which will become acceptable by society.

iii). Finally, also safety questions and the environmental impact of fusion power may lead to needs for improvements of the Tokamak system.

Category i) will be dealt with in this chapter. Requirements according to Categories ii) and iii) will result from Chapters 4 and 5 which deal with the economic potential of fusion and the environmental impact, respectively. For all three cases, a comparison with the expected Tokamak advances (para. 3.17 to 3.21) will then allow an assessment of the chances of meeting the above requirements.(Basis: reference [3.3])

3.13 As for category i), one has to distinguish strictly between advances needed in plasma performance and in reactor technology. This is a result of the priorities set in the fusion programme since its very beginning. Since it was by no means clear that physics would allow a sufficiently powerful burn of a plasma stably confined in a magnetic field of acceptable strength, all research activities were concentrated on solving the physics issues first, before embarking on any significant technology programme. Only recently, plasma parameters have been reached in the most powerful experimental devices, particularly JET, which are sufficiently close to those needed for a fusion reactor (See Fig. 3.2) and allowed the start of a programme aimed at the development of the technology needed for the next-step device, an engineering power reactor. But due to this policy, the maturities of these two programme parts, plasma physics and reactor technology, are out of phase so that, for the time being, the fusion programme has to fall back on technologies developed for fission application even if these are not optimal under fusion conditions. This means that the improvements needed in the various fields of fusion technology are much more numerous than in plasma physics, but by the same token, the development potential in fusion technology is rather large. Thus, with the long lead times typical for technology development, the essential improvements in reactor technology are expected on the DEMO timescale rather than on that of NET. By the same chain of arguments, it would be wrong, however, to assess the potential of fusion energy by considering only the technology of the state of the art. An example was already given above when discussing more advanced materials.

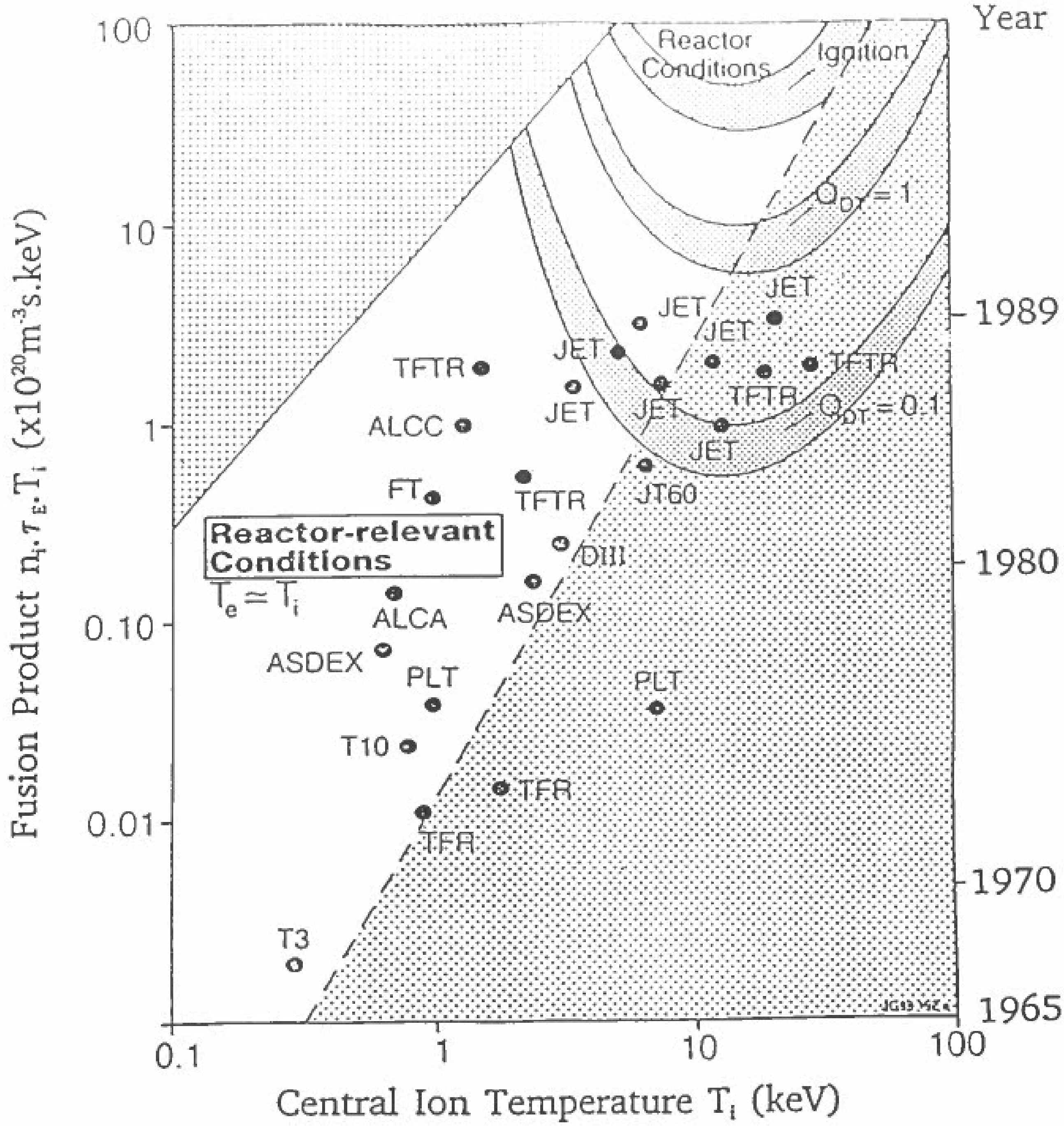


Fig 3.2 Performance of Tokamaks of the fusion programme. The product of the ion density, energy confinement time and ion temperature is a figure of merit whose dependence on plasma temperature allows comparison of the achievements with the reactor requirements.

3.14 In the field of plasma physics it is very difficult to make statements on needed improvements in plasma performance. The plasma parameters reached already support a strong level of confidence that a well confined, burning plasma can be established, although, this particular conclusion has still to be verified experimentally. The issue in plasma physics is much more to raise the experimental and theoretical beta limits to reduce the gap between these limits and the envisaged operating parameters of a reactor, in order to ensure that fusion conditions are attained and to give more reliable reactor operation. Furthermore, it is necessary to reduce the remaining uncertainties in the extrapolation to reactor conditions of the presently existing database, because it is too expensive to incorporate large margins in a design to cover these uncertainties. Their effect can easily be seen by comparing the parameters of the NET/ITER-like PCSR-E and the EEF Reference Reactor of Table 3.4. The EEF Reference Reactor is based on extrapolations "to the best knowledge" for the various physics laws governing the reactor performance, whereas PCSR-E incorporates margins in order still to perform properly if there are deviations for the worse. Rough estimates from references [3.1] and [3.2] show that the cost of electricity would be more expensive by 35% or so if it had to be produced by a PCSR-E-like device as compared to the EEF Reference Reactor. Experiments with a burning plasma in the next step device will certainly reduce considerably the range of the presently existing uncertainties.

3.15 For reactor technology the situation is qualitatively the same but quantitatively more stringent, as follows directly from the above arguments. Conceptual design work performed in the NET/ITER frame has led to conceptual solutions for all components. The necessary R&D programme is underway and is producing the database needed for producing acceptable solutions for the next step. The main issue about the technologies needed for the next step is to increase the load capacity of the plasma-facing components and to increase the durability of all components. With respect to future fusion reactors the first wall and blanket concepts are still a matter of concern. In contrast to the conditions of the next step, they have to perform at high temperature to allow a high efficiency of the fusion power plant. There are many potential solutions for such blanket systems. International collaboration has narrowed down the number on which the R&D work is to be concentrated. The leading concepts will later be tested in NET/ITER.

3.16 In essence: with respect to category i), the advances needed are quantitative in nature. In physics they consist mainly of a narrowing down of the present uncertainties. In technology, an increase of the tolerable power and energy load and the durability of the various components is the technical issue, with the exception of blankets where also qualitative improvements are still needed. Further advances needed arise from categories ii) and iii). These will mainly concern the development of more advanced, low activation materials and improvements in the plasma confinement concept. They will be dealt with in later chapters of this report.

Tokamak advances expected

3.17 In reference [3.4] a review of the maximum attainable beta, current drive efficiency, confinement and divertor designs has been made. These have been related to a wide range of Tokamak reactor studies which already exist and to potential reactors in the middle of the next century based upon possible advances in beta, confinement, current drive and impurity control. These reactors range from conventional D-shaped plasmas to tight aspect ratio systems, all of which lie within the theoretical bounds of the first stability regime, except for one reactor design in the second regime of stability. This device is attractive as it needs only a current of about 5 MA, but density limits and confinement then pose a problem as well as access to the regime.

There are several schemes to increase the maximum stable beta at which a Tokamak can operate. These are largely untested, but it seems likely that one or more will succeed, possibly even to the extent of allowing aneutronic D^3He designs. These configurations may deviate markedly from the base NET/ITER and the EEF Reference Reactor. With respect to confinement it is so far concluded that the advances already demonstrated on devices such as ASDEX, DIII-D, TFTR and JET are adequate to make a range of Tokamak reactors viable. Further advances in improving the confinement are foreseen, reducing the demands on current, current drive efficiency and size, though beta and density limits will then become more important.

3.18 Steady-state operation of a Tokamak reactor would reduce concerns over fatigue failure and might result in a cheaper design. Potential physics benefits include better stability, improved confinement and higher beta limits. Recirculating power and economic constraints probably limit the acceptable driver power to about 10% of the electrical output of the reactor which sets the minimum acceptable efficiency. Extrapolation to reactors of presently used schemes gives efficiencies of about 0.3 - 0.6 which are just adequate for operation of a reactor with I_p <15MA, albeit at densities which may be too low for operation of a high recycling divertor. Several schemes with higher theoretical current drive efficiencies exist, but waves with the required characteristics which can be used in reactor grade plasmas have yet to be identified. In all cases ways of increasing the contribution of the bootstrap current would be desirable. An alternative approach using helicity injection, either by the modulation of the equilibrium or using waves, offers very high efficiencies, but remains to be demonstrated experimentally. Operation utilising cyclic variation of plasma parameters but maintaining constant plasma current would be possible even with relatively low current drive efficiency. The benefits would then be smaller, but a reactor cheaper than a purely inductive design might result.

3.19 For a range of power reactors with double null divertor configurations operating in the high recycling regime and with substantial bremsstrahlung and synchrotron radiation losses, the target plate power density falls to acceptable levels (<10MW/m²); ergodisation and divertor sweeping may help to reduce this further. However the high densities needed for the high recycling regime significantly reduce the current drive efficiency and synchrotron radiation loss. Both disruptions and edge localised modes (ELMs) will probably lead to unacceptable erosion and their control is essential. There is potential to improve the power conversion efficiency with direct conversion of the diverted plasma and/or coupling the synchrotron radiation to MHD convertors.

3.20 Three particular approaches which would radically alter the conventional Tokamak reactor concept were noted. These are the second stability regime at low plasma current with high aspect ratio which makes steady state operation using the bootstrap current likely, the tight aspect ratio approach with substantial beta value and high power to mass ratio and the advanced conversion Tokamak using synchrotron radiation for both current drive and direct energy conversion.

Possible Tokamak advances are summarised in Table 3.5 for beta (Troyon coefficient), current drive power coefficient, and confinement. For definitions see Table 3.4.

TABLE 3.5

Main Tokamak advances expected

Case	Present	Needed for EEF Ref.	Expected	Far future
Troyon coefficient, g (%Tm/MA)	3.5	4	4*	>~7-8
Current drive power coefficient ($10^{20}m^{-2}A/W$)	0.35	0.7	0.6	>1
Confinement improvement (τ/τ_g)	2-3	2	3	4

* based on recent results from DIII-D

3.21 In reference [3.3] some of the expected advances are discussed individually for their influence on the cost of electricity. Using those of the expected advances which have a high enough probability of being realised and, in addition, a strong enough influence on the reactor size, the parameters of the EEF Advanced Model Tokamak Reactors (AMTR-1 and AMTR-3) have been defined and introduced in Table 3.4. These parameter sets give some information on the expected improvements of the presently discussed reactor concepts which might occur as the result of a successful research programme and be incorporated in the prototype reactors. With respect to the EEF Reference Reactor the most impressive features of the AMTR-3 Reactor are the reduction of the linear dimensions of the reactor by about one third, and of the energy stored in the TF-coils by nearly a factor of three. The current drive power coefficient is infinite because the bootstrap current of the plasma itself provides the drive mechanism in this case. It might well be that further advances are needed to contribute to the learning effect introduced in Chapter 4, Annex 4.3.

<u>Stellarators and Reversed Field Pinches</u>

3.22 It was a very early conclusion of the European Fusion Programme that the concept of toroidal magnetic confinement would offer the highest chances for the development of a feasible and competitive fusion power reactor. So far there has never arisen a need to modify this conclusion. Within this class of concepts the Tokamak has become the work horse world-wide and most of the resources are concentrated on its development. At the same time it was clear that some of the inherent Tokamak properties are not so desirable and require compensating measures to deal with them. Two other members of the family of toroidal confinement concepts are therefore also being investigated for their prospects, the Stellarator which has the inherent property of stationary operation and the Reversed Field Pinch which promises particularly high values of beta. As compared to the potential improvements which could arise from these two concepts, the additional effort for exploring their potential is only moderate, since one can concentrate on their differences from the Tokamak.

Stellarators

3.23 The Stellarators [3.5] is a toroidal magnetic confinement system with a net-current free plasma. Its magnetic field is produced by one single external coil system which avoids interlinked coil systems, provides confinement and stability, and gives rise to a separatrix to allow the adoption of suitable plasma exhaust systems. As the plasma is free of inductively driven currents, stationary operation is an intrinsic Stellarator property. Once ignited, a Stellarator reactor would work on refuelling and exhaust only. For the careful use of R&D resources, it is very important that most of the technologies developed in the frame of the Tokamak programme can be readily applied also to Stellarator reactors. Only minor adjustments should be necessary. Other technologies like current drive or feed-back stabilisation of plasma position are not needed.

Reversed Field Pinches

3.24 The Reversed Field Pinch [3.6] is a toroidal magnetic confinement system with a comparatively low toroidal magnetic field component so that the poloidal magnetic field produced by a large plasma current leads to a high twist of the magnetic field lines. The Reversed Field Pinch develops itself into a state of minimum energy and thus promises plasma confinement at particularly high values of beta. The comparatively low value of the toroidal magnetic field allows the combination of the TF-coils with the blanket and thus gives a particularly space saving construction. Stationary operation is assumed to be a conditio sine qua non also for an RFP, but the assumed means for current drive still awaits basic feasibility testing, as do the assumptions for the RFP divertor.

Advanced structural materials

3.25 Up to now, the Fusion Programmes have been very reluctant to start the development of materials specially designed to optimally match the conditions of fusion [see Ref 3.7]. It is well known that it takes at least 20 years to develop a new alloy with tailored properties. As already said in para. 3.11, next step devices will therefore use an existing stainless steel which will be sufficient for the rather relaxed conditions of a wall load of $1MW/m^2$ and an irradiation of up to 10 dpa. Martensitic steels promise to tolerate a neutron wall load of $2MW/m^2$ and irradiation up to 70 dpa which is expected for DEMO-like reactors and are favoured for their high heat conductivity.

3.26 However, all these materials have undesirable activation properties. Therefore, long-term programmes are being established with the aim to develop materials which, by improving or at least maintaining their thermomechanical properties, are less sensitive to activation under fusion reactor conditions. The use of such materials should ease reactor maintenance, reduce the environmental risks and improve the conditions for waste disposal and/or recycling. This is intended to be achieved by replacing the critical constituents of the alloys by more suitable ones, but of similar alloying influence. In this connection, the most critical elements are N, Ni, Nb, Mo and Cu.

Austenitic steels are very difficult to improve, because there is no real equivalent in sight for Ni. In martensitic steels, however, Mo and Nb could be replaced by V and W, which measure would promise a reduction of activation by six orders of magnitude (from 100 to $10^{-4}Ci/cm^3$) for a case with a dose of $5MWa/m^2$ and after a decay time of 100 years. Whether this factor can be utilised will depend on the achievable impurity concentration. Other programmes concentrate on vanadium alloys which also possess a high potential for low activation and good thermomechanical properties. These programmes are connected with rather long lead times, but offer the chance to lead to materials which are much more suitable for the particular conditions of fusion reactors.

Advances in superconductor technology

3.27 The magnet for the confining magnetic field is an essential component of any future fusion reactor built according to the concept of toroidal magnetic confinement. If based on the presently available technology, the magnet represents about one quarter of the cost of the reactor core. Since conventional water-cooled copper magnets would consume intolerably large amounts of power, the magnet has to be superconducting. In addition, the level of the magnetic field needed makes the use of Nb_3Sn mandatory, the technology of which is much more demanding than that of NbTi (see References [3.8], [3.9]).

3.28 Reliable operation of a superconducting magnet requires attenuation of the fusion neutron flux by six to seven orders of magnitude in order to avoid:

- too large a degradation of the insulating material,
- too large a degradation of the superconductor, and
- excessive neutron heating of the cold parts of the magnet

By order of magnitude, these three effects are rather similar.

3.29 The high-temperature superconducting materials recently discovered might develop the potential to allow:

- much higher operating temperatures than accessible today,
- higher magnetic fields at higher current densities than possible with today's superconductors, and
- higher neutron fluxes without degrading the properties of the superconductors.

3.30 If all three of these effects became a reality, a drastic reduction in complexity and cost could result for the magnet and the total cost of the fusion reactor core could be reduced by as much as a few percent. The state of the art reached up to now in this just discovered field does, however, not yet allow the consideration of these new materials for the construction of fusion reactor magnets, as their combined properties are too far away from what is needed to build the reactor magnets. But this may well change as time proceeds.

Advanced fuels

3.31 The European Communities Fusion Programme is fully oriented, at present, towards using a 50:50-mixture of deuterium tritium as fuel. DT has the great advantage of yielding the highest fusion power for a given plasma pressure, but has the disadvantage of needing the radioactive element tritium as one of the fuel constituents which, as an additional complication, has to be bred from lithium surrounding the plasma. In addition, 80% of the DT fusion power occurs via energetic neutrons, making necessary a blanket and a shield to capture these neutrons, using them for tritium breeding and converting their energy into high temperature steam. Both blanket and shield have to encapsulate the plasma and to be arranged inside the magnet to shield it from excessive neutron flux. A volume filled with magnetic flux much larger than the plasma volume is the further consequence.

It is thus quite natural to look for alternative fuels which promise to avoid or, at least, to largely reduce the above difficulties. In principle, there are two candidates, DD and D^3He.

3.32 DD has the advantage, that there is only one fuel constituent involved. Furthermore, no breeding blanket is needed any more, only a shield designed to simultaneously convert the neutron energy into useful heat. These are very positive aspects. Unfortunately, the process, together with its chain reactions, involves tritium and neutrons as well, so that there is no qualitative improvement as far as radioactivity is concerned. Furthermore, it is questionable, whether the fusion power occurring via charged particles is sufficient to balance the unavoidable bremsstrahlung. Thus, it might be impossible to maintain a burning DD plasma by simple means.

3.33 In the case of D^3He both constituents are stable. The reaction products are ^4He and protons, both of which are also stable. Unwanted side reactions occur from reactions between D and D, which involve T and neutrons again, though with reduced flux. This flux can be further reduced by shifting the fuel mixture towards a higher content of ^3He and, perhaps in the far future, by using spin polarized nuclei as fuel to reduce further the DD reaction rate.

No tritium breeding would be needed and the shield would be thinner. Most of the fusion products occur as charged particles. ^3He is not available on earth, except for some 100kg, which would allow testing.

3.34 In both cases the plasma pressure (and the confinement time) have to be raised by an order of magnitude as compared to a DT-plasma in order to establish the same fusion power density. The use of advanced fuels should only be viewed as a possible projection into the far future and should not interfere with the short-term aims of using DT. Within the scope of the D-T reaction there is the possibility of improving the power density by the use of nuclear spin polarized fuel. It is conceivable that the maximum enhancement of 50% of power output for the same magnetic field strength, could be approached by this method.

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Chapter 4

ECONOMIC POTENTIAL OF NUCLEAR FUSION

CHAPTER 4

ECONOMIC POTENTIAL OF NUCLEAR FUSION

THE ESSENTIAL COMPARISON OF THE COSTS OF TECHNOLOGIES

4.1 Chapter 4 (1) is concerned with the economic aspects of nuclear fusion, not the quest for the best technical structure (which has been examined in chapter 3), but the possible share of nuclear fusion in future energy supply. This future technology must be compared with those which will be competitive on the energy scene. This warrants two basic remarks:

- what is of interest is the relative costs of these different technologies at the time of competition (around 2050), much more than the absolute costs which rarely match.

- there are major difficulties of comparison with regard to the methodology, the uncertainty of the future and the barrier of languages amongst the group of experts (differences in concepts between countries, lack of relationship between the teams on fusion and utilities).

As regards the first point, two benchmark prices for the very long term (2050) for energy and for base-load electricity are adopted on the basis of the discussion in Chapter 2 (para.2.18)

- a base scenario corresponding to the average price of imported coal in Europe over the last thirty five years: the reference index 100 is associated with this price for the cost of electricity produced at the base of the load diagram.

- a variant with a 50% increase in the price of imported coal, which has a significant probability of occurring and being maintained over a period of approximately ten years or more. This would modify decision-making criteria: the base-load electricity cost would then be about 130 for a coal fired plant (2).

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(1) References are given in Annex 4.1

(2) See para. 4.12 Table 4.1. The share of coal in the kWhe cost is 54%

4.2 As regards the second point we assume that three reference technologies will be considered for electricity production in Europe in 2050:

- fossil fuel-fired power stations supplied with imported coal,
- PWR-type fission nuclear power stations,
- breeder-type fission power stations.

The cost of electricity for the three technologies is assumed to be the same and is used as the benchmark (index 100 in the base scenario); there is assumed to be an equilibrium between these technologies. The cost of the fusion power stations is compared with this benchmark. In the variant, the cost per kWhe taken for the coal-fired power station is about 130, but lower costs are taken for nuclear fission (120), because the energy context corresponds to a period of re-equilibrium of structures, the exhaustion of coal supply beginning to be felt (para. 4.15).

COMPARISON METHODOLOGY

Comparative criteria

4.3 The different technologies followed to meet human needs have their specific drawbacks and advantages. The analysis preceding the choice refers to several criteria which must be combined implicitly or explicitly. The problem of choice is simplified each time this combination can be given a quantitative expression: several criteria are reduced to one, which is the aggregate criterion used by the economists.

4.4 Total cost of the product: an aggregate criterion. In this chapter, the comparative criterion is the cost per kWhe produced using an electricity generation technology (1). The discounted present value of a well-defined total output over a given period could also be adopted: the results would be identical. This cost is the total cost, i.e. obtained from the sum of the capital charges, the operation-maintenance cost and the fuel cost. This summation has an economic meaning, because the conventions for this addition, mainly prices are clearly defined

It is very important to verify that the conventions adopted in the calculations are indeed homogeneous for the different solutions and that the service rendered by these solutions is identical. It is shown below that, although this remark is obvious, there are many examples of errors made by omitting some verifications (para. 4.8 and Annex 4.2).

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(1) It must be clear that only the factors which can be economically quantified are considered. This is discussed in para. 4.5 and 4.29.

The basic assumptions adopted herein are as follows:

- the value of money is assumed constant and the rate of discount is 5%. In the long run, this rate is rather high; the choice regarding capital intensive solutions is therefore rather stringent (case of fusion).

- energy prices are the very long term prices mentioned in chapter 2 and in para. 4.1.

- power stations have a 30 year lifespan, except in the case of the <u>fusion reactor</u> for which it is reduced to 25 years to take account of the problems of rapid wear of some parts of the reactor (1). The relationship between investment and capital charges is therefore not the same for the different technologies (these charges are 9% higher in the case of fusion, see Annex 4.4).

- construction times are consistent for series optimised power stations (five years for coal, seven for fission reactors, nine for fusion). Interest during construction, defined on the basis of a standard schedule, are expressed by the following coefficients with respect to capital cost: coal 1.086, fission: 1.133, fusion: 1.163 (this figure is assumed to be 3% higher for a prototype: para. 4.13).

- availability factor is 79% for coal-fired plant and 75% for nuclear plant (fission and fusion).

4.5 <u>Partial criteria</u> Unfortunately, although aggregated, the cost criterion does not provide a synthesis of all comparative factors. There are important factors for the decision-maker which cannot be expressed clearly in terms of <u>value</u>, such as risk or the standard of living or social justice. Confronted with these difficulties, the economist has to set boundaries to his projects, generally <u>physical</u> constraints. Partial criteria then appear which supplem ent the total cost criterion.

Examples abound (see chapter 2 and 5): the constraints of environmental quality are essential for decisions relating to energy matters; the protection of national production is another classical example in every country. A constraint can sometimes be transformed into a cost: for instance, the cost of the protection of some European coal basins can be estimated, but it is never simple.

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(1) It must be here underlined how the separation between maintenance and capital costs depends on the calculation conventions. It is a first example of variations in costing methodology (para. 4.8, 4.19 and Annex 4.2).

It may also be tempting to replace the global cost criterion by one or more partial criteria. There are many examples: number of jobs created, share of foreign currency in cost, energy content. It is very difficult to handle these criteria; they can be real constraints or just rhetorical arguments. For instance, the criterion of energy content is a very poor criterion as compared with total cost.

Uncertainties and ways of reducing them

4.6 On analysis, the uncertainties are considerable and discouraging for anyone wanting to quantify the future. It is thus necessary to be aware of this, but above all to control the figures. Uncertainties can be classified into two quite different categories (para. 4.7 and 4.8).

4.7 A category linked to the horizon considered (2050)
The forecaster is used to consider the future, but not as distant as 60 years.Usual study processes must thus be altered, lest they be ineffective.

(a) The economic and social situation over a 60 year horizon, leaves room for many changes and hypotheses (see chapter 2). Consistent scenarios must be considered and preference given to the essential aggregate data, leaving aside detailed analysis, where summing of figures often leads to too great errors in the total. The knowledge of technical, structural and cost breakdowns is important in the estimation of costs, but one should not go into too much detail: respect of some general conditions is far more useful (para. 4.11).

(b) In addition to the uncertainties relating to economic conditions, this study is considerably inhibited by ignorance of the nuclear fusion configuration which could prevail in 2050. The three other technologies taken as reference will probably have undergone profound changes of which only those of the next decade can be described; but the feasibility of net heat production by fusion has not been demonstrated, and the first prototype connected to a network will only enter into service around 2020. Under these circumstances, it is easy to understand how difficult it is to begin a dialogue between the physicist and the economist.

4.8 A second category of uncertainties is linked to the method used for calculating costs. These uncertainties relate more to the conventions adopted for the calculation of costs than inaccuracies of evaluation. Conventions vary from one team or one country to the next and major factors of error enter the comparison of technologies if it is not checked that the data processing methods form part of the same system of conventions. These errors can be corrected, but the corrections are not always simple.

Some examples are given in Annex 4.2 to illustrate the difficulty and the importance of this condition of consistency. The errors entered by the rules of calculation are not of second order by comparison with those linked to the uncertainty of the future. They can reach 50% to 100% and are particularly high in comparisons between countries or teams whose rules differ.

A reasonable and careful methodology

4.9 A simplified methodology limited to the basic factors and reducing to the minimum the uncertainties linked to conventions must be used to deal with these difficulties. This process will both lead to better confidence in the results and help the dialogue between the fusion physicist and the economist of the utilities (1). Three important rules have to be observed.

- The first rule is to adopt the same system of conventions and calculation for the different technologies; the international organisations are indeed working in this direction. Maximum consistency is sought by avoiding comparisons of absolute values of different countries and by checking cost breakdowns using some basic relationship at aggregate level (para. 4.11).

- The second rule is to bring the considered horizon closer: experts cannot discuss the year 2050 since they are not aware of the technical structures that will prevail at that time. By contrast, rather reliable information is available on the general trend of these technologies. Especially for fusion, insofar as investment is the basic element of kWhe cost , it is possible to transform the series reactor capital cost into the prototype reactor cost by applying the capital cost learning curve; it is the subject of para. 4.10. It is assumed that this prototype reactor will be commissioned in 2020; within a thirty year horizon, the specialists in the field of heavy investment are prepared to enter into a dialogue. The second and third commercial reactors could be commissioned ten years later, given the time needed to gain experience and apply it to the following reactors. A pre-series would then appear before 2040 and the series reactors would probably be built around 2050. It should be recalled in this regard that the European electricity generation market makes this scenario perfectly plausible, from the standpoint of both the size and the number of reactors (chapter 2, para. 2.12).

(1) Another advantage is to postpone the comparison of homogeneous but still uncertain figures as much as possible.

- The third rule is to consider the different technologies in competition around 2050 for electricity generation; this competitivity implies that they are optimised technologies with the same total kWhe cost (1). A breakdown of the kWhe cost generated by the competitive fusion reactor can then be defined with a satisfactory degree of accuracy, as will be discussed in para. 4.13 to 4.16. From the capital charges in the competitive kWhe cost, it is possible to estimate an upper limit in the capital cost of the prototype commissioned in 2020; this is also examined in para. 4.13 to 4.16. Finally, it is necessary to compare present estimates made on this prototype reactor of the year 2020 (para. 4.21 to 4.25) to the threshold of competitivity (para. 4.27 to 4.32).

BACKDATING THE HORIZON FOR INVESTMENT FROM 2050 TO 2020

4.10 The aim is to determine, for the total capital cost per kWe (in constant currency, interest during construction not included) the reduction coefficient between the prototype reactor (commissioned by 2020) and a "commercial series" reactor in operation around 2050. The capital cost of the prototype to the commercial series reactor cost ratio thirty years later is referred to as k.

This assessment of k can only be global because the technology is unknown. The methodology consists of referring to the experience with similar equipment, namely the learning curve. Considerations entering the estimate of k are developed in Annex 4.3. They include:

- the theoretical studies published over the last decades. They reduce the capital cost of each component by a percentage "a", each time a new unit or a new series is commissioned. In the case of heavy equipment, e.g. fusion, the capital cost is broken down into its main components; the percentage a is low. For classical components (5 to 15%) and high (10 to 30% for the headings relating to new technologies. It is found that 1/k = 0.57 for the fifth unit, declining to 0.47 for the eighth unit (the most likely values for this eighth unit are between 0.43 and 0.51).

- the data relating to the European experience of nuclear fission using the natural uranium technology (Magnox operated by CEGB and N.U. operated by EdF), and fast breeder technology (this is a forecast here, the prototype being Superphenix). Results are fairly in agreement with the previous ones: from the prototype to the series reactor commissioned 15 years later, it can be seen that 1/k = 0.45

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(1) This is no longer the case in a period of disequilibrium (variant : para. 4.1 and below para. 4.15).

Of course, these results correspond to rather accurate definitions of the prototype reactor and the commercial series reactor. The prototype is the first reactor integrated into an electric generation system. The commercial series reactor refers to a first group of 5 to 10 identical reactors when economic efficiency has been proven or nearly. It should be underlined that this series is not similar to a series of several hundred (case of planes) or several thousands (case of cars or some computer systems).

Finally, given that over the hirty years between the fusion prototype (2020) and the competitive reactor (2050), other progress can be expected especially in the new technologies, it can be estimated that 1/k is between 0.4 and 0.45 (k = 2.2 to 2.5) over this period.

PRACTICAL APPLICATION: RELATIVE CAPITAL COST OF THE COMPETITIVE FUSION REACTOR (2050)

The lessons of basic technico-economic constraints

4.11 The quest here is to determine the breakdown of the kWhe cost of the technologies in competition in 2050: the three reference technologies (para. 4.2) and the new technology, fusion. To reduce the margin of error, the data of the technical experts have to be used with the maximum common sense (para. 4.7).

(a) A basic datum of the structure of cost per kWhe; less fuel and more capital

A major characteristic enters the distribution of cost into three of four main headings (going beyond is too risky): the substantial efforts made in the development of new electricity generation technologies have been driven by the desire to reduce the kWhe cost. The fuel costs are replaced by capital costs. It is a natural tendency for technologically advanced countries which are poorly endowed with energy reserves (Europe, Japan and tomorrow the United States) to replace fuel costs by capital costs. In switching over from coal-fired plant to nuclear PWR, from the fast breeder to the fusion reactor, costs will reflect this trend.

Current presentations of nuclear fuel costs do not facilitate the task of taking this trend into account, since they do not separate raw material supply (U or Pu) from its transformation process, which corresponds to industrial operations in industrialised countries. At our level of approximation, a sufficient and very useful breakdown can be sketched out. Fusion, which only uses heavy water and lithium as fuel at a low economic cost, should incur a very low fuel cost (2% as an indication); the reactor itself produces the nucleus acting in the fusion reaction, so that the corresponding costs are included in the capital and maintenance expenses.

(b) <u>The other links between the main cost headings</u>
Past experience also reveals particular relationships between some cost of electricity headings. For instance, maintenance costs increase with the amount of investment, whereas operating costs (about 10% for PWR)are more or less independent because of the considerable amount of automation involved. Similarly, in capital costs a relationship, which is not immediately obvious, exists between mechanical equipment and civil engineering. Such relationships, gleaned from experience, are invaluable in expressing the three or four headings in the form of percentages with a reduced chance of error (para. 4.14 and Annex 4.4).

<u>Data on technologies which are known today</u>

4.12 Table 4.1 below can be prepared from Western Europe's experience of the three conventional technologies competing in 2050 (coal-fired plant, nuclear PWR and fast breeder reactor). As for coal fired plant and nuclear PWR, the data are extrapolated from a large sample of modern series plants having been in operation over this last decade, so that they give a fair idea of the breakdown of the future optimised plants (1). As regards the breeder technology, the breakdown is obtained from the data on the present European prototype and experts' studies relating to the future series reactors.

This table gives a good estimate of the structure of costs in 2050, given that total kWhe cost is, by definition, the reference cost, i.e. 100. The advantage of this table is its consistency, using in the same economic language for the different technologies. It is not necessary to describe this language; slightly different breakdowns can be proposed by having recourse to other languages but this would not change the results significantly (para. 4.14).

This table corresponds to the base scenario of para. 4.1 that is, a coal price in Europe which is the average price of imported coal over the last thirty five years. The capital cost in Tables 4.1, 4.2 & 4.4 only, include construction interest.

TABLE 4.1
Electricity generation kWhe cost (relative)

	Coal fired 2050	PWR 2050	Breeder 2050
Total (reference)	100	100	100
Capital (incl. decommis.)	29	43	56
Operation Maintenance	17	20	22
Fuel cycle (Transformation)	-	24	18
Fuel cycle (Raw material)	54	13	4

(1) It is assumed that improvements after 2000 will not chamge perceptibly this breakdown.

Consequences on the characteristics of costs per kWhe produced by fusion

4.13 It is then possible to define the breakdown of kWhe cost of the fusion reactor around 2050 by assuming competivity with the PWR and taking account of the relationships discussed above for fuel and maintenance work. The share of capital in this cost is the result of the calculation. In a second stage, by referring to learning coefficient k (para 4.10) and taking account of the fact that the longer construction time of the prototype reactor justifies the higher interest during construction (1.03, para 4.4), the kWhe cost of the prototype reactor is obtained (around 2020). Results are given in table 4.2. Comments on the detail of the calculation are made below.

TABLE 4.2

Fusion kWhe cost (reference PWR)

	PWR 2050 (reference)	Fusion	
		2050 (competitive)	Prototype reactor (2020)
Total	100	100	73x1.03k +15k+12
Capital (inc. decommis)	43	73	73x1.03k
Operation - Maintenance	20*	25**	10+15k
Fuel cycle (Transformation)	24	Included in "capital"	
Fuel cycle (Raw material)	13	2	2

* Operation : 10. Maintenance : 10 (roughly)
** Operation : 10. Maintenance : 15 (roughly)

In this table, the capital charges of the competitive fusion reactor (73) are equal to total cost (by definition 100) minus the estimated operating and fuel costs (25 + 2). The cost of the prototype reactor is deduced by considering that maintenance charges are higher and that capital charges are increased by the coefficient 1.03 for higher interest during construction and the coefficient k for learning. The total kWhe cost of this first reactor is:

$$\frac{73 \times 1.03k + 15k + 12}{100} = \frac{90.2k + 12}{100}$$

times the kWhe cost of the PWR.

In parallel, the capital cost kC_F of this first fusion reactor (per kWe), compared with that of the PWR (C_f), is, given the shorter lifespan and the longer construction time of fusion reactor (para. 4.4), (1):

$$\frac{kC_F}{C_f} = k \times \frac{73}{43} \times \frac{65.05}{70.95} \times \frac{1.133}{1.163} = 1.52k$$

As it has been seen in para. 4.10, k is approximately between 2.2 and 2.5. The relative values of capital cost (per kWe) and cost per kWhe of the prototype fusion reactor which will probably secure competitivity (the reference is the PWR) are defined by applying three values of k.

TABLE 4.3

Target costs of the prototype fusion reactor compared with the PWR (for competivity in 2050) for different values of k

Unit : cost of PWR

	k = 2.2	k = 2.35 (mean)	k = 2.5
Capital cost/kWe	3.34	3.57	3.80
kWhe cost	2.10	2.24	2.38

Probable errors due to the methodology and the uncertainty of data

4.14 In the previous paragraph, a threshold was established for the ratio kC_F/C_f which should not be exceeded by the capital cost kC_F of the fusion prototype, if fusion is to be competitive with fission (the capital cost of series fission reactor being C_f).

This ratio is subject to the following uncertainties:

a - the discount rate,
b - the cost components of technologies per kWhe,
c - the lifespan,
d - the future price of energy:this case is dealt with in para. 4.15 below.

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(1) Details of calculations are listed in Annex 4.4.
The annual rates of depreciation are 65.05 and 70.95 (in thousandths). The coefficients relating to interest during construction are 1.133 and 1.163 (para. 4.4).

Sensitivity calculations for the ratio are given in detail in Annex 4.4. They show that:

a - a variation in the discount rate has quite a substantial effect. This is normal for very capital intensive designs: the ratio C_F/C_f decreases by 10% when the discount rate increases from 5% to 8%. In reality, this rate is more a computation standard than an uncertain datum: it is up to the decision-maker to select his standard. It has nevertheless been indicated that 5% (in real terms) is probably rather high (para. 4.4).

b - the effects of variations relating to the breakdown of cost are small. The guaranteed consistency between the various cost components of both technologies authorises the statement that the possible error for each component does not exceed 10%; the different effects on C_F/C_f are then all lower than 3%. The 5 year difference taken between the lifespans of the fission (30 years) and the fusion (25 years) reactors alone results in a greater difference (7.5%); this hypothesis has been justified by the probably relatively short life of the blankets and protective elements (para. 4.4) (1) .The actual error margin is therefore lower.

c - with a set discount rate, if the different technico-economic inaccuracies are combined, it can be said that the reasonable uncertainty on C_F/C_f is of the order of $\pm 6\%$. The uncertainty on k about its mean value (2.35) is $\mp$ 6.4%. The uncertainty on kC_F/C_f is approximately $\pm$ 8.5% (2) The degree of accuracy is not surprising;kC_F is not an estimated value but the <u>result of a computation</u> expressing the <u>condition of competitivity</u>

4.15 <u>Sensitivity to the benchmark cost of base-load electricity</u>
The variant corresponding to a base-load cost of electricity increased to about 130 in a coal-fired plant must be considered here (para. 4.1). This scenario is in a period of disequilibrium and the total costs of energy sources which normally compete are no longer in balance (3). The frame which is usually thought of (but it is not the only one) is that of a fossil fuel crisis which, for a price per coal kWhe of about 130, produces some premium per nuclear kWhe, approximately 10 point i.e. a kWhe cost of 120.

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(1) In another presentation, maintenance costs can be increased

(2) The formula is rather complex.

(3) In economic terms, one of the sources is not competitive and its market share must be reduced. The <u>total</u> cost of this source is not an adequate benchmark.

It is then clear that international tension acts on the price of uranium and, to a lesser degree, on the cost of the nuclear PWR equipment. Table 4.2 given above can then be replaced by Table 4.4.

TABLE 4.4

Fusion kWhe cost (reference PWR = 120)

	PWR (reference) 2050	Fusion 2050 (competitive)
Total	120	120
Capital (inc.decommis)	45	90
Operation & Maintenance	20	28
Fuel cycle (Transformation)	24	Inc.in capital
Fuel cycle (Material)	31	2

Coefficient 1.52 para. 4.13 becomes

$$\frac{90}{45} \times \frac{65.05}{70.95} \times \frac{1.133}{1.163} = 1.79$$

i.e. a 18% increase. The capital cost of the prototype reactor of a series to be competitive can be up to 4 to 4.5 times that of the PWR.

The sensitivity to the benchmark cost of electricity is more important than that of other factors.

Summary

4.16 To stand a good chance that fusion series reactors will be competitive, the capital cost of the prototype fusion reactor compared with that of the PWR without interest during construction (per kWe) should not exceed the following limits (which should also be considered as targets):

3.6-fold when the energy price corresponds to a steady market

4.2-fold when the energy price is affected by long lasting international tension

The accuracy of these figures is ± 8.5%.

ESTIMATES OF THE CAPITAL COST OF A PROTOTYPE FUSION REACTOR

Data available in 1987

4.17 Many (roughly twenty but only a few are independent) estimates have been made over the past fifteen years of the total capital cost (1) of fusion reactors based on different configurations. Given the degree of approximation of this study, the only design of Tokamak DT, which is adequate for present purposes, is considered here. If this configuration does not prove to be the best, it is sufficient to say that another configuration would be less costly.

These data appear in the 1986 CEC report (reference 2 in Annex 4.1). An abstract is given in Annex 4.5 with some comments.

One of the problems with these data is that they are generally expressed in absolute terms, and do not give the cost of competing technologies with enough consistency and accuracy. Estimates made in different countries are often compared with those of another country simply by applying the rate of exchange, which is rather dangerous (para. 4.8 and Annex 4.2)

The data of the ESECOM-Holdren report (1987)

4.18 In 1987, a committee of the U.S.Department of Energy , chaired by J P Holdren, examined the economic and environmental aspects of fusion. A summary of the report was given in the summer of 1988 and the final report in September 1989.

In addition to updating earlier data, the major interest of this study is the constant search for consistent estimates to afford a meaningful comparison of the nuclear technologies available beyond 2020. For fusion reactors, this effort is translated by the use of a capital cost evaluation model (Generomak), which, starting from standard costs per unit of equipment (e.e. per kg of electro-magnet) and formulae involving size (volume of power), gives homogeneous costs for the different variants. For fission reactors, another model is used for capital costing (United Engineering Constructors). The report does not indicate whether the unit prices of current materials or components (e.g. concrete or electricity generator) are the same, but on examination of the details of the capital cost breakdown, the results are fairly consistent.

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(1) Direct and indirect costs, without interest during construction.

4.19 The unit costing conventions used are those of Nuclear Energy Cost Database of US.DOE. Some main points warrant special attention:

(a) the methodology followed for calculating the annual capital charges is different from that of European calculation, which could lead to confusion. The main differences are listed in Annex 4.2 (para. 2).

(b) as in the present report, the reference models are based on fission reactors. Four cases are given, but three of them are fast breeder reactor designs (1). The fourth case is a PWR - for which the ESECOM report provides two estimates (2)

- PWR-BPE (Best Present Experience) which is stated to be the official reference model of an optimised series reactor. Capital cost without interest during construction is 1170 (1986) $/kWe; kWhe cost is 33.4 mil/kWhe.

- PWR-ME (Median Experience), with very high constraints (12 years instead of 6 for construction time). Capital cost is 2260 $/kWe; kWhe cost is 56.6 mil/kWhe.

(c) difficulties arising from the periodic replacement of certain fusion reactor components (mainly blankets) are clearly mentioned. The report indicates that it is possible to earmark the corresponding expenses to either maintenance costs or capital charges by reducing lifespan.

(d) nuclear fuel expenses are included in operation and maintenance expenses.

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(1) The capital cost without interest during construction for two of them are 1645 and 1575 1986 $. The average capital cost is 37.6% higher than that of the PWR-BPE.

(2) These differences show the difficulty of defining a valid benchmark. In this report, the choice of optimised technologies is made clear in para. 4.9 and Annex 4.2. Consequently, the comparisons made below with ESECOM report will refer to PWR-BPE.

4.20 For the present purpose, the main lessons of the ESECOM study are as follows:

(a) This study evaluates the capital cost of ten examples of 1200 MW(e) fusion reactors (excluding interest during construction), of which four are Tokamaks with conventional steam cycle electricity generation (1). The capital costs per kWe for a single unit, which is something like the tenth of a series, are as follows, in 1986 US$ (p.123)

2178 2193 2563 1873

i.e. an average of 2202 US $ per kWe.

(b) The breakdown of capital cost is referred to in para. 4.22 and 4.23 below. As regards the share of the conventional electric-island in the total direct cost, the ESECOM report indicates:

- Tokamaks 21.1% (average of the four Tokamaks)
- PWR-BPE 33.3%

This last PWR figure is approximately the same in table 4.6 below (34%). For a fusion plant, the European estimates are 9% (table 4.5) for a prototype, that is 18.9% for a series unit (2); consistency between EURATOM and ESECOM report is not so fair but neither the breakdown conventions are the same, nor are the reactor designs.

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(1) Two other examples are given referring to advanced energy generation.
The PWR-BPE fission reactor is costed at $1170/kWe, excluding interest during construction. The mean Tokamak capital cost is then 1.88 times this benchmark PWR capital cost. This figure can be compared with the ratio 1.52 given in para. 4.13 and 1.79 in para 4.15 as the targets for competitivity.

(2)
$$18.9 = 9 \times 2.35 \times \frac{1.15}{1.29}$$

where 2.35 is coefficient k of para. 4.13 for total capital cost. 1.15 and 1.29 are the coefficients linking total capital costs to direct costs (para. 4.23).

Recent Euratom estimates and the SCAN model (System Cost Analysis of NET)

4.21 Since 1985, Euratom (W. R Spears) has made evaluations of prototype reactors i.e. the first reactor starting an industrial-scale experience. A cost model referred to as SCAN was designed to this end; its principle is close to that of ESECOM (fractioning of the power station into its main components: site, civil engineering, mechanical parts of the nuclear island, electricity production, other electrical equipment, P.I.C., management of the nuclear fuel), each component being estimated on the basis of standard costs with respect to volume and power. Costs are expressed in ECU at 1984 prices.

Three estimates are currently available in SCAN language (see Ch. 3, para. 3.10):

- the first relates to the PCSR-E reactor, which was used in the 1986 report and is an extrapolation of the NET-ITER physics and technology to a power reactor, with optimisation of cost, but also with many safety factors in order to cope with possible difficulties. This reactor is a prototype, power : 1250 MWe.

- the second estimate relates to the EEF Reference Reactors as described in Ch. 3 (para. 3.8 to 3.11); it is also a prototype, based on present knowledge with plausible improvements above the state of the art and reduced safety factors. Its direct cost is 28% lower than that of PSCR-E (1); Power 1200MWe.

- the third estimate relates to the EEF Advanced Reactor AMTR 3 which illustrates potential advances that could be the result of the fusion research programme for a protoype commissioned by 2020. Its direct cost (1) is about 23% lower than that of the EEF Reference Reactor. Power: 1200 MWe.

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(1) Total capital cost includes direct costs which roughly relate to hardware and indirect costs which refer to engineering, administration and miscellaneous expenses.

4.22 The advantage of these three estimates is that the SCAN model makes them homogeneous. They are summarised in Table 4.5 for direct cost and its breakdown into main headings, this breakdown being the IAEA language, which is different from that of ESECOM.

TABLE 4.5

Esimated direct capital cost per kWe
(1988-89 European studies) in 1984 ECU per kWe
(prototype of 1200 MWe)
(breakdown : IAEA language

		PSCR.E*			EEF Ref			AMTR3	
		1984 ECU		%	1984 ECU		%	1984 ECU	%
1+2	Site + civil works	1040		20	720		20	520	18
3	Thermonuclear island	2530		48	1620		43	1130	39
	- Torus		670			360			
	- Magnets		840			510			
	- Reactor coolant		410			120			
	- Others		610			630			
4+5	Steam and electricity island	360		7	330		9	305	11
6	Prot. Instr. Control (nuclear & electricity)	200		4	210		6	210	7
7	Plant service systems	370		7	310		8	265	9
8	Nuclear fuel management	110		2	90		2	85	3
9	Contingency and miscellaneous	620		12	460		12	360	13
	Total (direct cost)	5230		100	3740		100	2875	100

* With power adjustment for 1200 MWe

It can be observed that the differences between the estimates (- 1490 and -865) are nearly all due to the nuclear island and its equipment (-910 and - 490 on nuclear equipment, - 320 and -200 on civil works). These differences correspond mainly to a much smaller size and better efficiency for the EEF Reference and AMTR3 Reactors.

As regards the breakdown of direct cost, reasonably good convergence can be observed in the headings. Running ahead of the next paragraph, we assume that the base in the estimate of consistency costs is heading (4 + 5), i.e. the conventional electro-mechanical system (turbogenerator, steam circuit, auxiliary equipment). The total cost of the above estimates in relation to the cost of heading 4 + 5 works out as follows:

- PCSR-E total direct cost: 100/7 = 14.3 times (4 + 5)
- EEF Ref. total direct cost: 100/9 = 11.1 times (4 + 5)
- AMTR-3 total direct cost: 100/11 = 9.1 times (4 + 5)

Comparison of the cost of the fusion prototype with that of other technologies (series)

4.23 The objective here is to connect the estimates of the capital cost of a fusion prototype with the costs of competing technologies corresponding to series units (because the methodology has adopted this hypothesis, the important thing being that these units be economically "optimised", i.e. in current use on the market).

The ideal procedure would have been to apply the SCAN model to the estimate of the capital cost of all these conventional technologies in the language of SCAN (IAEA); this would have eliminated many factors of uncertainty. Unfortunately, in the time available, this work could not be executed, but it will have to be done one day.

It is thus necessary to have recourse to a more summary method which consists of referring to a component of equipment which is practically identical in all electrical power stations, irrespective of the technology. The comparisons of technologies by the utilities show that, in a well-defined evaluation system for a given net capacity, the expenditure incurred for the turbine and electricity generation plant is, in absolute terms, practically independent of the steam generation system; it must nevertheless be necessary to take into account an additional electrical power, in the case of fusion; it is 20% higher in size and about 10% more expensive in terms of capital cost for PCSR-E and EEF ref; the supplement of cost is assumed to be 5% for AMTR3.

Taking the PWR technology as benchmark (once again a series reactor which is economically optimised), the table 4.6 of total direct construction cost (excluding interest) can then be prepared using the utilities' data (1) (2). The fusion column presents the three cases with the values found above (para 4.22): total direct cost is 14.3, 11.1 and 9.1 times that of the steam-electricity equipment.

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(1) For PWR, the breakdown is given by the HOLINGER contract in SCAN model language (IAEA language). A joint EDF-CEGB study performed in 1988 provides also very useful information.

(2) Taking account also of the links between the nuclear island and civil engineering headings.

TABLE 4.6

Relative capital cost of electrical power stations
(direct costs, excluding interest during construction)

	Fission PWR (series) reference	Fission breeder (series)	Fusion (prototype)		
			PSCR-E	EEF ref	AMTR-3
a) Steam + electricity * (4+5)	31.5	31.5	35**		33**
b) Nuclear island* (3+6)	34.0	55	260	191	138
c) Civil works + site (1+2+7)	33.3	42	135	109	81
d) Others (8+9)	1.2	1.5	40	55	48
Total	100	130	500**	390***	300***

* Civil works not included.
** 10% and 5% more than PWR. Total costs are obtained from these figures.
*** 35 x 14.3, 35 x 11.1, 33 x 9.1.

4.24 To obtain total capital costs, indirect costs must be added to these direct costs (para. 4.21). In Europe, overall rates of indirect costs are 15% of direct costs for a series, 29% for a prototype (1) (2), so that the range of relative total capital costs is summarised by table 4.7 (3).

---

(1) These figures are those of the SCAN methodology; 15% is given by the HOLINGER AG COLENCO report, one constraint of which is consistency with the SCAN model. Indirect cost concept in USA is different: in ESECOM report, "indirect costs are figured at 37.5% of direct costs" for series reactors (fusion and fission).

(2) Note that one effect of the learning curve is to rub out the difference between 15% and 29%.

(3) It is assumed that decommissioning costs are, as a percentage, the same for fission and fusion.

TABLE 4.7

Total capital cost (as compared to series PWR)
(excluding interest during construction)

FISSION (series)		FUSION (prototype)		
PWR	Breeder	PCSR-E	EEF Ref	AMTR-3
100 x 1.15 = 115	130 x 1.15 = 149	500 x 1.29 = 645	390 x 1.29 = 503	300 x 1.29 = 387
100 (base)	130	560	437	337

4.25 These calculations taken together yield a very important result: excluding interest during construction, the capital cost estimates in Europe for prototype fusion reactors are in the range three to six times the cost of a series PWR.

In the ESECOM report, the capital cost of a series fusion reactor is 1.88 times the capital cost of the PWR-BPE (para. 4.20) with a range of ± 16%. Taking account the effects of learning (para. 4.10), the capital cost of a fusion prototype is 1.88 x 2.35 = 4.42 times the PWR-BPE costs, with the range 3.7 - 5.1.

Thus, the ESECOM and EEF estimates seem to be in accord.

SYNTHESIS AND DISCUSSION

4.26 The aim of this chapter is to grasp the profitability conditions for nuclear fusion, avoiding the methodology errors occurring in some economic comparisons , for instance by comparing the estimated capital cost of the prototype fusion reactor with reference technologies known today (like PWR). The method as applied here is not completely satisfactory, because the model used to estimate the capital cost of the fusion reactor could not be applied directly to the PWR. It would be useful to correct this lacuna in the near future.

4.27 Using practically no purchased fuel, nuclear fusion will reach competitiveness mainly by controlling capital cost. With this route to competitiveness in view, it can be said with fair degree of accuracy that the capital cost kC_{FP} of the prototype fusion reactor must be less than about 4 times the capital cost C_f of a series PWR fission reactor per kWe (para. 4.16)

4.28 Today, European estimates of kC_{FP} (capital cost of prototype towards 2020) are between 3 and 6 (para. 4.25). More accurately, the different estimates are given in table 4.8).

TABLE 4.8

Capital costs of prototype fusion reactor
(without interest during construction)

PWR series capital cost : 100

TODAYS ESTIMATES		TARGET (Upper limit for competitiveness)
EURATOM study (para. 4.24)		para. 4.16
- PCSR-E:	560	
- EEF ref reactor:	440	- 360 in the base scenario (price of imported coal constant)
- AMTR-3:	340	
ESECOM study (para. 4.25)		- 420 in the variant
- Reactors with conventional electricity generation	[510 [370	(price of imported coal increased of 50%)

4.29 It has been said in para. 4.16 that the accuracy of the limit cost (target) is rather fair. It is above all sensitive to the reference energy price, but less than could be expected (para. 4.15 and 4.16). Of course, the assumption on the reference energy price may be increased changing for instance the limit from 420 to 460. But it should clearly be seen that the reference energy price is then 1.8 times the energy price over the last thirty five years, when evolution was stable with fluctuations of less than 50%. Taking the field of progress in energy utilization and supply into account, this assumption is unlikely.

Two factors are in favour of fusion: limited risks with regard to the environment and independence for industrialised countries concerning their energy supply. It is not yet possible to quantify these advantages which are dealt with in Ch. 2 and Ch. 5. However some tentative estimates have been made for such quantification and some other estimates can be assessed from European energy policies over the last decades (see for example EEC drafts and studies), but we had no time to analyse these documents.

4.30 Attention must also be drawn to possible confusion in the calendar and nature of our figures: the upper limit of capital cost is dated 2020 for an actual prototype value; capital cost is an estimate dated 1989, the middle of the research period. In short, other uncertainties are coming on one side from the difference between estimated and actual costs and on another side from what can happen until the date of the prototype construction. Para. 4.31 and 4.32 below deal qualitatively with these uncertainties.

4.31 As for the difference between actual and estimated capital costs, it may be characterized by α, the ratio of real cost/estimated cost. This ratio takes into account not only uncertainties but also the tactics in developing the design.

If research is sufficiently advanced to provide the definition of a prototype, a rough idea of the range of α may be given by referring to experience. Annex 4.6 lists some examples of European nuclear developments over the last 30 years (natural uranium technologies, enrichment, fast breeder reactors). It is clear that α depends on the designer's care at the moment of his estimate.

Of course, it is more difficult to define α when the state of advancement of research does not allow the design of a real prototype to be performed; it is the case of fusion today.

4.32 As for the dates of assessments, today's estimates are made in the period of research and not of developement. Decisions to be made in respect of the immediate future will not be related to the construction of a prototype, but to the extension of the research effort which will eventually lead to a practical technology. The present cost estimate of the prototype can greatly exceed the limit based on competitivity; this situation is common to any research. The cost of a product estimated over the period of research is often ten times or much more the cost of competitivity; the research itself yields cost reductions. This potential is illustrated in this report by the case of the AMTR-3 reactor (ch 3 and para. 4.21)

This applies all the more as the assumptions made of stability in long-term basic energy prices implies substantial scientific and technical research efforts being made in all energy sectors, including utilisation. These efforts should be comparable with those made over the last four decades.

Teams of researchers have to estimate the costs of industrial designs and gauge future profitability from the information acquired. However, checks must be made in order to ensure that the horse always precedes the cart. Frequently, complex economic analyses conceal the real problems. It should be borne in mind that research relating to thermonuclear fusion is only part way to completion.

A clear message results from these considerations to the research teams ; the key to the industrial success of fusion is the reduction of the capital cost of the nuclear island and the associated maintenance costs. Once the basic plasma physics is mastered, it will be necessary to develop cheaper structures and operational procedures.

The only problem is the reduction on licensing

ANNEX 4.1

CHAPTER 4 REFERENCES

N.B. These references are limited to papers used for writing chapter 4. Documents from UKAEA, CEGB and EDF not included.

1.Construction costs for a European PWR plant (SCAN 2 model language). (HOLINGER AG-COLENCO AG) July 1989.

2.Environmental impact and economic prospects of nuclear fusion. CEC Fusion Programme. Nov. 1986 Report, EUR FU BRU/XII-828/86

3.Fusion production costs. A study in uncertainty (P.E. LOVE. The Energy Management Center) March 1989. EEC Contract NE3M-0084.

4.Costs of nuclear power stations in England and Wales (E.J.Pipe). IAEA Istanbul Conference (1969)

5.INTOR. Report 1988. IAEA Vienna.

6.Nuclear power: Its development in the UK (R.F. POCOCK). The Gresham Press, England 1977).

7.Nuclear power: policy and prospects (P.M.S. JONES). John Wiley & Sons Ltd, London 1987.

8.Projected costs of generating electricity in 1995 (P.M.S. JONES)1986 OECD report. Paris. 1989 draft.

9.A Reference Tokamak Reactor (P.I.H. COOKE, R. HANCOX, W.R. SPEARS). May 1989. EEF Report (see Annex 1.5)

10.Report of the Senior Committee on Environmental, Safety and Economic Aspects of Fusion (J.P. HOLDREN). Summary 1987. Report June 1989. Lawrence Livermore National Laboratory.

11.Review of commercial power producing D-T Tokamak reactor designs (J.D.JUKES and T.E. JAMES) 1989. EEF Report (see Annex 1.5)

12. The SCAN-2 Cost Model (W.R. SPEARS) 1986. NET report.

13.Towards an economic fast reactor (R.S. HALL, J.L. GRAY and others) April 1989. Nuclear Engineering International. VOL. 34, No.417, pp.17-21

ANNEX 4.2

ERRORS DERIVING FROM METHODOLOGY
(Chapter 4 para. 4.8 Examples)

1) The criterion adopted for the comparisons is an economic cost (para. 4.4) i.e. a cost as perceived by the economist progressively adopted by firms and international organisations (AEI, AIEA, EEC, UNIPEDE, etc), although it has not come into general practice today. The financial cost, better known to the managers of firms is quite different, because the reasoning behind this financial cost is generally in present currency terms with the fiscal amortisation rules in force in each country and the conditions of repayment of loans effectively in place. Differences of 25% are normal.

2) As regards the European conventions for the calculation of capital charges (chapter 4, para. 4.4), they differ from those of the USDOE which are used in the ESECOM report. The major differences are as follows:

	ESECOM report	CEC report
Real rate of return (constant currency)	2.83%	5%
Annual charges with 30 year lifespan (% of capital cost)	8.44%	6.50%

In the European language, the ESECOM conventions seem heterogeneous, because in this language, the rate of return relating to capital annual charges of 8.44% is 7.5% and not 2.83%.

3) Unless well specified (case of the prototype), the technologies should be in the economic state, namely "optimised" in an electrical network. It is not always the case. For example, when the economist consider the comparison of costs per kWhe of coal-fired stations and PWR nuclear power stations commissioned in 1995, figures which are published by the OECD, he observes that the ratio of these costs is between 1 and 1.5 for countries with the same degree of industrialisation and the same coal price: he then realises that the power stations are not optimised.

4) The comparison of costs per kWhe of an installation between countries is usually performed by applying the exchange rate (or an equivalent operator involving currencies). It is then surprising to see how this factor can distort comparisons especially when an adjustment for currency depreciation is added. The calculation below, mentioned by W.R.Spears, allows

us to realise this (1): to estimate in ecu at 1984 prices a unit of equipment estimated in US $ at 1980 prices in the United States (Starfire), two methods are possible. Its cost can be re-estimated in US $ at 1984 prices and then converted to ecu of 1984 (the dollar was then worth 1.21 ecu) which yields a coefficient of 1.334 x 1.21 = 1.61. It is also possible to calculate the cost in ecu at 1980 prices and then re-estimate in ecu at 1984 prices; the dollar was worth 0.688 ecu in 1980, whence a total coefficient of 0.688 x 1.44 = 0.99. The figure secured by the first method is 62% higher than the second (2).

5) The cost breakdown between the main components poses also difficulties: differences in content between headings are not the same from one country to the next (e.g. between capital and maintenance costs) and on examination of international evaluation models (e.g. SCAN), it is not very easy to see which real commercial system they correspond to. The same question occurs when considering the proposed breakdown for fusion reactors using different languages (see INTOR 1988 report, volume 2, pp. 322-323 and chapter 4, para. 4.22).

6) This provides the opportunity to underline the difference in the breakdown of the benchmark electricity cost (PWR) between the ESECOM report and this CEC report (chapter 4, para. 4.12).

	ESECOM report (BPE)	CEC report
Capital	56%	43%
Operation-maintenance	21%	20%
Fuel	23%	37%
	100%	100%

The profitability calculation of fusion reactor is sensitive to this breakdown (chapter 4, para. 4.14 and Annex 4.4).

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(1) The contract with HOLINGER-COLENCO gives other examples.

(2) Similar difficulties are met when an attempt is made to grasp the oil prices: there have been "dollar shocks" as well as "oil shocks".

ANNEX 4.3

FROM THE PROTOTYPE TO THE SERIES REACTOR: THE LEARNING CURVE

1) OBJECTIVE AND DIFFICULTIES (Chapter 4, para. 4.10)

The aim is to estimate the ratio k (capital cost of a prototype to the commercial series reactor cost).

Such a coefficient cannot be determined by analysing the cost of fusion reactor and the progress to be achieved over thirty years. The discussion must be limited to an overall approach based on experience with similar equipment.

The problems can be summarised as follows:

a- The change occurs over a long period; if the elements compared over this period are not specified, there is a risk of major error, since the learning curve is non-linear. The capital cost of new technology is high at the outset, decreases and only stabilises after some time. The concepts of prototype and series reactor must thus be specified. Here, the first prototype reactor is the first industrial scale reactor which is integrated into an electric generation system (it will have been preceded by several research development machines proving the feasibility of the technology, but basically not concerned with integration in an industrial system). The series reactor corresponds to a group of roughly ten identical reactors whose efficiency has been demonstrated or nearly demonstrated, the objective being to take advantage of the learning and scale effect on the manufacturer's costs. Intermediate installations will of course be built between the prototype and the series reactor e.g. the pre-series reactors (one or two identical units).

b- The many factors are difficult to disentangle because they occur simultaneously during this long development period:

- reduction of engineering costs and the uncertainties attaching to the estimate of expenditure. This applies to two practically identical units constructed one shortly after the other.

- reduction of cost due to the acquisition of knowledge relating to design and construction proper: the prototype reactor is built "artisanally"; the second, although identical in overall design, is built in much better conditions and with far simpler structures.

- this acquisition of knowledge is naturally multiplied when development is viewed, not over a 2 to 3 year term, but over 30 years, because of the progress in designs, materials and structures.

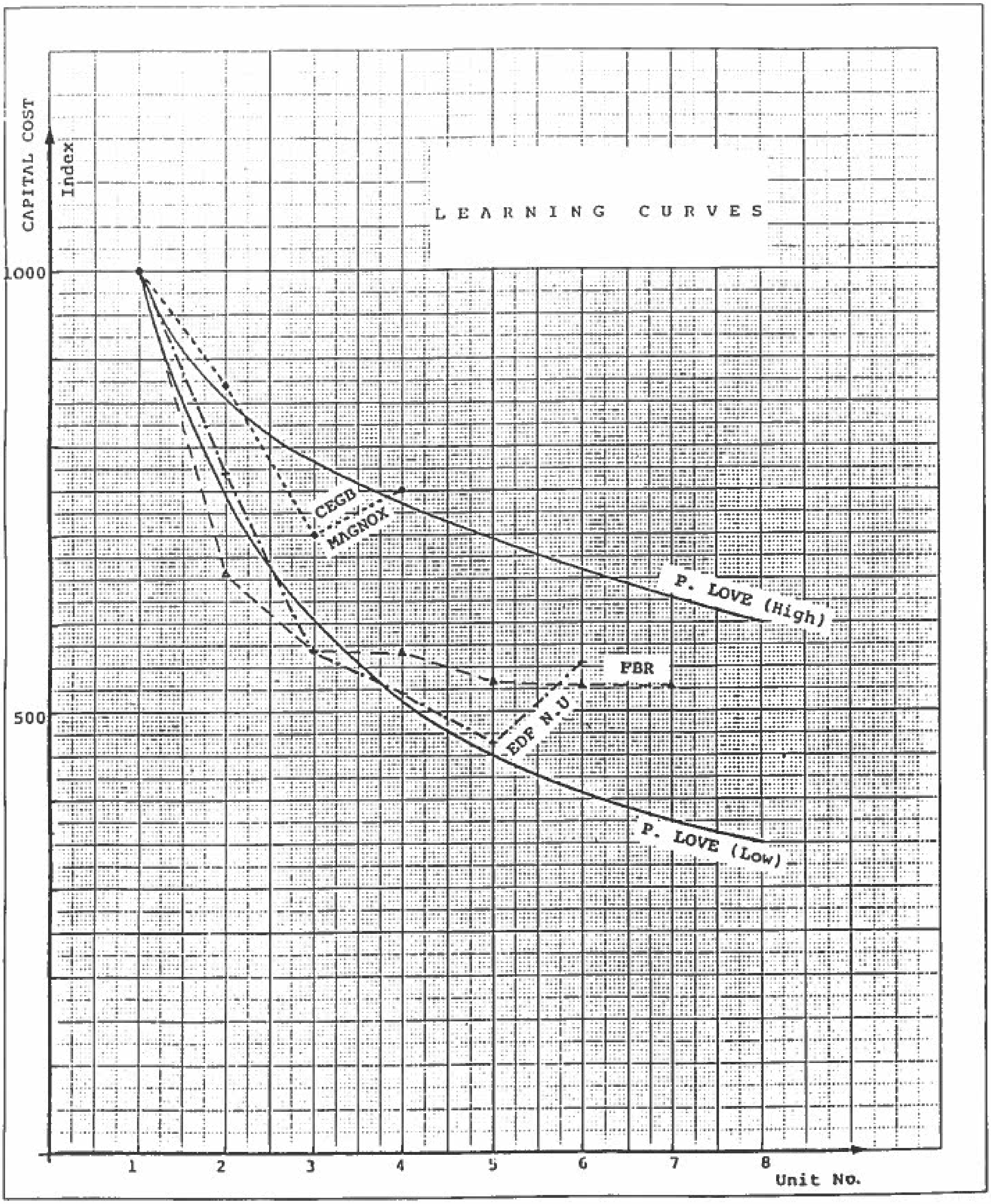
- the series effect, for an unchanged technology, is substantial. In building several units, rather than one, constructors can use different industrial equipment, use it better and amortise it over longer production runs, leading to lower costs. Attempts to estimate possible gains from this effect have often been made. Some of the remarks below refer to studies of this kind, but it is very difficult to discern the separate structure of fabrication costs within a complex whole. It must at least be remarked, to avoid making dangerous parallels that, as regards the number of units in a series, the construction of power stations cannot be compared with aircraft manufacture. A prototype aircraft can be far more expensive than the series product (a hundred-fold, a thousand-fold?) because the series will consist of hundreds of planes to be built over 5 or 6 years, and the financial risk is spread widely over a large potential market. This is not true for large construction projects whose potential market over 5 or 6 years is only a few dozen units.

- the size effect of the power station is also relevant. The power of the prototype reactors is often limited, and this factor must be dissociated from the others. In the samples below this is done by adjusting the capital cost for a given technology by a factor of $P^{0.67}$ where P is the electric power of the station.

2. INFORMATION DERIVED FROM THEORETICAL STUDIES AND THEIR APPLICATION TO THE CASE OF NUCLEAR FUSION (Contract with the P.E.Love Bureau)

Starting from analyses of the learning effect conducted over the last thirty years, the P.E. LOVE bureau defines an aggregate learning curve for nuclear fusion and margins of uncertainty that are of considerable interest. The method, which therefore covers many explanatory factors, consists of considering that the cost of an industrial product is reduced by a constant percentage, say a, each time production or capacity doubles. The estimated cost of a fusion reactor is broken down into eight headings, with each of which is associated a reduction rate a taking account of the experience available regarding the component. Conventional parts have a low rate (a = 5 to 15%) while the headings relating to new technologies have a high rate (a = 10 to 30%).

For the fusion reactor, the figure overleaf indicates the two curves between which the learning curve as a function of the number of installations will most likely lie. It shows that, from the fifth unit, the cost is approximately 0.57 times that of the demonstration reactor falling to 0.47 for the 8th unit.



3. ACTUAL EXPERIENCE OF NUCLEAR POWER IN EUROPE

It is interesting to look at the nuclear industry itself, which has had opportunity to develop several technologies over the last four decades:

a- The enriched uranium fission chain (PWR).
This technology was developed in the United States, and the first European plants were built under American licence. As a result, this technology offers no feedback as regards the changeover from a prototype to series reactors in Europe.

b-The natural uranium fission chain (graphite-gas)
Two European countries, the United Kingdom and France initially focused their efforts on this reactor family, but they did not succeed in building a series of five to ten units of the same characteristics. It may be noted that before the design of a reactor for electricity generation, reactors for military purposes had contributed greatly to the development of the technology.

Data given below refer to the experience of the same owner (EdF for France, CEGB for UK). As mentioned earlier, the size adjustment has been applied here. Similarly, the second and third units are often built of the same site as the first, which also affects their cost.

In the case of France, the data relating to natural uranium-fired power stations are as follows:

FRANCE(EdF) - Natural uranium experience

Unit No./Name	Commis-sioning date	Net capa-city MWe	Capital cost/kWe (index at constant prices, excluding IDC)	Capital cost adjusted for the size effect (Ref300MW)	Cost adjusted for the site (one unit/ site)
1 Ch 1	1961	60	1000(ref)	1000(ref)	1000(ref)
2 Ch 2	1965	200	466	696	769
3 Ch 3	1967	480	253	506	564
4 SL 1	1969	480	261	521	521
5 SL 2	1971	415	212	405	462
6 B 1	1972	540	266	556	566

In the case of CEGB MAGNOX reactors, data are given in the table overleaf. In this table:

- the first two stations of the UK programme (Calder Hall and Chapelcross, owned by the UKAEA) are not included; even if they supplied many kWhe to the electrical grid, they were justified by military priority.

- 2 or 3 stations are sometimes re-grouped because they were commissioned the same year (as a pre-series of a civil programme).

U.K. (CEGB) Magnox experience

No.	Group of units Name	Commis-sioning date	Net output MWe	Capital cost/kWe (index at constant prices. No IDC)	Capital cost adjusted for size effect (REf 500MWe
1	Berkeley Bradwell	1962	275 300	1000(ref)	1000(ref)
2	Hinkley A Dungeness A Trawsfynydd	1965	500 550 500	720	870
3	Sizewell A Oldbury	1966 1967	580 600	550	700
4	Wylfa	1971	1180	470	750

CEGB and EdF figures are presented in the above figure (1). There is an adequate similarity in the trend of capital cost in the two countries. Starting from a No.1 prototype unit (2), this cost fell and the cost of the third unit (or group of units) was roughly 60% (France) or 70% (UK) of the cost of the prototype; in the case of France, a stabilisation at 50% to 55% appears with Nos. 4 and 5.

The series effect of several units ordered at the same time (namely 5 to 10) did not operate. Had it done so, it may be considered that approximately 20% of the expenditure undertaken could have been spread over five units in the cost of each unit. It can therefore be assessed that in moving from the prototype to the series unit (roughly 15 years later), the cost (for the same capacity) of the series reactor would have been approximately 0.525 x 0.84 = 0.45 times the cost of the prototype reactor.

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(1) An index value of 1000 refers to prototype (No.1)

(2) Note that, given the experience of some previous military reactors, this No.1 is not exactly a prototype.

C - The fast breeder reactor fission chain

Several identical units of fast breeder reactor have never been built, but on the basis of prototypes whose costs have been reasonably well established, the experts were able to estimate the probable cost under clearly defined conditions (e.g. a single power station of the same capacity, etc.) of the unit following the prototype, and then of the pre-series and the series units.

The studies conducted on the reactors to be built after Superphenix suggest the following conclusions (excluding interest during construction, for a capacity of 1200 MWe):

	Superphenix (reference)	Next unit	Pre-series (two units)	Series
Nuclear Island (excluding civil engineering)	610	370	290	260
Electrical island and civil engineering	390	290	280	260
TOTAL	1000	660	570	520

The installation cost of the first series units is reduced to 52% by comparison with the prototype reactor, the most substantial reduction (approximately one-third) occurring between the prototype unit and its successor. After that, the cost reduction is approximately 20% viz. $\frac{660 - 520}{660} = 0.21$

The gain secured between the prototype and the next unit is basically explained by the simplification and the lightening of structures. For identical capacity, the weight of the steel in the nuclear island is reduced by more that 40%. In contrast, it should be observed that there is no major technological change from one unit of equipment to the next, either in general design or the nature of materials.

Estimates for the last breeder reactor were also made in the United Kingdom, in 1987. But the interval covered is shorter than the period required to change over from prototype to series; the comparison relates to the first 1450 MW fast breeder reactor to be built in the United Kingdom and the unit which will follow it.

4. CONCLUSION

The above data are plotted in the graph. They display reasonable convergence and it can be said that for large scale equipment, costs start to come under control from the 4th or 5th unit (or group of units) following the commercial prototype reactor, settling at slightly over half (say 0.55 times) the cost of the prototype unit.

It can be estimated that the fifth unit will be built some ten years after the first one. Beyond that time, the following factors will begin to operate:

- in the short term, the series effect which produces a saving of about 10%
- in the long run, over a period of 20 to 30 years, technical progress relating mainly to new technologies, can be estimated to contribute to reducing costs by 10 - 15%.

All in all, it can be estimated that between the prototype reactor and the series reactor of the year 2050, the cost reduction coefficient is 0.55 x 0.90 x 0.875 = 0.43. Excluding interest during construction, the cost of the prototype reactor 30 years distant in time from the series should normally be some 2.2 to 2.5 times that of the series reactor (k = 2.2 to 2.5).

ANNEX 4.4

ERROR AND SENSITIVITY COMPUTATIONS
(Chapter 4. para. 4.14)

1) GENERAL PRESENTATION

To ascertain the effect of uncertainties and hypotheses, it is practical to express the results of para. 4.14 of chapter 4 in a simple mathematical form.

The basic elements are the operating, maintenance and fuel costs of table 4.2, chapter 4; capital charges, the highest component, are viewed as complements of these basic elements. In these conditions, the total cost per kWhe can be higher than 100.

The notations are as follows (figures between brackets are those of table 4.2):

	Fission (PWR)	Fusion (competitive)
- Capital cost without IDC (1)	C_f	C_F
- Lifetime (years)	L_f (30)	L_F (25)
- Rate of return	r (5%)	r (5%)
- IDC coefficient	t_f (r)(1.133)	t_F (r) (1.163)
- Annual capital charges rate	$A(L_f,r)$ (6.505%)	$A(L_F,r)$ (7.095%)
- Capital charges per kWhe	$c_f=A(L_f,r)t_f(r)C_f$	$c_F=A(L_F,r)t_F(r)C_F$
- Other charges: . operation-maintenance	10 + 10	$10 + 10\ C_F/C_f$
. fuel transformation	24	0
. fuel raw materials	13	2

The equality of costs per kWhe is written:

$$c_f + 10 + 10 + 24 + 13 = c_F + 10 + 10\ C_F/C_f + 2$$

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(1) Interest during construction.

Knowing that:

$$\frac{c_F}{c_f} = \frac{A\ (L_F,\ r)\ t_F(r)}{A\ (L_f,\ r)\ t_f(r)}\ \frac{C_F}{C_f} = \frac{1}{R}\ \frac{C_F}{C_f}$$

with $R = \dfrac{A\ (L_f,\ r)\ t_f(r)}{A\ (L_F,\ r)\ t_F(r)}$

the ratio C_F/C_f is given in the formula below:

$$\left(1 + R\ \frac{10}{c_f}\right)\frac{C_F}{C_f} = R\left(1 + \frac{10 + 24 + 13 - 2}{c_f}\right)$$

or

$$\left(1 + R\ \frac{10}{c_f}\right)\frac{C_F}{C_f} = R\left(1 + \frac{34 + 11}{c_f}\right)$$

In the second part of the formula, 34 corresponds to the maintenance cost and the cost of transformation of the fissile substance of the PWR; 11 is the difference in the cost of raw materials used for combustion. The uncertainty on this difference gives rise to the energy cost variant (chapter 4, paras 4.1 and 4.15)

It is appropriate to observe how the wish for consistency of the computation of costs simplifies the calculation. For instance, operating costs (10) no longer enter (chapter 4, para. 4.11).

A distinction must then be drawn between the uncertainties associated with the approximations made in the breakdown of cost per kWhe and those linked to the hypothesis relating to the calculation of capital charges (lifespan and discount rate).

2. UNCERTAINTIES LINKED TO THE BREAKDOWN OF COST PER kWhe

Lifespan L and construction time, as well as the discount rate r, are assumed to be certain; this is also true of coefficient R. Since the fuel price variant is dealt with separately, the remaining factors of uncertainty are:

- the figure 10: maintenance cost of the PWR; the degree of inaccuracy is $\pm$ 1;

- the figure 24: fissile fuel transformation cost; the degree of inaccuracy is $\pm$ 2;

- the term c_f (= 43): capital charges of the PWR. Since rate r is fixed, the error can only originate from an error of C_f; it is not higher than 20% ($C_f = 43 \pm 4$).

The effects of these variations are as follows:

$$R = \frac{6505}{7095} \times \frac{1}{1.163} = 0.8932$$

Variation of the factor	Initial $\frac{C_F}{C_f}$	Final $\frac{C_F}{C_f}$	Variation of $\frac{C_F}{C_f}$ (%)
10 to 11 (+ 1)	1.5135	1.5049	- 0.6%
24 to 26 (+ 2)	1.5135	1.5479	+ 2.3%
c_f: 43 to 47 (+ 4)	1.5135	1.4692	- 2.9%

All these errors are lower than 3%.

3. SENSITIVITY TO CONVENTIONS RELATING TO THE CALCULATION OF CAPITAL CHARGES

A change in these conventions alters both R and c_f.

a - Effect of an increase in the discount rate from 5% to 8%

($L_f = 30$, $L_F = 25$).

	Initial conditions	Final conditions	Variation
$\frac{A\ (L_f,\ r)}{A\ (L_F,\ r)}$	0.9168	0.9482	+ 3.4%
$\frac{t_f\ (r)}{t_F\ (r)}$	$\frac{1.133}{1.163}$	$\frac{1.222}{1.277}$	- 1.3%
R	0.8886	0.9074	+ 2.1%
c_f	43	$43 \times \frac{8883}{6051} = 63.12$	+ 46.8%
C_F/C_f	1.5071	1.3589	- 9.8%

A change from 5% to 8% of the discount rate has a major effect (approximately - 10%) owing to the substantial change in the term c_f. The direction of the change, a decrease, is perfectly logical; the increase in r penalises the most capital-intensive solution: the limit value of C_F should be lower.

b - <u>Effect of a 5 year increase in the lifespan L_F of the fusion reactor</u>. The lifespans L_F and L_f are then equal to 30 years.

The term A (L_F, r) is multiplied by 0.9168 and R by 1.0907.

The ratio C_F/C_f (1.5135 at the start) becomes 1.6254; it is increased by 7.4%.

c - <u>Effect of a 5 year increase in L_F and L_f (35 and 30 years)</u>

	L_f = 30 L_F = 25	L_f = 35 L_F = 30	Variation %
$\frac{A(L_f, r)}{A(L_F, r)}$	0.9168	0.9388	+ 2.4%
R	0.8932	0.9146	+ 2.4%
C_F/C_f	1.5135	1.5434	+ 2.0%

4. SYNTHESIS

It should be recalled that C_F/C_f sets the limit not to be exceeded for fusion to be competitive. This ratio is most sensitive to the discount rate: it declines by 10% when the discount rate increases from 5% to 8%. However, this rate is more of a policy-related computation standard than a random datum. As mentioned in chapter 4 (para. 4.4), when considering a rate of interest at constant prices, the 5% rate seems to be rather high.

The other factors correspond to the uncertainty of the technical data. The 5 year difference in lifespan between the fission and the fusion reactor is the most important; the effect on ratio C_F/C_f is 7.4%, but one is aware that this difference corresponds to the probable speed of wear of some units of equipment of the fusion reactor which is not taken into account in maintenance costs; the error due to L_F is therefore much lower than 7.4%. The other factors correspond to possible errors of the order of 2% to 3%. The combination of all these errors of random character shows that the total probable error of C_F/C_f is approximately $\pm$ 6%. This low figure is not surprising: it is due to the methodology followed and in particular the wish for homogeneity in the breakdown of cost per kWhe.

ANNEX 4.5

DATA OF THE 1986 CEC REPORT ON CAPITAL COST OF THE FUSION REACTOR

(Chapter 4, para. 4.17)

The 1986 CEC report indicates the cost in U.S $ per kWe of eight projects designed between 1974 and 1980. For the reasons already mentioned of errors arising from the exchange rate (Annex 4.2), the American figures must be separated from the European estimates: the table is summarised as follows (reference 1 for STARFIRE; comparison in currency adjusted for inflation).

It should also be noted that the reactor is not always a prototype; STARFIRE is the tenth of a series.

<u>Estimates relating to the D.T. Tokamak projects (direct capital cost in constant currency)</u>

	American estimates		European estimates	
	Power (MWe)	Cost/ kWe	Power (MWe)	Cost/ kWe
1974 PPLP	2030	0.47		
UWMAK I	1474	0.78		
1975 UWMAK II	1709	0.69		
UWMAK III	1985	1.14		
1976 CULHAM I			2500	0.7
1977 CULHAM II			1200	1.28
1978 NUWMAK	660	1.05		
1980 STARFIRE (ref.: 10th of a series)	1200	1		

On the examination of the trend of costs in estimates made by the same team after adjustment for the power effect, it can be observed that:

- for UWMAK, the trend is as follows (for 1200 MWe): 0.84 (0.78 for 1474 MWe), 0.78 (0.69 for 1709 MWe), 1.35 (1.14 for 1985 MWe), 0.78 (1.05 for 660 MWe). After a sharp increase for UWMAK III, the estimate returns to its former value for NUWMAK.

- for CULHAM, the estimates for 1200 MWe are 0.89 (for 0.7) and 1.28; there has been a 44% increase within a year due to the difference between designs.

In calculating cost per kWe, the 1986 report presents a comparison with the technologies that will be competing with the fusion reactor. Unfortunately, the high and low capital cost estimates of the other technologies relate to different countries and non-optimised scenarios, which leads to margins of uncertainty such that those references are no longer meaningful. The estimate for the fission reactor ranges from 1 to 3 and the estimate for the coal-fired plant from 1 to 2. The uncertainty attached to these much more well known techniques is greater than that for the new fusion technology.

ANNEX 4.6

COMMENTS ON THE ACCURACY OF THE COST ESTIMATE

(Chapter 4, para 4.31)

In para. 4.31, the difference between actual and estimated costs of a prototype is expressed by the ratio α of these two costs.

The value of α is difficult to ascertain. In addition to the uncertainty of the future, it involves the tactics pertaining to decision-making processes, in particular in the dialogue between technicians and financial bodies. It does not fall within the scope of this report to analyse mechanisms which, moreover, are not well known, although the causes of variations in α are often described in historical documents.

Some examples taken from the history of nuclear energy, mainly in Europe,of α are given below (1). Generally, the coefficient varies with the date of the estimate; α may be high at the moment of decision but would draw nearer to 1 in new estimates as construction is proceding. Insofar as checking was possible, the figures below refer to α at the moment the official decision of achieving was met.

- France: (2)	
. 1st isotopic separation plant	= 2
. 1st EDF power station (natural uranium)	= 1.25
. 2nd EDF power station (natural uranium)	= 1.25
- United Kingdom: (3)	
. Berkeley-Bradwell station (excluding the losses suffered by the constructors)	= 1.8
. Hunterston A	= 1.5
- European prototype fast breeder reactor (Superphenix)	= 1.8
- US prototype fast breeder reactor (Clinch River)	= 3.4

(1) In these cases, technology was known.
(2) From French studies.
(3) From R.F.POCOCK (ref.6, Annex 4.1)

Chapter 5

ENVIRONMENTAL POTENTIAL OF NUCLEAR FUSION

CHAPTER 5

ENVIRONMENTAL POTENTIAL OF NUCLEAR FUSION

INTRODUCTION

5.1 This chapter reviews those qualitative features of fusion energy with particular attention to the D-T Tokamak reactor, which are relevant to environmental potential

Environmental impacts

5.2 A comprehensive analysis of impacts on the human environment would include all those issues relating to the construction of a power station today. The list in Table 5.1 can be seen to include both specific technical features of the plant and more general issues such as might apply to any industrial development.

TABLE 5.1

Environmental impact issues	
. normal toxic emissions to air and water	
. accidental toxic emissions	. construction traffic
. waste management	. transmission lines
. waste disposal	. noise
. decommissioning	. fuel & waste traffic
. nuclear 'safeguards'	. waste heat
. size of plant	

Any important distinguishing qualities of fusion power plants are likely to centre around the fuel cycle and the radiological characteristics of the reactor so it is in these areas that we have concentrated attention. There is however one more general issue which deserves comment, namely the traffic due to transport of fuel and waste and the risk which that presents in the form of road accidents. Like a fission reactor with on-site fuel cycle facilities, or a "renewable" energy source, a fusion reactor would generate negligible traffic in fuel and waste during its operating life. Construction and decommissioning of a 1GW(e) power station would involve, however, the movement of about 25000 te of fusion reactor components, plus the steam raising and electricity generation equipment and associated buildings. In comparison with fossil-fuelled stations, however, the fusion reactor station would show overall a much reduced risk from movement of materials to and from the site.

THE RADIOACTIVE INVENTORY

5.3 Central to the potential environmental impact is the inventory of radioactive isotopes likely to be present in an operating fusion reactor. Many previous papers have pointed out that the fusion reactor has an inherent advantage over the fission reactor in that neither the primary fuel nor the reaction products are radioactive at all. The radioactive inventory arises from the intermediate fuel tritium which is produced, processed and consumed within the reactor complex, and from the capture of neutrons in structural materials. Thus less than 3 tonnes per year of lithium are consumed to produce about a hundred kg of tritium per year to fuel a 1GW(e) power station using the reactions:

$$^{6}Li + n \rightarrow {}^{3}H + {}^{4}He + 4.8\ MeV$$

$$^{7}Li + n \rightarrow {}^{3}H + {}^{4}He + n - 2.5\ MeV$$

$$^{2}H + {}^{3}H \rightarrow {}^{4}He + n + 17.6\ MeV$$

It is the safe containment of the tritium and the neutron activated materials which dominates the radiological characteristics of the fusion reactor.

5.4 The conceptual reference fusion reactor used in this study is the "EEF Reference Reactor" as defined by Hancox, Spears and Cooke [5.3]. A description of this 1200MW(e) Tokamak fusion reactor is given in Chapter 3; important features in relation to the calculation of an inventory of its radioactive material content are:

- ferritic steel construction for first wall and blanket
- 17Li 83Pb breeder with water cooling
- 4.15MW/m^2 mean neutron loading of first wall
- 25 year life, with seven replacements of first wall and blanket, and four replacements of the divertor for each first wall
- 75% load factor

TABLE 5.2

Principal constituents of first wall/blanket materials assumed for the two variants of "EEF Reference Reactor"

Element	wt%	
	(a) Ferritic Steel (FV.448)	(b) Low Activation Variant V-3Ti-1Si
B	8.0×10^{-3}	
C	1.3×10^{-1}	
N	3.0×10^{-2}	1.0×10^{-2}
O		1.0×10^{-2}
Al	1.0×10^{-3}	5.0×10^{-3}
Si	4.5×10^{-1}	1.0
K	2.0×10^{-4}	
Ca	2.0×10^{-4}	
Ti		3.0
V	2.2×10^{-1}	95.975
Cr	10.5	
Mn	3.5×10^{-1}	
Fe	86.5	
Co	1.0×10^{-3}	2.0×10^{-6}
Ni	8.7×10^{-1}	
Cu	2.0×10^{-3}	
Zr	3.0×10^{-3}	
Nb	1.5×10^{-1}	1.0×10^{-5}
Mo	7.8×10^{-1}	2.0×10^{-4}
Ag	5.0×10^{-5}	5.0×10^{-7}
Sn	1.0×10^{-3}	
Ta	1.0×10^{-3}	
W	1.0×10^{-3}	

Figure 5.1: The assumed radial build of the EEF Reference Reactor

(see also Tables 5.3 & 5.4)

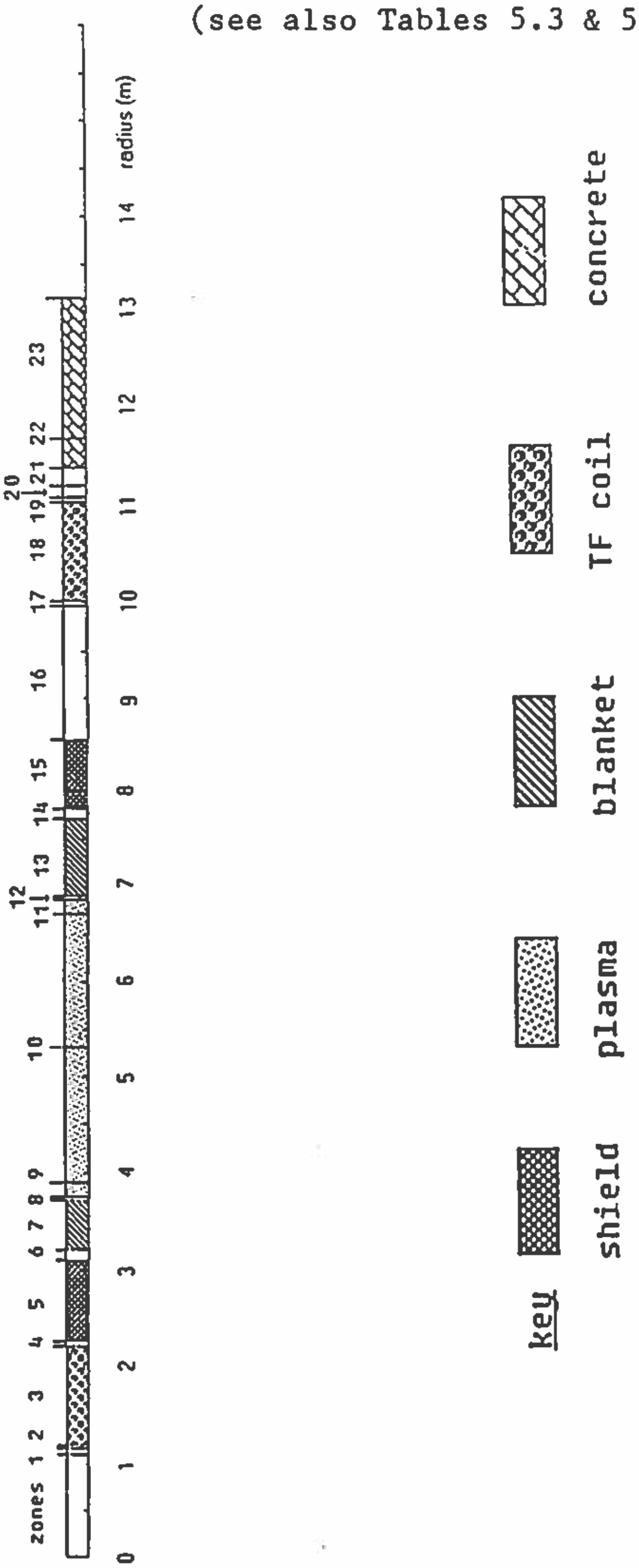

Table 5.3

The Components of EEF Reference Reactor (Ferritic Variant)

Zone	Component	Material	Mass (Tonnes)
1	Cryostat	Austenitic steel	80.58
2	PF Coil	NbTi	0.60
		Copper	33.56
		Austenitic steel	31.24
		Total	66.40
3	TF Coil	Nb,Sn	13.87
		Copper	762.72
		Austenitic steel	1216.56
		Total	1993.15
4	Cryostat	Austenitic steel	73.63
5	Shield	Austenitic steel	1605.59
		Water	54.08
		Total	1659.67
6	Gap		
7	Blanket	Ferritic steel	98.84
		Lithium lead	491.75
		Water	8.64
		Total	599.23
8	First wall	Ferritic steel	42.91
		Lead	13.38
		Water	1.18
		Total	57.47
9	Scrape-off layer		
10	Plasma		
11	Scrape-off layer		
12	First wall	Ferritic steel	66.09
		Lead	20.62
		Water	1.82
		Total	88.53
13	Blanket	Ferritic steel	267.16
		Lithium lead	1329.25
		Water	23.36
		Total	1619.77
14	Gap		
15	Shield	Austenitic steel	3174.41
		Water	106.92
		Total	3281.33
16	Empty space		
17	Cryostat	Austenitic steel	266.34
18	TF Coil	Nb,Sn	30.13
		Copper	1657.28
		Austenitic steel	2643.43
		Total	4330.85
19	Cryostat	Austenitic steel	352.82
20	PF Coil	NbTi	5.40
		Copper	299.44
		Austenitic steel	278.76
		Total	583.60
21	Gap		
22	Bio shield	Borated concrete	1102.00
23	Bio shield	Ordinary concrete	6817.60
24	Blanket flange	Ferritic steel	600.00
		Lithium lead	300.00
		Water	32.00
		Total	938.00
25	Shield flange	Austenitic steel	5640.00
		Water	190.00
		Total	5830.00
26	Torus support	Austenitic steel	1350.00
27	Divertor	Tungsten rhenium	44.00
		Water	1.00
		Total	45.00

Table 5.4

The Components of EEF Reference Reactor (Low Activation Variant)

Zone	Component	Material	Mass (Tonnes)
1	Cryostat	OPSTAB2	81.60
2	PF Coil	NbTi	0.60
		Copper	33.56
		OPSTAB2	31.64
		Total	65.80
3	TF Coil	Nb,Sn	13.87
		Copper	762.72
		OPSTAB2	1231.96
		Total	2008.55
4	Cryostat	OPSTAB2	74.56
5	Shield	HYFORM 409	1569.01
		Water	54.08
		Total	1623.09
6	Gap		
7	Blanket	V3Ti1Si	75.38
		Lithium lead	491.75
		Water	8.64
		Total	575.77
8	First wall	V3Ti1Si	32.73
		Lead	13.38
		Water	1.18
		Total	47.29
9	Scrape-off layer		
10	Plasma		
11	Scrape-off layer		
12	First wall	V3Ti1Si	50.40
		Lead	20.62
		Water	1.82
		Total	72.84
13	Blanket	V3Ti1Si	203.76
		Lithium lead	1329.25
		Water	23.36
		Total	1556.37
14	Gap		
15	Shield	HYFORM 409	3102.08
		Water	106.92
		Total	3209.00
16	Empty space		
17	Cryostat	OPSTAB2	269.71
18	TF Coil	Nb,Sn	30.13
		Copper	1657.28
		OPSTAB2	2676.89
		Total	4364.30
19	Cryostat	OPSTAB2	357.29
20	PF Coil	NbTi	5.40
		Copper	299.44
		OPSTAB2	282.29
		Total	587.13
21	Gap		
22	Bio shield	Borated concrete	1102.00
23	Bio shield	Ordinary concrete	6817.60
24	Blanket flange	V3Ti1Si	457.60
		Lithium lead	300.00
		Water	32.00
		Total	795.60
25	Shield flange	HYFORM 409	5511.49
		Water	190.00
		Total	5701.49
26	Torus support	OPSTAB2	1367.09
27	Divertor	Tungsten rhenium	44.00
		Water	1.00
		Total	45.00

In order to examine the effect of using a low activation vanadium alloy for the first wall and blanket structure the inventory calculation was repeated for the EEF Reference Reactor with that material. Table 5.2 lists the major elements assumed to be present in the materials for first wall and blanket used in the two variants. For the purpose of inventory calculations a much more comprehensive analysis of the compositions of all major reactor components, including minor impurities, was used and can be found in Sowerby et al [5.18]

5.5 Figure 5.1 shows a schematic diagram of the radial build of the EEF Reference Reactor to illustrate the components, assumed to be exposed to the neutron flux in a cylindrical approximation of the two variants. Some parts of the reactor (zones 24-27 cannot be dealt with in this way and additional assumptions have to be made. Tables 5.3 and 5.4 give mass and composition data for all these components. Neutron fluxes and their energy spectra were calculated and the resultant inventory of neutron interaction products obtained using the code FISPACT [5.16]. The principal applications for this inventory are in the estimation of the consequences of accidents to an operating reactor, the significance of liquid and gaseous discharges during normal operation and the cost and risks from the management and disposal of solid radioactive wastes arising during decommissioning.

The calculation of complete radioactive isotope inventories for the materials in every zone of the two reference reactor variants, together with the important derived parameters of thermal power, ingestion toxic content, inhalation toxic content and surface dose-rate, required a formidable data handling exercise and produced correspondingly voluminous output. The results are assembled quite fully by Sowerby et al [5.18] so that the reader may easily identify the important contributing isotopes for particular parameters at any given decay time. In the present overview we present only summary data, although the importance of some activation products in particular zones will be referred to in our conclusions.

"Toxic content" of an inventory [5.18] is simply a crude measure of potential to cause radiation dose to Man by inhalation or ingestion. It is calculated directlv from the Committed Effective Dose Equivalent (CEDE) data (Man.Sv/Bq) for each constituent nuclide by multiplying the CEDE for each particular constituent by the Bq present. Toxic content is not a measure of actual dose to Man since it ignores all pathway effects.

"Dose-rate" is an estimate of gamma dose-rate at the surface of an infinite slab of the material in question [5.18].

In Tables 5.5 and 5.6 the activities, thermal powers, toxic content and surface dose-rates of the zones and components of each reactor variant are given for times 0.01, 10 and 100 years after final shutdown. Note that these totals include all replaceable components discharged during the life of the reactor and assumed to be in store at the reactor. The tritium inventory of the reactors is not included in these Tables except insofar as tritium is generated in the structural materials themselves. This is because the main tritium inventory, generated from lithium, will not be a waste product and is discussed in para.5.7. Figures 5.2 to 5.11 present these results in graphical form. Figures 5.3 and 5.8, for example, show that the tungsten-rhenium divertor (which is represented as zone 27 in our cylindrical approximation to the EEF Reference Reactor), dominates the thermal decay power of both reactor variants for several weeks after final shutdown.

5.6 The inventory calculations presented here are necessarily based upon a very simplified conceptual design of fusion reactor. The volumes of components, and the activities associated with them, might vary considerably from any eventual engineering design. However, the qualitative features of results from the present work will be of value in identifying important properties of the radioactive inventory of fusion reactor components.

Sowerby et al [5.18] have examined the results of the inventory calculation to identify nuclides which appear to dominate the radioactivity or toxic content. In the EEF reference (ferritic) concept, ^{55}Fe, ^{54}Mn, ^{56}Mn, ^{60}Co and ^{51}Cr are important. Most of the activity, and of the toxic content, is found in the shield, blanket and first wall. The divertor inventory of ^{187}W and ^{188}W is an important contributor at short decay times. In the low activation variant the shield, blanket, first wall and divertor again dominate the radioactivity and toxic content. ^{49}V, ^{52}V and ^{46}Sc are important in addition to ^{55}Fe, ^{60}Co, ^{187}W, ^{188}W and ^{188}Re. At short cooling times the ^{210}Po generated in the lead-lithium blanket and the ^{108m}Ag in the blanket are very large contributors to system toxic content. In neither reference reactor do the impurities in structural metals appear to dominate the situation, although Co in the shield becomes important after ten years decay.

The tritium inventory at the EEF Fusion Reactor site

5.7 It was noted in para.5.3 that about 100kg of tritium would be burned in the 1GW(e) reactor each year, assuming a 75% load factor. This fuel would be produced in the blanket and processed continuously, so that the actual inventory of tritium on site at any time would be considerably smaller. Watson et al [5.24] give estimates for tritium inventory in a 1GW(e) station based on a stainless steel-lithium-helium cooled Tokamak which can reasonably be assumed to apply to the present EEF reference concept. These data are represented in Table 5.7 together with the additional tritium generated in structural materials from neutron interactions in the EEF reference concept, calculated as at ten years after final shutdown of the reactor.

Table 5.5

Summary Inventory Data for EEF Reference Reactor (Ferritic)
1200 MW(e)

Zone	Mass (t)	Activity (Bq/kg) 1.00E-02	1.00E+01	1.00E+02	Power (kW/kg) 1.00E-02	1.00E+01	1.00E+02
1	8.06E+01	4.58E+01	3.99E+00	7.43E-01	5.13E-16	4.74E-17	8.52E-18
2	6.54E+01	6.60E+01	5.69E+00	1.10E+00	1.70E-15	5.50E-17	4.25E-17
3	1.99E+03	1.07E+06	1.05E+05	2.54E+04	4.21E-11	2.98E-12	2.14E-13
4	7.36E+01	3.41E+07	2.39E+06	3.00E+05	9.86E-10	3.52E-11	8.39E-13
5a	1.61E+03	1.32E+12	9.08E+10	1.09E+10	3.82E-05	1.39E-06	3.03E-08
5b	5.41E+01	1.30E+06	1.26E+06	1.19E+06	9.59E-12	9.61E-12	9.45E-12
7a	1.07E+02	1.23E+13	7.51E+11	2.64E+09	2.12E-04	3.09E-06	4.94E-08
7b	4.92E+02	4.12E+11	1.33E+11	8.37E+08	3.95E-06	1.89E-07	3.22E-08
8	5.75E+01	8.74E+13	5.39E+12	1.98E+10	1.26E-03	2.03E-05	1.48E-07
12	8.85E+01	1.16E+14	7.18E+12	2.23E+10	1.68E-03	2.56E-05	1.62E-07
13a	2.91E+02	1.03E+13	6.31E+11	2.02E+09	1.75E-04	2.39E-06	3.71E-08
13b	1.33E+03	2.97E+11	1.01E+11	6.66E+08	3.31E-06	1.41E-07	2.50E-08
15a	3.17E+03	1.92E+11	1.36E+10	1.76E+09	4.93E-06	1.86E-07	4.91E-09
15b	1.07E+02	1.89E+05	1.82E+05	1.72E+05	1.39E-12	1.38E-12	1.36E-12
17	2.66E+02	1.31E+07	9.20E+05	1.14E+05	3.74E-10	1.32E-11	3.19E-13
18	4.33E+03	3.27E+05	3.33E+04	7.80E+03	1.27E-11	9.04E-13	7.06E-14
19	3.53E+02	9.04E+01	7.78E+00	1.33E+00	9.39E-16	8.54E-17	1.02E-17
20	5.84E+02	1.88E+01	1.62E+00	3.24E-01	5.57E-16	2.81E-17	1.22E-17
22	1.10E+03	4.33E+02	4.33E+02	4.33E+02	4.71E-14	4.71E-14	4.71E-14
23	6.82E+03	9.28E+01	9.28E+01	9.28E+01	1.01E-14	1.01E-14	1.01E-14
24a	6.32E+02	8.49E+12	4.65E+11	1.67E+09	1.41E-04	1.96E-06	3.08E-08
24b	3.06E+02	2.15E+11	7.56E+10	5.17E+08	2.64E-06	1.05E-07	2.00E-08
25a	5.64E+03	1.54E+11	1.10E+10	1.41E+09	3.94E-06	1.49E-07	3.92E-09
25b	1.90E+02	1.51E+05	1.45E+05	1.37E+05	1.11E-12	1.10E-12	1.09E-12
26	1.35E+03	3.52E+01	3.09E+00	5.75E-01	3.35E-16	3.48E-17	8.02E-18
27a	4.10E+01	3.98E+14	9.39E+10	2.70E+10	2.22E-02	2.52E-06	2.79E-07
27b	4.00E+00	3.98E+14	2.32E+09	3.04E+07	2.22E-02	5.51E-07	1.40E-09

Component	Mass (t)	Activity (Bq/kg) 1.00E-02	1.00E+01	1.00E+02	Power (kW/kg) 1.00E-02	1.00E+01	1.00E+02
Cryostats	7.73E+02	7.76E+06	5.44E+05	6.78E+04	2.23E-10	7.91E-12	1.90E-13
PF Coils	6.49E+02	2.36E+01	2.03E+00	4.02E-01	6.71E-16	3.48E-17	1.52E-17
TF Coils	6.32E+03	5.61E+05	5.72E+04	1.33E+04	2.19E-11	1.56E-12	1.16E-13
Shield	1.08E+04	3.34E+11	2.34E+10	2.88E+09	9.21E-06	3.40E-07	8.02E-09
Blanket	3.16E+03	3.27E+12	2.47E+11	1.07E+09	5.39E-05	8.16E-07	2.88E-08
First Wall	1.46E+02	1.05E+14	6.48E+12	2.13E+10	1.52E-03	2.35E-05	1.56E-07
Concrete	7.92E+03	1.40E+02	1.40E+02	1.40E+02	1.52E-14	1.52E-14	1.52E-14
Divertor	4.50E+01	3.98E+14	8.57E+10	2.46E+10	2.22E-02	2.35E-06	2.54E-07
Torus Support	1.35E+03	3.52E+01	3.09E+00	5.75E-01	3.35E-16	3.48E-17	8.02E-18
Total	3.11E+04	1.51E+12	6.37E+10	1.24E+09	4.79E-05	3.14E-07	6.79E-09

Component	Mass (t)	Activity (Bq) 1.00E-02	1.00E+01	1.00E+02	Power (kW) 1.00E-02	1.00E+01	1.00E+02
Cryostats	7.73E+02	6.00E+12	4.21E+11	5.25E+10	1.72E-04	6.11E-06	1.47E-07
PF Coils	6.49E+02	1.53E+07	1.32E+06	2.61E+05	4.36E-10	2.26E-11	9.89E-12
TF Coils	6.32E+03	3.55E+12	3.61E+11	8.44E+10	1.39E-04	9.87E-06	7.33E-07
Shield	1.32E+04	3.60E+18	2.52E+17	3.10E+16	9.92E+01	3.66E+00	8.64E-02
Blanket	1.04E+04	7.80E+19	4.69E+18	1.68E+16	1.31E+03	1.84E+01	3.40E-01
First Wall	1.17E+03	1.22E+20	7.57E+18	2.49E+16	1.77E+03	2.75E+01	1.83E-01
Concrete	7.92E+03	1.11E+09	1.11E+09	1.11E+09	1.21E-07	1.21E-07	1.21E-07
Divertor	4.88E+02	1.94E+20	3.12E+16	8.86E+15	1.09E+04	9.16E-01	9.16E-02
Torus Support	1.35E+03	4.75E+07	4.17E+06	7.76E+05	4.52E-10	4.70E-11	1.08E-11
Total	4.23E+04	3.98E+20	1.25E+19	8.17E+16	1.40E+04	5.05E+01	7.00E-01

Percentages for total amounts

Component	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
Cryostats	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
PF Coils	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TF Coils	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Shield	0.90%	2.01%	38.01%	0.71%	7.25%	12.34%
Blanket	19.60%	37.38%	20.63%	9.34%	36.40%	48.50%
First Wall	30.74%	60.36%	30.52%	12.61%	54.46%	26.09%
Concrete	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Divertor	48.75%	0.25%	10.85%	77.34%	1.81%	13.08%
Torus Support	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	100.00%	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

Table 5.5 (Continued)

Dose rate (Sv/h)			Ingestion (Sv/kg)			Inhalation (Sv/kg)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
7.13E-10	6.26E-11	2.97E-12	1.40E-08	4.51E-09	3.43E-09	1.23E-06	1.19E-06	1.10E-06
2.54E-09	1.31E-10	5.32E-11	2.37E-08	4.81E-09	3.36E-09	6.73E-07	5.87E-07	5.70E-07
6.35E-05	4.67E-06	1.97E-07	1.05E-03	6.87E-05	9.75E-06	2.57E-03	4.46E-04	8.52E-05
1.46E-03	5.44E-05	1.16E-08	3.26E-02	9.06E-04	5.15E-05	5.37E-02	5.41E-03	5.92E-04
5.63E+01	2.15E+00	3.82E-04	1.20E+03	3.52E+01	1.86E+00	2.09E+03	2.10E+02	2.12E+01
0.00E+00	0.00E+00	0.00E+00	6.78E-04	6.76E-04	6.70E-04	6.78E-04	6.77E-04	6.70E-04
3.02E+02	3.96E+00	5.76E-02	3.99E+03	1.61E+02	3.39E+00	1.09E+04	7.74E+02	2.13E+01
2.02E+00	6.63E-02	2.94E-02	3.22E+03	2.67E+01	2.31E-01	1.55E+04	2.96E+01	4.33E+00
1.67E+03	2.48E+01	1.17E-01	2.45E+04	1.12E+03	9.25E+00	7.28E+04	5.33E+03	6.98E+01
2.25E+03	3.07E+01	1.25E-01	3.25E+04	1.46E+03	1.00E+01	9.65E+04	6.94E+03	7.59E+01
2.73E+02	2.98E+00	4.32E-02	3.29E+03	1.31E+02	2.54E+00	9.03E+03	6.30E+02	1.59E+01
1.79E+00	5.92E-02	2.23E-02	1.84E+03	1.71E+01	1.84E-01	8.67E+03	1.99E+01	3.72E+00
7.23E+00	2.85E-01	6.14E-05	1.62E+02	4.94E+00	3.02E-01	2.84E+02	2.96E+01	3.43E+00
0.00E+00	0.00E+00	0.00E+00	9.74E-05	9.72E-05	9.63E-05	9.74E-05	9.72E-05	9.63E-05
5.52E-04	2.04E-05	4.64E-09	1.23E-02	3.44E-04	1.95E-05	2.05E-02	2.05E-03	2.27E-04
1.91E-05	1.41E-06	6.71E-08	3.14E-04	2.10E-05	3.25E-06	7.77E-04	1.38E-04	2.81E-05
1.30E-09	1.18E-10	3.00E-12	2.38E-08	5.66E-09	3.55E-09	1.28E-06	1.20E-06	1.19E-06
8.36E-10	3.70E-11	1.31E-11	8.23E-09	2.38E-09	1.96E-09	5.98E-07	5.71E-07	5.68E-07
1.93E-08	1.93E-08	1.93E-08	2.21E-06	2.21E-06	2.21E-06	1.49E-07	1.48E-07	1.47E-07
4.11E-09	4.11E-09	4.11E-09	4.73E-07	4.73E-07	4.73E-07	3.15E-08	3.15E-08	3.15E-08
2.03E+02	2.45E+00	3.61E-02	2.71E+03	1.08E+02	2.11E+00	7.45E+03	5.18E+02	1.32E+01
1.55E+00	4.15E-02	1.75E-02	1.21E+03	1.13E+01	1.51E-01	5.70E+03	1.43E+01	3.26E+00
5.77E+00	2.27E-01	4.91E-05	1.30E+02	3.94E+00	2.41E-01	2.26E+02	2.36E+01	2.74E+00
0.00E+00	0.00E+00	0.00E+00	7.77E-05	7.74E-05	7.68E-05	7.77E-05	7.76E-05	7.68E-05
4.49E-10	4.35E-11	2.96E-12	1.10E-08	4.18E-09	3.39E-09	1.22E-06	1.19E-06	1.18E-06
5.65E+03	3.57E+00	1.07E-01	2.57E+05	4.17E+01	2.97E+00	6.14E+05	2.43E+02	1.25E+01
5.65E+03	8.57E-01	2.64E-05	2.57E+05	9.21E+00	3.20E-02	6.14E+05	5.52E+01	2.20E-01

Dose rate (Sv/h)			Ingestion (Sv/kg)			Inhalation (Sv/kg)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
3.29E-04	1.22E-05	2.70E-09	7.34E-03	2.05E-04	1.18E-05	1.22E-02	1.22E-03	1.35E-04
1.01E-09	4.65E-11	1.72E-11	9.78E-09	2.63E-09	2.10E-09	6.05E-07	5.72E-07	5.69E-07
3.31E-05	2.44E-06	1.08E-07	5.46E-04	3.61E-05	5.31E-06	1.34E-03	2.36E-04	4.61E-05
1.35E+01	5.24E-01	1.01E-04	3.06E+02	8.77E+00	4.92E-01	5.13E+02	5.24E+01	5.60E+00
7.72E+01	9.41E-01	2.88E-02	2.37E+03	5.16E+01	8.99E-01	9.31E+03	2.02E+02	7.39E+00
2.02E+03	2.84E+01	1.22E-01	2.93E+04	1.33E+03	9.73E+00	8.72E+04	6.30E+03	7.35E+01
6.23E-09	6.22E-09	6.22E-09	7.15E-07	7.15E-07	7.15E-07	4.79E-08	4.77E-08	4.76E-08
5.65E+03	3.33E+00	9.78E-02	2.57E+05	3.88E+01	2.71E+00	6.14E+05	2.27E+02	1.14E+01
4.49E-10	4.35E-11	2.96E-12	1.10E-08	4.18E-09	3.39E-09	1.22E-06	1.19E-06	1.18E-06
3.01E+01	4.15E-01	3.67E-03	8.56E+02	1.45E+01	3.11E-01	2.42E+03	6.85E+01	3.05E+00

Dose rate (Sv/h)			Ingestion (Sv)			Inhalation (Sv)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
3.29E-04	1.22E-05	2.70E-09	5.68E+03	1.58E+02	9.12E+00	9.41E+03	9.46E+02	1.05E+02
1.01E-09	4.65E-11	1.72E-11	6.35E-03	1.70E-03	1.37E-03	3.93E-01	3.72E-01	3.69E-01
3.31E-05	2.44E-06	1.08E-07	3.45E+03	2.28E+02	3.36E+01	8.48E+03	1.49E+03	2.92E+02
1.10E+01	4.27E-01	8.20E-05	3.29E+09	9.44E+07	5.30E+06	5.53E+09	5.64E+08	6.04E+07
1.85E+02	2.20E+00	3.68E-02	2.92E+10	1.03E+09	1.99E+07	8.89E+10	4.79E+09	1.30E+08
2.02E+03	2.84E+01	1.22E-01	3.43E+10	1.55E+09	1.14E+07	1.02E+11	7.36E+09	8.58E+07
6.23E-09	6.22E-09	6.22E-09	5.66E+00	5.66E+00	5.66E+00	3.79E-01	3.78E-01	3.77E-01
5.65E+03	2.68E+00	7.21E-02	1.26E+11	1.52E+07	9.80E+05	3.00E+11	8.86E+07	4.14E+06
4.49E-10	4.35E-11	2.96E-12	1.48E-02	5.64E-03	4.58E-03	1.65E+00	1.60E+00	1.60E+00
7.87E+03	3.37E+01	2.31E-01	1.92E+11	2.69E+09	3.75E+07	4.96E+11	1.28E+10	2.81E+08

1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.14%	1.27%	0.04%	1.71%	3.51%	14.14%	1.11%	4.41%	21.51%
2.36%	6.54%	15.95%	15.17%	38.31%	52.96%	17.93%	37.42%	46.41%
25.66%	84.25%	52.79%	17.81%	57.61%	30.30%	20.54%	57.48%	30.60%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
71.84%	7.95%	31.22%	65.30%	0.56%	2.61%	60.41%	0.69%	1.40%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

Table 5.6

Summary Inventory Data for EEF Reference Reactor (Low Activation), 1200 MW(e)

		Activity (Bq/kg)			Power (kW/kg)		
Zone	Mass (t)	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
1	8.16E+01	4.10E+02	3.04E+00	1.32E-01	7.56E-14	1.32E-17	6.81E-18
2	6.58E+01	6.21E+02	6.01E+00	4.12E-01	1.17E-13	8.79E-17	6.55E-17
3	2.01E+03	8.21E+06	2.10E+05	4.26E+04	1.44E-09	5.34E-12	4.00E-13
4	7.46E+01	3.09E+08	4.32E+06	1.28E+04	5.55E-08	7.08E-12	1.02E-13
5a	1.57E+03	3.02E+12	1.85E+11	7.66E+08	2.70E-05	3.87E-07	2.93E-05
5b	5.41E+01	2.57E+06	2.37E+06	2.11E+06	1.72E-11	1.70E-11	1.67E-11
7a	8.44E+01	3.59E+11	5.89E+07	2.43E+07	1.04E-04	2.75E-09	1.98E-10
7b	4.92E-02	4.68E+11	1.43E+11	8.73E+08	4.52E-06	2.08E-07	3.55E-08
8	4.73E+01	3.63E+12	5.73E+09	1.58E+08	6.51E-04	2.76E-06	8.15E-09
12	7.28E+01	5.32E+12	6.23E+09	1.90E+08	6.97E-04	3.67E+08	1.01E-08
13a	2.27E-02	3.06E+11	4.73E+07	1.89E+07	8.92E-05	2.02E-09	1.54E-10
13b	1.33E+03	3.40E+11	1.10E+11	7.06E+08	3.78E-06	1.56E-07	2.77E-08
15a	3.10E+03	4.89E+11	3.05E+10	1.32E+08	3.27E-06	4.76E-08	4.74E-10
15b	1.07E+02	4.10E+05	3.60E+05	3.39E+05	2.76E-12	2.73E-12	2.68E-12
17	2.70E+02	1.20E+08	1.70E+06	5.40E+03	2.13E-08	2.93E-12	4.29E-14
18	4.36E+03	2.65E+06	6.90E+04	1.36E+04	4.58E-10	1.67E-12	1.37E-13
19	3.57E+02	8.42E+02	6.60E+00	1.36E-01	1.62E-13	2.08E-17	6.85E-18
20	5.87E+02	1.85E+02	1.74E+00	1.42E-01	3.61E-14	2.47E-17	1.82E-17
22	1.10E+03	4.34E+02	4.33E+02	4.33E+02	4.71E-14	4.71E-14	4.71E-14
23	6.82E+03	9.28E+01	9.28E+01	9.28E+01	1.01E-14	1.01E-14	1.01E-14
24a	.4.90E+02	2.51E+11	3.57E+07	1.28E+07	7.41E-05	1.66E-09	1.05E-10
24b	3.06E+02	2.45E+11	8.18E+10	5.49E+08	2.99E-06	1.15E-07	2.20E-08
25a	5.51E+03	3.90E+11	2.44E+10	1.05E+08	2.60E-06	3.74E-08	3.79E-10
25b	1.90E+02	3.27E+05	3.03E+05	2.70E+05	2.20E-12	2.18E-12	2.14E-12
26	1.37E+03	3.61E+02	3.19E+00	1.31E-01	7.02E-14	1.30E-17	6.81E-18
27a	4.10E+01	4.43E+14	1.30E+11	3.80E+10	2.46E-02	2.78E-06	3.78E-07
27b	4.00E+00	4.43E+14	2.43E+09	3.09E+07	2.46E-02	5.90E-07	1.43E-09

		Activity (Bq/kg)			Power (kW/kg)		
Component	Mass (t)	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
Cryostats	7.83E+02	7.07E+07	9.97E+05	3.08E+03	1.26E-08	1.68E-12	2.45E-14
PF Coils	6.53E+02	2.29E+02	2.17E+00	1.69E-01	4.43E-14	3.11E-17	2.30E-17
TF Coils	6.37E+03	4.40E+06	1.13E+05	2.27E+04	7.69E-10	2.82E-12	2.22E-13
Shield	1.05E+04	7.98E+11	4.99E+10	2.08E+08	5.60E-06	9.13E-08	7.75E-10
Blanket	2.93E+03	3.35E+11	8.25E+10	5.29E+08	2.51E-05	1.18E-07	2.09E-08
First Wall	1.20E+02	4.66E+12	7.24E+09	1.77E+08	7.97E-04	3.31E-08	9.32E-09
Concrete	7.92E+03	1.40E+02	1.40E+02	1.40E+02	1.52E-14	1.52E-14	1.52E-14
Divertor	4.50E+01	4.43E+14	1.19E+11	3.46E+10	2.46E-02	2.58E-06	3.44E-07
Torus Support	1.37E+03	3.61E+02	3.19E+00	1.31E-01	7.02E-14	1.30E-17	6.81E-18
Total	3.07E+04	9.72E+11	2.52E+10	1.73E+08	4.34E-05	4.65E-08	2.80E-09

		Activity (Bq)			Power (kW)		
Component	Mass (t)	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
Cryostats	7.83E+02	5.54E+13	7.81E+11	2.41E+09	9.88E-03	1.32E-06	1.92E-08
PF Coils	6.53E+02	1.49E+08	1.42E+06	1.10E+05	2.89E-08	2.03E-11	1.50E-11
TF Coils	6.37E+03	2.81E+13	7.23E+11	1.45E+11	4.90E-03	1.80E-05	1.42E-06
Shield	1.30E+04	8.40E+18	5.26E+17	2.19E+15	5.89E+01	9.61E-01	8.18E-03
Blanket	8.54E+03	2.54E+18	2.42E+17	1.64E+15	5.30E+02	3.57E-01	6.18E-02
First Wall	9.61E+02	4.47E+18	6.96E+15	1.70E+14	7.66E+02	3.18E-02	8.95E-03
Concrete	7.92E+03	1.11E+09	1.11E+09	1.11E+09	1.21E-07	1.21E-07	1.21E-07
Divertor	4.88E+02	2.16E+20	4.32E+16	1.25E+16	1.20E+04	1.01E+00	1.24E-01
Torus Support	1.37E+03	4.94E+08	4.36E+06	1.79E+05	9.59E-08	1.77E-11	9.31E-12
Total	4.01E+04	2.31E+20	8.18E+17	1.65E+16	1.34E+04	2.36E+00	2.03E-01

	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
Percentages for total amounts	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	3.63%	64.29%	13.34%	0.44%	40.81%	4.02%
	1.10%	29.58%	9.95%	3.97%	15.15%	30.44%
	1.93%	0.85%	1.04%	5.74%	1.35%	4.41%
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	93.34%	5.28%	75.68%	89.85%	42.69%	61.13%
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	100.00%	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

Table 5.6 (Continued)

Dose rate (Sv/h)			Ingestion (Sv/kg)			Inhalation (Sv/kg)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
1.10E-07	9.08E-12	2.97E-12	5.52E-07	3.03E-09	3.31E-09	4.45E-06	1.19E-06	1.18E-06
1.62E-07	1.13E-10	8.84E-11	8.14E-07	5.75E-09	4.53E-09	5.40E-06	5.95E-07	5.87E-07
2.02E-03	8.27E-06	3.91E-07	1.01E-02	1.29E-04	1.86E-05	6.01E-02	8.29E-04	1.50E-04
7.70E-02	4.90E-06	4.13E-10	3.70E-01	7.36E-04	7.12E-06	2.27E+00	3.32E-03	8.97E-06
2.94E+01	3.47E-01	6.86E-06	5.41E+02	3.30E-01	1.10E-01	2.09E+03	1.55E-02	1.25E+00
0.00E+00	0.00E+00	0.00E+00	1.19E-03	1.19E-03	1.18E-03	1.20E-03	1.19E-03	1.18E-03
1.60E+02	3.60E-03	7.23E-06	3.75E+02	5.65E-02	1.37E-02	4.25E+02	2.56E-01	1.60E-02
2.21E+00	1.02E-01	3.27E-02	3.60E+03	3.26E+01	2.51E+01	1.72E+04	3.52E+01	4.50E+00
9.38E+02	3.11E-02	8,17E-03	2.60E+03	4.81E+00	1.16E-01	3.45E+03	6.26E+00	1.21E+00
1.28E+03	4.08E-02	1.02E-02	3.55E+03	6.75E+00	1.38E-01	4.61E+03	7.94E+00	1.30E+00
1.38E+02	3.10E-03	5.47E-06	3.22E+02	4.19E-02	1.07E-02	3.65E+02	1.55E-01	1.24E-02
1.96E+00	6.98E-02	2.50E-02	2.10E+03	2.11E+01	2.01E-01	9.85E+03	2.37E+01	3.93E+00
4.29E+00	3.08E-02	2.11E-06	8.49E+01	5.17E+00	1.90E-02	3.29E+02	2.36E+01	2.16E-01
0.00E+00	0.00E+00	0.00E+00	1.92E-04	1.91E-04	1.89E-04	1.92E-04	1.91E-04	1.89E-04
2.95E-02	2.18E-06	1.76E-10	1.45E-01	2.93E-04	3.00E-06	8.69E-01	1.32E-03	4.46E-06
6.39E-04	2.57E-06	1.34E-07	3.22E-03	4.11E-05	6.31E-06	1.91E-02	2.64E-04	5.03E-05
2.23E-07	1.64E-11	2.97E-12	1.12E-06	4.46E-09	3.31E-09	7.84E-06	1.19E-06	1.18E-06
5.01E-08	2.98E-11	2.23E-11	2.50E-07	2.60E-09	2.28E-09	2.06E-06	5.75E-07	5.73E-07
1.94E-08	1.93E-08	1.93E-08	2.21E-06	2.21E-06	2.21E-06	1.52E-07	1.49E-07	1.47E-07
4.11E-09	4.11E-09	4.11E-09	4.73E-07	4.73E-07	4.73E-07	3.16E-08	3.16E-08	3.15E-08
1.16E+02	2.62E-03	4.58E-06	2.68E+02	3.34E-02	7.25E-03	3.03E+02	1.62E-01	8.65E-03
1.67E+00	4.80E-02	1.94E-02	1.39E+03	1.40E+01	1.64E-01	6.48E+03	1.69E+01	3.47E+00
3.42E+00	2.37E-02	1.79E-06	6.77E+01	4.12E+00	1.52E-02	2.62E+02	1.88E+01	1.72E-01
0.00E+00	0.00E+00	0.00E+00	1.53E-04	1.52E-04	1.51E-04	1.53E-04	1.52E-04	1.51E-04
9.66E-08	8.52E-12	2.97E-12	4.84E-07	3.85E-09	3.31E-09	4.07E-06	1.19E-06	1.18E-06
6.44E+03	3.82E+00	1.49E-01	2.89E+05	4.58E+01	3.95E+00	7.05E+05	2.68E+02	1.62E+01
6.44E+03	9.18E-01	2.95E-05	2.89E+05	9.86E+00	3.26E-02	7.05E+05	5.91E+01	2.24E-01

Dose rate (Sv/h)			Ingestion (Sv/kg)			Inhalation (Sv/kg)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
1.75E-02	1.22E-06	1.02E-10	8.59E-02	1.71E-04	1.71E-06	5.15E-01	7.71E-04	3.05E-06
6.14E-08	3.82E-11	2.90E-11	3.07E-07	2.92E-09	2.52E-09	2.39E-06	5.77E-07	5.75E-07
1.07E-03	4.37E-06	2.15E-07	5.39E-03	6.88E-05	1.02E-05	3.20E-02	4.42E-04	8.18E-05
7.43E+00	7.32E-02	2.58E-06	1.41E+02	8.68E+00	2.99E-02	5.45E+02	4.00E+01	3.40E-01
3.61E+01	5.46E-02	1.89E-02	1.78E+03	1.65E+01	1.53E-01	8.13E+03	1.85E+01	2.91E+00
1.15E+03	3.70E-02	9.42E-03	3.17E+03	5.98E+00	1.29E-01	4.15E+03	7.29E+00	1.26E+00
6.23E-09	6.22E-09	6.22E-09	7.15E-07	7.15E-07	7.15E-07	4.83E-08	4.79E-08	4.76E-08
6.44E+03	3.56E+00	1.35E-01	2.89E+05	4.26E+01	3.60E+00	7.05E+05	2.49E+02	1.48E+01
9.66E-08	8.52E-12	2.97E-12	4.84E-07	3.85E-09	3.31E-09	4.07E-06	1.19E-06	1.18E-06
1.99E+01	3.57E-02	2.03E-03	6.53E+02	4.64E+00	3.07E-02	2.01E+03	1.59E+01	4.20E-01

Dose rate (Sv/h)			Ingestion (Sv)			Inhalation (Sv)		
1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
1.75E-02	1.22E-06	1.02E-10	6.73E+04	1.34E+02	1.34E+00	4.03E+05	6.04E+02	2.39E+00
6.14E-08	3.82E-11	2.90E-11	2.00E-01	1.91E-03	1.65E-03	1.56E+00	3.77E-01	3.75E-01
1.07E-03	4.37E-06	2.15E-07	3.43E+04	4.39E+02	6.50E+01	2.04E+05	2.82E+03	5.21E+02
6.03E+00	5.93E-02	2.09E-06	1.49E+09	9.15E+07	3.16E+05	5.74E+09	4.21E+08	3.58E+06
9.56E+01	2.06E-02	6.47E-03	6.87E+09	4.86E+07	4.98E+05	2.57E+10	5.51E+07	8.57E+06
1.15E+03	3.70E-02	9.42E-03	3.05E+09	5.75E+06	1.24E+05	3.99E+09	7.00E+06	1.21E+06
6.23E-09	6.22E-09	6.22E-09	5.66E+00	5.66E+00	5.66E+00	3.83E-01	3.79E-01	3.77E-01
6.44E+03	2.87E+00	9.99E-02	1.41E+11	1.66E+07	1.30E+06	3.44E+11	9.73E+07	5.35E+06
9.66E-08	8.52E-12	2.97E-12	6.62E-01	5.27E-03	4.53E-03	5.56E+00	1.62E+00	1.62E+00
7.68E+03	2.99E+00	1.16E-01	1.52E+11	1.62E+08	2.24E+06	3.79E+11	5.80E+08	1.87E+07

1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02	1.00E-02	1.00E+01	1.00E+02
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.08%	1.99%	0.00%	0.90%	56.31%	14.11%	1.51%	72.52%	19.14%
1.24%	0.69%	5.59%	4.51%	29.93%	22.25%	6.77%	9.50%	45.79%
14.93%	1.24%	8.14%	2.00%	3.54%	5.55%	1.05%	1.21%	6.49%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
83.75%	96.08%	86.27%	92.51%	10.22%	58.09%	90.67%	16.77%	28.58%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

TABLE 5.7

Tritium Inventory of a 1GW(e) Tokamak Site
Based on a SS-Li-He Reactor

Location	Tritium Inventory	
	TBq	g
Storage Vacuum pumps Fueler Fuel purification Blanket Blanket processing	6.8×10^5 8.9×10^4 2.9×10^4 1.1×10^5 5.7×10^5 1.6×10^5	1900 250 80 300 1600 450
TOTAL - Fuel cycle	1.6×10^6	4580
Structural Materials: (a) EEF Ferritic (b) EEF Vanadium	 1.2×10^4 8.9×10^4	 34 250

Comparison of operating radioactive inventory with other power plants.

5.8 The radioactive and toxic chemical inventory of a coal-fired power plant does not accumulate on the site like the fission products and activated structural materials in a nuclear reactor. Instead, the waste materials are dispersed, largely to sea and air, as they arise. In the context of potential operating hazards therefore we should compare the Fusion Reactor with a PWR. Figures 5.12 to 5.15 illustrate the activity, thermal decay power and toxic content obtained in calculations based on a 1GW(e)PWR operated for 25 years at 75% load factor. The calculations sum all fuel, fission product and activation products existing at final shut down, including discharged fuel and all decommissioning wastes. Sowerby et al [5.18] give details of the approximations made in reaching the results. The figures compare the PWR results with the results given earlier for the two variants of the EEF Reference Reactor. In the important areas of toxic content and external dose-rate it is clear that the fusion reactor offers large advantages over the PWR soon after shutdown and that this difference increases with time over the 100 year span considered. Note however that tritium fuel is not included in these comparisons. The additional increments of activity, thermal power and toxic content corresponding to a site inventory of 5kg tritium are shown separately in figures 5.12 to 5.15

The potential for harmful environmental impact can be seen in Figures 5.12 to 5.15 to be significantly lower for a 1 GWe fusion reactor than for a PWR of similar output. The key inventory results are summarised in Table 5.8

TABLE 5.8

Comparison of total* radioactive inventory results for fission and fusion reactors of 1 GWe

* the tritium in the fusion fuel cycle is not included; it would comprise an additional 1.6 x 10^6 TBq at shutdown.

System	Parameter	Time after shutdown (Years)		
		0.01	10	100
EEF (ferritic)	radioactivity (Bq)	3.32 E20	1.04 E19	6.81 E16
EEF (low act.)		1.93 E20	6.82 E17	1.38 E16
PWR		6.64 E20	9.62 E18	9.98 E17
EEF (ferritic)	decay power (kW)	1.17 E4	4.21 E1	5.83 E-1
EEF (low act.)		1.12 E4	1.97 E0	1.69 E-1
PWR		7.12 E4	7.39 E2	1.92 E2
EEF (ferritic)	ingestion toxic content (Sv)	1.60 E11	2.24 E9	3.13 E7
EEF (low act.)		1.27 E11	1.35 E8	1.87 E6
PWR		3.69 E11	2.11 E11	1.42 E11
EEF (ferritic)	inhalation toxic content (Sv)	4.13 E11	1.07 E10	2.34 E8
EEF (low act.)		3.16 E11	4.83 E8	1.56 E7
PWR		2.04 E13	1.86 E13	1.69 E13

At 0.01 years decay the PWR shows a hundred times greater inhalation toxicity, which is dominated by the actinide content. At longer times the differences between fusion and fission are much larger, with the PWR showing much greater potential for harm. The low activation fusion reactor shows order of magnitude lower toxicity than the ferritic variant at 100 years decay, but at short times there is no significant difference.

5.9 The neutron activation of the tungsten/rhenium divertor is a dominant contributor to all the key parameters for the fusion reactors in the first year after shutdown. In fact the high thermal power of divertors (about 1.7 kW/kg at shut-down) is likely to require careful attention in addressing loss of cooling accidents.

5.10 The production of ^{14}C is larger in the fusion reactors than in the PWR. The lifetime arisings per GW(e) are:

EEF Reference Reactor (ferritic)	3.2 kg
EEF Reference Reactor (low activation)	1.0 kg
PWR	0.082 kg

The main source is nitrogen in structural metals, which is subjected to $^{14}N(n,p)^{14}C$ reactions; this means that the ^{14}C should be well contained during reactor operation and decommissioning and that it is unlikely to be released until released by corrosion processes in the underground repository. This aspect is considered in para. 5.21 to 5.31

Discussion of neutron activation problem

5.11 A fusion reactor will have some components, notably the first wall and blanket structures, which will be replaced several times during the life of the reactor on account of fast neutron damage effects on their metallurgical properties. These same components will contain at least half the radioactivity produced in the reactor by absorption of neutrons in structural and blanket/coolant materials

5.12 In the EEF Reference Reactor, replacement of components would lead to 5000 tonnes of radioactive waste of this kind to be dealt with at the time of decommissioning of the reactor. This waste has, for the first ten years, a specific activity and thermal power output at 1% - 2% of the levels found in spent fuel or vitrified High Level Waste from a fission reactor, [5.1] and its radioactivity decays much more rapidly after that.

5.13 Designers of conceptual fusion power reactors have for many years known that avoidance of particular elements in the components most exposed to the neutron flux can be beneficial. Table 5.9 shows some of the elements to be avoided if the aim is to achieve more rapid decay of gamma emitters and of isotopes which give rise to the greater risks in accidents or in a waste repository. Essentially this is a strategy of absorbing the waste neutrons in elements which transmute to short-lived radioactive products.

5.14 There are however other constraints: The chemical, physical, and mechanical properties of a new material must satisfy the severe demands made by the operating environment of the reactor. It typically takes 10 to 20 years to develop a new alloy [5.2] or ceramic to the point where it can be specified by engineers for real applications. The cost of the new material must be acceptable, noting that in our reference reactor, a doubling of the cost of replacing the first wall, blanket and divertor throughout life would add about 5% to electricity generating costs [5.3].

5.15 Figures 5.3 and 5.8 illustrate the thermal power after shutdown of the two variants of the EEF Reference Reactor. It will be necessary to examine in more detail the cumulative energy release during the first minutes and hours in such cases before drawing conclusions about shutdown cooling problems or making comparisons with the PWR. Holdren et al [5.8] have already shown that Fusion reactors will produce a very much smaller thermal power (MW per m^3 of core) at shutdown than the PWR, typically by between one and two orders of magnitude.

5.16 It is clear that there is much work to be done in optimising the materials choice for a given design of fusion reactor. The three radiological aspects of material performance:

- hazard resulting from loss of cooling
- rate of decay of gamma activity after removal
- risk from underground disposal.

must be taken into account alongside the important metallurgical considerations.

TABLE 5.9

Disadvantages of elements in structural materials

Element	Context of Problem				Reference
	γ emission	repository intrusion	repository groundwater	volatility in LOCA	
N			^{14}C		5.1/.6
Mo		^{94}Nb	^{99}Tc ^{93}Mo	^{99}Mo	5.1/.6
Re	^{192}Ir ^{193}Pt	^{186m}Re	^{186m}Re		5.1/.5/.6
Ta	^{192}Ir ^{193}Pt	^{186m}Re	^{186m}Re		5.1/.6
Nb		^{94}Nb			5.1/.6
Tb	^{158}Tb	^{158}Tb			5.1/.5/.6
Ni		^{63}Ni			5.1/.6
Ag Cd	^{108m}Ag	^{108m}Ag			5.1/.5/.6
Co	^{60}Co				5.1/.6
Eu	^{152}Eu ^{154}Eu	^{152}Eu ^{154}Eu			5.1/.6
Fe				^{54}Mn ^{56}Mn	5.4/.6
Mn				^{54}Mn	5.4/.6
Ti				Sc	5.4/.6
Pb Bi	^{207}Bi				5.5/.6

RELEASES OF RADIOACTIVE AND CHEMICAL EFFLUENTS IN NORMAL OPERATION

5.17 For a nuclear reactor the volume of material involved in the fuel cycle and in renewable activated structures is small, so the extent of dispersal of radioactive substances to air and water in the environment in normal operation is a matter largely of engineering judgements in selecting the "best practicable environmental option". For a coal-fired power station the volume of fuel and combustion products is so large that there is much less scope for containment. In this section we examine the effluents from typical PWR and coal-fired power stations and consider whether or not the fusion reactor offers major improvements.

5.18 An estimate has been made of the lifetime production of gaseous and solid wastes dispersed in the environment from 25 years operation (82% load factor) of a 1GW(e) modern coal-fired plant similar to Drax B in the UK. It was assumed that 90% of sulphur dioxide and 30% of nitric dioxide are removed in a limestone/gypsum desulphurisation plant. The results [5.18] are summarised in Table 5.10. Where the waste has a radioactive content, this is also expressed in "Toxic Content" terms; this cannot be done for toxic chemical content because the understanding of low dose effects is less advanced for such substances.

The corresponding releases of radioactive material in the gaseous and liquid effluents from a PWR operating at 1GW(e) for 25 years with a 75% load factor can be derived from reference [5.17]. The results are summarised in table 5.11 together with derived data for Toxic Content for each radionuclide. Table 5.11 assumes that the PWR fuel is not reprocessed; if the lifetime emissions from reprocessing this fuel in a modern plant such as THORP are included the toxic content of aqueous and gaseous emissions becomes much larger.

5.19 For the reference fusion reactor it is not practicable to estimate releases during normal operation until a detailed design is available. We can assume that only ^{3}H and ^{14}C will be of significance in the gas phase. In liquid discharges the ^{3}H will again be a key radionuclide to be controlled and it is likely to be accompanied by amounts of the corrosion products ^{54}Mn, ^{55}Fe, ^{58}Co, ^{60}Co, ^{63}Ni and ^{65}Zn similar to those in the PWR effluent (Table 5.11).

The total amount of tritium on the fusion reactor site (Table 5.7) will be of the order of 5kg, of which up to half would be actually in the EEF Reference Reactor and its associated breeder blanket. We see no reason to doubt that estimates, made in the STARFIRE assessment [5.15], of annual releases to atmosphere and liquid waste at around 300TBq and 30TBq respectively could be achieved.

Table 5.10
<u>Lifetime discharges of ash and effluents from a</u>
<u>1GW(e) coal-fired power station</u>
(25 years at 82% load factor)TABLE 5.10

Content	Mass (te) (typical)	Activity (TBq)	Toxic Content (Sv)	
			Ingestion	Inhalation
(a) gaseous effluent:				
CO_2	1.6×10^8			
SO_2	2.1×10^5			
NO_x	4.4×10^5			
Al	1.0×10^4			
Ca	5.0×10^3			
Fe	1.0×10^4			
Mg	2.0×10^3			
K	7.0×10^3	4.0×10^{-2}	2.0×10^2	1.4×10^1
Na	1.0×10^3			
Ti	5.0×10^2			
Sb	5.0×10^0			
As	1.0×10^2			
Br	3.0×10^1			
Cd	5.0×10^0			
Cr	1.0×10^2			
Hg	1.0×10^0			
V	1.0×10^2			
Zn	5.0×10^1			
Se	5.0×10^0			
Th		2.8×10^{-2}	8.5×10^3	3.7×10^6
U		2.9×10^{-2}	2.0×10^3	9.5×10^5
Ra		2.1×10^{-2}	6.5×10^3	3.8×10^4
Pa		7.0×10^{-4}	2.0×10^3	2.5×10^5
Ac		7.0×10^{-4}	2.8×10^3	1.3×10^6
Rn		1.4×10^0		
Pb		7.0×10^{-2}	9.8×10^4	2.4×10^5
Po		7.0×10^{-2}	3.0×10^4	1.5×10^5
(b) solids:				
Ash	1.3×10^7			
Gypsum	8.9×10^6			
Sludges	4.3×10^5			
Ash (^{238}U)		1.4×10^0	3.9×10^6	3.6×10^8
(^{232}Th)		7.0×10^{-1}	8.6×10^5	3.6×10^8
(^{40}K)		7.0×10^0	3.6×10^4	2.4×10^4

Table 5.11

Lifetime discharges of principal liquid and gaseous radioactive effluents from a 1GW(e) PWR (25 years at 75% load factor)

Content	TBq		Toxic Content (Sv)	
	Liquid	Gas	Ingestion (liquid)	Inhalation (gas)
^{85}Kr		$7.1 \times 10^{[illegible]}$		6.25×10^{6}
^{88}Kr		3.1		1.92×10^{3}
^{133}Xe		3.2×10^{3}		3.2×10^{6}
^{131}I	4.0	6.4×10^{-3}	5.2×10^{4}	5.12×10^{1}
^{3}H	4.5×10^{2}	4.5×10^{1}	7.65×10^{3}	7.65×10^{2}
^{14}C	6.4×10^{-1}	6.3	3.58×10^{2}	3.53×10^{3}
^{41}Ar		4.7		6.58×10^{2}
Actinides (α)		4.3×10^{-6}		
^{134}Cs	1.0		1.7×10^{4}	
^{137}Cs	9.4×10^{-2}		1.13×10^{4}	
^{237}U	9.4×10^{-3}			
^{241}Pu	2.3×10^{-3}		4.37×10^{1}	
^{241}Am	4.0×10^{-6}		3.92×10^{0}	
^{242}Am	3.2×10^{-4}		8.00×10^{-2}	
^{242}Cm	9.4×10^{-5}		2.82	
^{54}Mn	3.6×10^{-1}		2.59×10^{2}	
^{55}Fe	1.5×10^{-1}		2.40×10^{1}	
^{58}Co	4.0		3.76×10^{3}	
^{60}Co	3.6×10^{-1}		2.52×10^{3}	
^{63}Ni	3.6×10^{-2}		5.40	
^{65}Zn	8.7×10^{-2}		3.39×10^{2}	
^{90}Sr	1.2×10^{-3}		3.96×10^{1}	
^{95}Zr	1.2×10^{-1}		3.12	
^{99m}Tc	1.4×10^{-2}		2.24×10^{-1}	
^{106}Ru	4.9×10^{-2}		2.84×10^{2}	
^{110m}Ag	3.4×10^{-1}		9.86×10^{2}	
^{140}Ba	1.6×10^{-1}		3.68×10^{2}	
^{144}Ce	1.2×10^{-1}		6.48×10^{2}	

Table 5.12 lists estimated operational releases from the fusion reactor site, based on the STARFIRE work. together with derived data on Toxic Content. Sowerby et al [5.18] indicate that the annual dose received by a member of the Critical Group as a result of such tritium releases would be around 0.1mSv.

5.20 In comparing normal discharges to the environment for the three systems the following conclusions may be drawn.

- The coal-fired plant disperses to the air over one hundred million times the mass of waste material dispersed from any kind of nuclear plant, about one percent of it being gases and particulate material of recognised toxic effect.

- The coal-fired plant discharges 20 million tonnes of ash and gypsum during its life; this material is potentially of substantial environmental concern because of its huge bulk.

- Apart from the special case of tritium, the radioactivity dispersed to the biosphere is of similar order of magnitude for the coal-fired, PWR and fusion power stations; uranium,thorium and potassium dominate the fossil waste radioactive inventory, and carbon-14 the PWR and fusion dispersals. Toxic content is largest for the coal-fired dispersals and smallest for fusion.

- The PWR and fusion reactor are likely to be similar in discharging a few hundred TBq of tritium to aqueous effluents over their lifetime. The toxic content is small.

- A few thousand TBq of tritium are likely to be released to atmosphere over the lifetime of the fusion reactor. The toxic content of this tritium is small.

Quantities of solid radioactive waste from decommissioning

5.21 Since there is no requirement during the operating life of a fusion reactor to remove solid radioactive materials from the site it is reasonable to treat the lifetime arisings as part of the decommissioning wastes. In addition to making estimates of the radioisotope contents of these wastes it is necessary to consider the mass or volume to be packaged and disposed of because this has a bearing on costs and on the environmental impact of the industrial operations involved.

TABLE 5.12

Lifetime discharges of principal liquid and gaseous radioactive effluents from the fusion reactor site (25 years at 75% load factor)

Content	TBq		Toxic Content (Sv)	
	Liquid	Gas	Ingestion (liquid)	Inhalation (gas)
^{3}H	7.0×10^{2}	7.0×10^{3}	1.2×10^{4}	1.2×10^{5}
^{14}C	8.6×10^{-1}	2.0×10^{-3}	4.8×10^{2}	1.1×10^{0}
^{41}Ar	-	6.0×10^{-3}		
	+ activated corrosion products as in Table 5.11 (Mn,Fe,Co,Ni)			

5.22 Fusion wastes in general are of shorter half-life than fission wastes, due to the absence of the high fission yield isotopes ^{137}Cs and ^{90}Sr (30years) and of the transuranium isotopes. It will be a practical proposition to store solid wastes from a fusion reactor until the gamma emission has fallen to a level where packaging and disposal operations are much simpler. The same property makes possible the recycling of metals if their intrinsic value justifies the melting and re-fabrication costs.

The neutron activation products, which dominate the overall radioactive waste products from a fusion reactor, present no new waste packaging problems. Where high gamma dose rates exist, remote handling equipment will be required to cut up and grout the wastes into boxes or drums for disposal. Such techniques are already in use for fission reactor decommissioning.

5.23 Tritium and tritiated water [5.9, 5.18], which are embedded in or absorbed on structural materials, will require special measures in waste packaging and disposal. The principal requirements will be the control of worker and public exposure to tritium released during processing and packaging of fusion reactor wastes, and the containment of tritium within a waste disposal repository until it has decayed. It is too early to predict quantities of tritium associated with the various decommissioning wastes, but it must be assumed that gramme quantities will remain after emptying the reactor of fuel and breeder materials at end of life. The most satisfactory solution would be to oxidise the tritium which is not firmly embedded in metal matrices and incorporate it in a cement matrix for disposal in a geological repository. Formation of stable metal hydrides is another possibility which is already used in storage of hydrogen isotopes. The relatively short half-life of tritium would ensure that no return to the biosphere could occur. New development work will be required on these subjects.

5.24 Jukes et al [5.7] surveyed three earlier conceptual Tokamak reactor designs to estimate the mass and volumes of waste generated by the reactor cores, including fuel processing and steam raising plant. Taking into account both the accumulated first wall, divertor and blanket structure wastes and also those components which last the whole reactor life, the authors arrived at the figures in Table 5.13. A distinction is made in this table between Very Low Level Waste (VLLW), as defined in the UK (<0.4MBq/te), and Repository Waste, which is all waste of higher specific activity. A decay period of 50 years is assumed between reactor shutdown and waste disposal. This distinction is relevant because in principle VLLW may be disposed in normal landfill without authorisation by the UK regulatory departments.

5.25 The larger waste volumes from the PCSR-E system reflect the lower power density and more massive blanket structure of the Tokamak. The overall range of these estimates, which are dominated by the shield volumes, is not too different from the range (5000 - 10000m^3/GWe) given in the ESECOM study [5.8] for the net volumes. The volumes may be reduced by recycling; for example first wall and blanket material could be remelted for further use. This would have little effect on the total inventory of waste radionuclides for disposal and in considering it as a strategy one would have to balance the saving in raw material and waste disposal costs against the doses and costs arising in the processing plant. Also if surface doses need to be below 25μSv/hr in the plant it may be necessary to store the irradiated components up to 100 years before processing [5.5]

Similarly the shield material could be recycled in another reactor at the end of its 20-40 year life. The strategy on recycling can only be decided when the reactor design is at a more advanced stage. Jukes [5.7] has estimated that savings in repository waste volumes could reach 30 - 50% in a very long programme of fusion power in which the maximum amount of material is continuously recycled.

TABLE 5.13

Volumes of radioactive waste from Tokamak reactor decommissioning [5.7]

Reactor system	Radioactive waste volume (m^3/GWe)		
	VLLW (volume at theoretical density)	Repository waste (volume at theoretical density)	Repository waste (packaged)
STARFIRE	1720	1940	10400
DEMO R254	2840	1990	10700
PCSR-E	1940	8050	43400

5.26 Using the STARFIRE reactor as a basis, Devell et al [5.9] compiled details of the masses and volumes of all reactor components. A comparison with the EEF Reference Reactor (Tables 5.3 and 5.4) showed that the total structure in each design weighs around 25000te to 30000te per 1200MW(e).

5.27 To compare the EEF Reference Reactor with a modern PWR operating on "once-through" fuel cycle, we can set aside all waste arisings from operation and decommissioning of coolant and steam cycle and fuel handling plant on the basis that there will be no major differences between the fission and fusion cases. Furthermore, we should assume that all PWR spent fuel is stored on site after discharge and disposed of at the time of stage 3 decommissioning.

5.28 Passant [5.17] gives estimates of the cost of decommissioning the proposed 1175MW(e) PWR at Hinkley Point, UK. It is assumed that Stage 3 is delayed until about 100 years after final shutdown. Table 5.14 shows the volumes of repository waste produced at each stage of decommissioning; the division between intermediate (ILW) and low (LLW) level waste is based on the UK definition of that boundary as 4 GBq/te of alpha and 12 GBq/te of beta/gamma activity.

5.29 The stage 3 data alone can be compared with the volumes of waste from decommissioning the EEF Fusion Reactor core, since the stages 1 and 2 comprise the operational and steam cycle wastes. In Table 5.15 this comparison is made after assigning the EEF Fusion Reactor core wastes to the ILW and LLW categories 100 years after shutdown using the results from Tables 5.5 and 5.6. A waste package density of 1 te/m^3 is used.

5.30 A decommissioning strategy for a fusion reactor will not differ in principle from the familiar three-stage approach defined by the IAEA. There is the same incentive to delay stage 3 for at least a few decades to reduce the cost and worker dose involved in cutting up and packaging bulky components which, even in the case of special vanadium alloys, will give surface dose rates of several mSv/hr after 30 years [5.9]. Decontamination techniques developed for LWR primary circuits will be of value in removing activated dust from the vacuum vessel and activated corrosion products from coolant circuits. Remote cutting equipment will then allow components to be reduced to a size suitable for packaging for a geological repository or for emplacement in near-surface vaults. Cooke et al assume [5.3] that decommissioning and waste management and disposal for a large fusion reactor will cost about 20% of the original investment, a figure broadly in line with results of decommissioning assessments for fission reactors.

In this context we should note that experience with fission wastes shows that whilst the cost of disposing of waste packages falls within the ranges:

£200-£1000/m^3 (near-surface) or £2000-£5000/m^3 (geological)

the cost of packaging and transporting the waste can be several times larger than this. A large variation in packaging costs arises from the capital intensive nature of remotely operated plants and the consequent importance of waste throughput rates on the unit costs in any particular plant

TABLE 5.14

Decommissioning waste volumes for a large PWR [5.17]

Decommissioning stage	Volume of packaged radioactive waste (m^3/GWe)		Spent fuel (te) (25 years at 75% load factor)
	ILW	LLW	
1	500	1150	
2	0	11000	
3	270	1700	670
TOTAL	770	13850	670

TABLE 5.15

A comparison of waste volumes from decommissioning EEF Reference Reactor and a large PWR (Hinkley Point)

(Reactor core plus lifetime spent fuel or replaceable core components)

Reactor	Volume of packaged repository waste [cubic metres per GW(e)]		Spent fuel (te)
	ILW	LLW	
EEF Reference (ferritic)	9200	5000	-
EEF Reference (low activation)	8300	5800	-
PWR	270	1700	670

5.31 It seems probable that for the EEF Reference Reactor a decommissioning cost (undiscounted) of around 1 BECU must be expected, corresponding to 850 MECU per GW(e). This is likely to comprise about 100 MECU for the packaging, transport and disposal of the 14000m^3 of packaged radioactive waste, and 750 MECU for engineering work in stage 3 dismantling of the reactor. Such estimates cannot be accurate to better than a factor two at this early stage in reactor design.

In the PWR case Passant [5.17] estimates a cost of around £95M per GWe for stage 3 decommissioning and associated waste management but this does not include the cost of packaging and disposing of the 670 te of spent fuel (Table 5.14). Assuming an undiscounted £300,000 per tonne for that work, the total cost of PWR core decommissioning would be around 500MECU/GWe. This may be compared with 850MECU/GWe for the EEF Fusion Reactor, which is a reflection of the much larger "intermediate" level waste volumes coming from the shield and blanket structure of the fusion reactor, even after 100 years cooling. The low activation variant of the EEF Fusion Reactor does not change the waste volume situation significantly although there would be some unquantified gain from the reduction in dose rates to decommissioning workers. The difference between the stage three costs of PWR and the fusion reactor would be much greater were it not for the very high cost of dealing with PWR spent fuel. The 150 tonnes of first wall and divertor waste from the fusion reactor has a similar thermal power to that of spent fuel after shutdown but after 100 years cooling these metal wastes will be quite normal intermediate level waste requiring no special heat removal provision.

Radioactivity to be disposed of as solid wastes

5.32 In para 5.21 to 5.29 we saw that the fusion reactor, being of lower power density than the PWR, produces a larger volume of solid radioactive waste for disposal. In this section we first compare the radioactivity in these solid wastes ten years after final shutdown and then compare the risks which would arise from their disposal in a deep underground repository.

5.33 Sowerby et al [5.18] have collected data on the lifetime inventory of all waste radionuclides from 25 year operation of a 1GW(e) PWR at a load factor of 75%. The totals, ten years after the final shutdown are dominated by the accumulated spent fuel inventory. Table 5.16 lists the principal radionuclides (5.16a activity, 5.16b inhalation toxic content and 5.16c ingestion toxic content). Wastes arising during mining and milling are not included in Table 5.16.

Sowerby et al [5.18] have also presented analogous calculations of the radioactive inventory of the EEF Reference Fusion Reactor, in its ferritic steel and vanadium alloy forms, ten years after final shutdown. These data, also in Table 5.16, are based on the assumption that all activity generated remains on the site to be dealt with when the reactors are decommissioned. The tritium inventory in the Pb-Li breeder and in processing plant or stores on the site is not included, because even in circumstances where this tritium was not wanted as fuel for another fusion reactor, there would be no case for disposing of it as solid waste.

5.34 A major international research programme over the past fifteen years has established most of the data and engineering design principles necessary for the safe disposal underground of solid radioactive wastes. With the exception of residual amounts of a few radioactive isotopes such as ^{238}U, ^{129}I and ^{36}Cl, which have extremely long half lives and feeble radioactivity, it is quite practicable to isolate radioactive wastes in underground repositories so that they decay completely away without reaching the biosphere. Sites of stable geology are chosen, in rocks least likely to attract inadvertant human intrusion and where groundwater, if present, takes tens of thousands of years to reach the biosphere. The wastes are packaged in stable, solid form, often with extra containment features such as retentive matrix materials and corrosion resistant containers.

Fission and fusion wastes can be managed alike by these methods. Fusion wastes are of shorter half-life and in particular do not include the ^{129}I and ^{238}U isotopes which usually feature in estimates of very long-term return of residual traces of radioactivity to the biosphere. On the other hand fusion wastes will contain gramme quantities of tritium which, whilst no problem in a geological repository due to its short half-life, will need special attention to avoid exposure of workers to inhalation risk during processing and emplacement.

5.35 for the present study, the risks from the inventories of the EEF Reference Reactor variants and the PWR, assuming deep underground disposal ten years after final shutdown, were calculated using the typical methodology developed by the UKAEA. All solid wastes from the fusion cores and all spent fuel from the PWR after a 25 year life at 75% load factor were included in the inventory.

5.36 The repository was assumed to be 500m deep at a hard rock site, with a path length for groundwater flow to the biosphere of 2.5km representing a travel time of just below 100,000 years. For the purposes of this comparison exercise the biosphere pathway to Man was assumed to be via drinking water from a stream. The "near-field" solubilities of radionuclides in the groundwater, which was allowed immediate access to the waste, were determined by the chemical equilibria of dissolution and adsorption reactions in a cement backfilled repository at high pH and low oxygen potential. This "near-field" contaminated groundwater was then allowed to move by advection and diffusion through the "far-field", eventually to be diluted in the stream.

5.37 It is interesting to note in Table 5.16a that at ten years after final shutdown there is not a large difference in total radioactivity between the ferritic variant of the fusion reactor and the PWR. ^{55}Fe dominates the fusion reactor case, whereas ^{241}Pu and the high yield fission products ^{90}Sr and ^{137}Cs are major components of the PWR radioactivity. The low activation variant of the fusion reactor contains much less ^{55}Fe, ^{60}Co and ^{63}Ni so its total radioactivity at the ten year decay point is only about 5% of that of the ferritic variant. Actual disposal of these wastes might well not take place until 100 years after the final shutdown, but that would not change the long-term groundwater risk calculations presented here. Figure 5.12 shows how the total radioactivity inventories develop up to 100 years after the final shutdown, with the ferritic variant of the fusion reactor becoming more like the low activation variant and less like the PWR. Tables 5.16b and 5.16c show that the toxic content of the fusion reactor is at all times much smaller than that of the PWR.

5.38 In estimating risk to the Critical Group from stream contamination in the distant future it is ingestion toxicity and mobility in groundwater which are the important factors. Figure 5.14 suggests at once that the fusion reactors will offer big advantages on that basis.

The results of the repository risk calculations are summarised in Figures 5.16 and 5.17

5.39 Figure 5.16 shows the hypothetical dose (committed effective dose equivalent) in Sv/year to an average adult taking all his water supply directly from the equilibrated groundwater actually within the deep underground repository containing the inventory of radioactive wastes from the EEF Reference Reactor (ferritic variant), the EEF Reference Reactor (low activation variant) and the PWR. These "near-field" calculations show clearly that over the first few hundred years the PWR repository water is about four orders of magnitude more toxic than in the fusion cases. As the ^{90}Sr and ^{137}Cs decay, this difference is reduced to approximately a factor of 30, but it increases again to a very large factor at very long times due to the actinide content.

5.40 Figure 5.17 shows the dose in Sv/year to an average adult taking all his water supply from the stream into which the repository containing the inventory of radioactive wastes from the three reactor types eventually drains. The fusion case shows peak toxicities at least two orders of magnitude below the PWR case occuring in the far future (i.e. beyond 100,000 years). The fusion advantage stems from the absence of ^{238}U and ^{129}I in the fusion reactor wastes.

TABLE 5.16a

Principal Radionuclide Content of All Wastes from 25 Years Operation at 1GW(e) and 75% Load Factor Activity (TBq)

Radionuclide	Ten years after final shutdown		
	EEF Reference Reactor		PWR
	Ferritic	Low Activation	
^{3}H	1.2×10^{4}	8.9×10^{4}	4.8×10^{3}
^{14}C	5.3×10^{2}	1.7×10^{2}	1.4×10^{1}
^{36}Cl	2.0×10^{-2}	4.2×10^{-2}	2.9×10^{-4}
^{49}V	2.5×10^{2}	5.6×10^{2}	
^{54}Mn	3.9×10^{3}		8.5×10^{1}
^{55}Fe	1.0×10^{7}	4.3×10^{5}	9.0×10^{4}
^{57}Co	1.0×10^{2}		
^{59}Ni	7.4×10^{2}		9.7×10^{2}
^{60}Co	7.4×10^{4}	2.6×10^{3}	1.8×10^{5}
^{63}Ni	7.5×10^{4}	3.3×10^{3}	5.5×10^{4}
^{85}Kr			1.2×10^{5}
^{90}Sr			1.5×10^{6}
^{91}Nb	4.7×10^{3}		
^{93}Zr			7.4×10^{1}
^{93}Mo	3.1×10^{3}		
^{94}Nb	7.8×10^{2}		
^{99}Tc			3.5×10^{2}
$^{106}Ru/^{106}Rh$			1.2×10^{4}
^{108m}Ag	2.3×10^{2}	2.3×10^{2}	
^{126}Sn			1.4×10^{1}
^{129}I			6.5×10^{-1}
^{134}Cs			1.7×10^{5}
^{135}Cs			1.3×10^{-2}
^{137}Cs			2.0×10^{6}
^{144}Ce			3.6×10^{3}
^{147}Pm			2.6×10^{5}
^{151}Sm			5.3×10^{3}
^{154}Eu			1.2×10^{5}
^{179}Ta	4.0×10^{2}	3.8×10^{2}	
^{192}Ir	4.0×10^{2}	5.6×10^{2}	
^{193}Pt	2.3×10^{4}	3.2×10^{4}	
^{204}Tl	3.8×10^{4}	4.7×10^{4}	
^{207}Bi	2.5×10^{2}	3.1×10^{2}	
^{237}Np			6.0×10^{0}
^{238}U			7.9×10^{0}
^{238}Pu			5.2×10^{4}
^{239}Pu			8.5×10^{3}
^{240}Pu			1.3×10^{4}
^{241}Pu			2.0×10^{6}
^{241}Am			4.4×10^{4}
^{242}Pu			5.1×10^{1}
^{242}Cm			1.0×10^{2}
^{244}Cm			3.3×10^{4}

TABLE 5.16b

Principal Radionuclide Content of All Wastes from 25 Years Operation at 1GW(e) and 75% Load Factor Inhalation Dose (Sv)

Radionuclide	Ten years after final shutdown		
	EEF Reference Reactor		PWR
	Ferritic	Low Activation	
^{3}H	2.38×10^{5}	3.23×10^{6}	8.16×10^{4}
^{14}C	3.58×10^{5}	1.12×10^{5}	7.84×10^{3}
^{36}Cl	1.10×10^{2}	2.31×10^{2}	1.59
^{49}V	2.28×10^{4}	5.09×10^{4}	
^{54}Mn	7.99×10^{6}		1.44×10^{5}
^{55}Fe	8.52×10^{9}	3.69×10^{8}	6.39×10^{7}
^{57}Co	2.88×10^{5}		
^{59}Ni	6.59×10^{5}		7.18×10^{5}
^{60}Co	3.65×10^{9}	1.27×10^{8}	7.38×10^{9}
^{63}Ni	1.55×10^{8}	6.63×10^{6}	9.35×10^{7}
^{85}Kr			
^{90}Sr			5.10×10^{11}
^{91}Nb			
^{93}Zr			6.43×10^{6}
^{93}Mo	2.77×10^{7}		
^{94}Nb	8.37×10^{7}		
^{99}Tc			7.00×10^{5}
$^{106}Ru/^{106}Rh$			1.44×10^{9}
^{108m}Ag	1.46×10^{7}	1.46×10^{7}	
^{126}Sn			3.22×10^{5}
^{129}I			2.73×10^{4}
^{134}Cs			1.87×10^{9}
^{135}Cs			1.43×10^{1}
^{137}Cs			1.54×10^{10}
^{144}Ce			3.42×10^{8}
^{147}Pm			2.42×10^{9}
^{151}Sm			4.08×10^{7}
^{154}Eu			8.28×10^{9}
^{179}Ta	7.2×10^{5}	6.90×10^{5}	
^{192}Ir	3.02×10^{6}	4.22×10^{6}	
^{193}Pt	1.54×10^{6}	2.22×10^{6}	
^{204}Tl	2.90×10^{7}	3.53×10^{7}	
^{207}Bi	1.10×10^{6}	1.41×10^{6}	
^{237}Np			7.80×10^{8}
$^{238}U/^{234}U$			3.07×10^{8}
^{238}Pu			5.20×10^{12}
^{239}Pu			9.35×10^{11}
^{240}Pu			1.43×10^{12}
^{241}Pu			4.40×10^{12}
^{241}Am			5.28×10^{12}
^{242}Pu			5.61×10^{9}
^{242}Cm			4.50×10^{8}
^{244}Cm			2.14×10^{12}

TABLE 5.16c

Principal Radionuclide Content of All Wastes from 25 Years Operation at 1GW(e) and 75% Load Factor
Ingestion Dose (Sv)

Radionuclide	Ten years after final shutdown		
	EEF Reference Reactor		PWR
	Ferritic	Low Activation	
^{3}H	2.38×10^{5}	3.23×10^{6}	8.16×10^{4}
^{14}C	3.58×10^{5}	1.12×10^{5}	7.84×10^{3}
^{36}Cl	1.64×10^{1}	3.44×10^{1}	2.38×10^{-1}
^{49}V	4.50×10^{3}	1.00×10^{4}	
^{54}Mn	3.38×10^{6}		6.12×10^{4}
^{55}Fe	1.92×10^{9}	8.32×10^{7}	1.44×10^{7}
^{57}Co	3.48×10^{5}		
^{59}Ni	4.98×10^{4}		5.43×10^{4}
^{60}Co	6.23×10^{8}	2.17×10^{7}	1.26×10^{9}
^{63}Ni	1.36×10^{7}	5.85×10^{5}	8.25×10^{6}
^{85}Kr			
^{90}Sr			4.95×10^{10}
^{91}Nb			
^{93}Zr			3.11×10^{4}
^{93}Mo	1.11×10^{6}		
^{94}Nb	1.69×10^{7}		
^{99}Tc			1.22×10^{5}
^{106}Ru/^{106}Rh			6.69×10^{7}
^{108m}Ag	5.4×10^{5}	5.4×10^{5}	
^{126}Sn			6.58×10^{4}
^{129}I			4.29×10^{4}
^{134}Cs			2.89×10^{9}
^{135}Cs			2.21×10^{1}
^{137}Cs			2.40×10^{10}
^{144}Ce			1.94×10^{7}
^{147}Pm			6.76×10^{7}
^{151}Sm			4.88×10^{5}
^{154}Eu			3.00×10^{8}
^{179}Ta	3.17×10^{4}	3.04×10^{4}	
^{192}Ir	6.72×10^{5}	9.38×10^{5}	
^{193}Pt	7.83×10^{5}	1.13×10^{6}	
^{204}Tl	4.00×10^{7}	4.87×10^{7}	
^{207}Bi	3.77×10^{5}	4.81×10^{5}	
^{237}Np			6.60×10^{6}
^{238}U/^{234}U			6.52×10^{5}
^{238}Pu			4.47×10^{10}
^{239}Pu			8.07×10^{9}
^{240}Pu			1.23×10^{10}
^{241}Pu			3.80×10^{10}
^{241}Am			4.31×10^{10}
^{242}Pu			4.59×10^{7}
^{242}Cm			3.00×10^{6}
^{244}Cm			1.78×10^{10}

5.41 Calculations of this kind, involving deterministic calculations with typical site data, serve to illustrate the main features of groundwater risk. In practice there will be uncertainty distributions for key data on groundwater velocity, radionuclide sorption, etc, which will broaden the stream toxicity results and may introduce some shorter half-life isotopes into the total. However, computer cases run with "pessimistic" data sets of that kind showed even larger advantages for the fusion systems. Of interest is the result that the "low activation" variant offers no benefits in terms of groundwater risk, compared to the ferritic fusion reactor variant.

HEALTH HAZARDS DUE TO ACCIDENTS

5.42 A fusion reactor contains considerable quantities of radioactive material. As discussed in para.5.48 this material under normal conditions is enclosed by multiple barriers. Safety systems will be provided to prevent failure of barriers even in case of accidents. In spite of these provisions releases into the environment of radioactive material caused by major accidents cannot be absolutely excluded. To estimate the accidental risk to the public from a fusion reactor, consequences from, and probabilities of, accidental releases have to be investigated.

5.43 In the literature many articles can be found which deal with possible accidents in fusion reactors. This information, however, cannot be directly applied to an envisaged commercial fusion reactor. In a study, sponsored by the EC, accidental risks from such a reactor have been investigated [5.23]. For this study the STARFIRE concept has been used as reference reactor (with some modifications concerning the structure material), although several points of the STARFIRE design do not reflect present day concepts, STARFIRE is the most elaborate concept of a commercial fusion reactor, for which details of construction and operation are available.

Nevertheless the knowledge about the design of the reference reactor and the processes during an accident is limited, so that a quantitative evaluation in terms of frequencies and consequences of accidents is not possible.

5.44 The dominating hazard potential of a fusion reactor is caused by the tritium and the activation products inside the containment.

The most significant "vulnerable" tritium inventory inside the reactor is found in the blanket. This tritium could be mobilised if temperatures exceed 1000K. The quantity is rather uncertain but it is to be expected that for a future commercial reactor the amount of "vulnerable" tritium will be minimised. Current research is indicating that, by using improved materials for a solid breeder, the amount of tritium entrapped in the blanket can be significantly reduced compared to the STARFIRE reference value of 10 kg. In more recent studies a blanket tritium inventory of some 100 g has been assumed. For the present study a reference value of 1 kg will be used.

The same amount, or even higher, of tritium may be in areas other than the reactor itself. But by appropriate technical measures this tritium can be made relatively "non vulnerable" to accidents [5.20 pp 14-26]

For the radioactive inventory in structural material five groups of mobility can be distinguished [5.21], ranging from gaseous or extremely volatile elements (group I) to elements resistant to volatilisation even under extreme accident conditions (group V).

5.45 Specific safety and accident related features of the STARFIRE reactor, which has been used as a reference design for the accident analysis, are the following:

- solid breeder ($LiAlO_2$)
- emergency plasma shutdown system, in addition to the inherent shutdown mechanism by ablation of beryllium coating
- steady state operation
- series connection of TF-coils
- high pressure water coolant
- primary coolant loops and residual heat removal system
- leak-tight reactor building ("containment") inerted with CO_2.

Specific features of the reference reactor can strongly influence an accident. For example, the Be-coating of all surfaces facing the plasma is a basic assumption of the STARFIRE concept. This material is very toxic and would chemically react with water, thus posing hazards by itself, but it would instantaneously evaporate in the case of a plasma disruption, shut down the plasma reaction and prevent severe temperatures of structures. Present information indicates that Be will not be used as a coating in a future design. Graphite coating, which will possibly be used in NET, would behave totally differently. In this case a main safety aspect is the water-gas-reaction of graphite with steam. Other choices are metal coatings, but up to now the coating material for a commercial fusion reactor cannot be finally specified.

Another important item is the design and safe operation of a divertor. STARFIRE is designed without divertors but with a limiter.

5.46 The barriers preventing release of radionuclides to the environment are the in-vessel components (mainly blanket and first wall), the vacuum vessel, and the leak-tight building (containment). Loss of barriers is possible as a consequence of various physical effects (mechanical forces, temperature increases, pressure increase). Events, which could initiate such effects ("accident initiating events") and which could finally lead to failure of barriers can be categorised as follows:

• loss of coil control	LOCC
• loss of coolant inside containment	LOCIC
• loss of heat removal	LOHR
• loss of vacuum in vessel	LOVA
• loss of cryogenic fluid	LOCF
• loss of coolant in first wall	LOCFW
• loss of coolant in blanket element	LOCIB
• plasma excursion	PLEX
• loss of plasma control (including plasma disruption)	LOPC
• loss of decay heat removal	LODHR

The initiating events can cause various accident sequences, depending, for example, on the functioning of safety systems. Most accident sequences have minor consequences and are irrelevant in terms of health hazards. For the present topic only those sequences are of interest which can make barriers ineffective and thus lead to a release of radioactive substances.

The first barrier is the activated first wall and the breeding material itself. If there is no temperature increase the solid breeding material provides a good protection against release. But a temperature increase of about 200 K would be sufficient to release practically all the tritium from the blanket within a few hours [5.20]. The first wall is less vulnerable. According to the volatility of the radioactive elements, it will retain the majority of hazardous substances as long as it remains solid. The same does not apply to liquid blankets.

Since most accidents would be accompanied by temperature transients, the breeding material cannot be considered to be a very effective barrier. Therefore this mechanism for tritium retention is only some additional safety feature, while the blanket element cans and/or the first wall are regarded as the first real barriers for the tritium in the blanket and for the activated elements as well.

The second barrier is the toroidal vacuum vessel. The massive radiation shielding is located at the inside of the vacuum vessel. This shielding represents a very large thermal inertia. Consequently thermal transients for the vacuum vessel are slow. This reduces the thermomechanical problems and provides much time for protective countermeasures. The numerous ducts and windows in the vessel wall are potential weak points if the vessel is subject to mechanical forces. Therefore the vacuum vessel seems to be more vulnerable by mechanical forces such as overpressurisation than by thermal transients.

The third barrier is the reactor building (containment). It is, for the STARFIRE concept, a steel-lined structure of reinforced concrete designed for 166 kPa internal overpressure. Its atmosphere is inerted with carbon dioxide and it is designed to withstand external impacts such as earthquakes. Because the building volume is very large the overpresssure due to loss of coolant accidents would be lower than for present day light water reactors.

The inert atmosphere prevents chemical reactions, so that fires or chemical explosions do not have to be considered. If the isolation and venting systems are designed properly there is hardly any event which could seriously threaten the tightness of the containment building; therefore it is an extremely reliable barrier to protect the environment in major accidental releases.

The first criterion for an accident sequence to be significant in terms of health hazards is the failure of all barriers. The amount of released material depends on the conditions which prevail when the barriers fail. Therefore the second criterion for a relevant sequence is the mobility of activated material. The third criterion is the probability. Sequences which could mobilize large amounts of material but have a negligible probability for a failure of all barriers do not contribute much to the overall risk.

Loss of vacuum (LOVA) and plasma excursion (PLEX) are not further considered for the Reference Reactor since:

- the effect of loss of vacuum is limited since the containment atmosphere is inerted by CO_2

- plasma excursions can be easily prevented by shutting off the radio frequency. It is expected that loss of plasma control has comparable effects.

Each initiating event can have relations to other initiating events. For example, a spontaneous loss of coolant in the first wall (LOCFW) can be caused by a local leak which has nothing to do with plasma control or with the systems outside the vessel. But coolant will be injected into the plasma region and thus induce plasma transients which can end up in a loss of plasma control (LOPCO). Depending on location and size of leak and also depending on the capability of the plasma control system, the plasma may be extinguished without further complications. Thus the probability for a loss of plasma control under the conditions of a LOCFW depends on specific aspects of the LOCFW and on specific properties of the plant. Obviously it is very difficult to quantify this probability and it is nearly impossible to do so with a lack of detailed plant specifications.

The probabilities are needed for an accident analysis, because only the combination of the effects of several initiating events can break all barriers and mobilize activated structural material. At the present state of knowledge the assumptions to be made on these probabilities have to be based on engineering judgement. The same is valid for the frequency of initiating events.

5.47 An evaluation of initiating events and of accident sequences [5.23] has shown five sequences which can release significant amounts of radioactive substances into the environment. In Table 5.17 these releases together with their "qualitative" probabilities are listed:

The probability is expressed as "degree of unlikeliness". Although this is not intended to be interpreted quantitatively, but rather to give a qualitative ranking of accident sequences, the numbers can be considered as rough orders of magnitude.

The comparison between the five sequences shows the dominance of the LOCIC-LODHR and the LOCC-LODHR sequences. In both cases the loss of decay heat removal (LOHDR) mobilizes the material, while the loss of coolant inside the containment (LOCIC) or the loss of coil control (LOCC) causes the containment failure.

TABLE 5.17

Qualitative probabilities of release of radioactive substances

Event sequence (see para.5.46)	"Degree of unlikeliness"	Radionuclides released (mobility groups)
LOCIC-LODHR	7	I - IV
LOPC-LOCC	7	I - III (fraction)
LOPC-LOCC-LOCIB-LODHR	10	I - IV
LOCC-LODHR	7	I - IV
LOHR-LODHR-LOCIB-LOCC	11	I - IV
LOCIB-LODHR-LOPC-LOCC	7	I - III
	8	I - IV

The failure of the containment as a consequence of accident loads is a very remote event. Whether the unintentional opening of the containment, due to failures in the reactor safety system, is of importance, can be answered only after the review of the detailed plant design, which is not yet available. There is, however, no doubt that an adequate design can reach a very low level of probability.

The analysis of accident sequences has shown that the reference reactor is a plant where serious accidents with internal consequences have to be expected with a certain significant frequency, while severe releases to the environment seem to be almost impossible. Therefore accidents may interfere with the economic performance of the reactor but they are not expected to pose health hazards to the public.

Nevertheless the consequences of even very unlikely accidents have been investigated, in order to put the (theoretical) hazard potential of a fusion reactor in perspective with that of a fission reactor.

5.48 If the release of tritium as gas (HT) and subsequent conversion to tritiated water (HTO) in the soil is considered, many kilograms of tritium can be released without exceeding a dose to the most exposed individual of 50 mSv which is generally accepted as the dose limit for abnormal events of low probability in most countries. If significant amounts of HT are converted to HTO at an earlier point of time, the dose values could be increased by several orders of magnitude.

Under very pessimistic assumptions a release of 1 kg tritium (3.6×10^{17} Bq) could cause doses of 0.1-0.2 Sv from which severe health effects would not be expected [5.25]. This statement is further qualified by the following remarks: Old ref wrong

- A failure of the leak-tight reactor building (containment) would be necessary for a massive release. For a properly designed and constructed containment, the failure probability is very low.
- Instead of an HTO release, there will probably be a release of tritium gas, which has considerably lower radiological consequences.
- There is a high probability for more favourable weather conditions than those underlying the above statement.
- In the calculations a release height of 20m has been assumed. A release from a 100m stack would significantly reduce the dose for the maximum exposed individual.
- The doses caused by ingested HTO can be reduced by consuming large amounts of non-contaminated beverages.

5.49 Evaluations for the release of, and health hazards from, activated structural material indicate that this material has very limited radiological consequences even for the worst plausible accidents in the reference reactor. There are many arguments that the release of these substances will not even violate existing regulations.

Presently there is not a sufficient data base to evaluate in detail the amount of mobilized structural material which can be released from the plant in an accident. Some release fractions are given in [5.21] and [5.8]. These data have been evaluated for reactor systems which are different from the reference reactor of this study. For the vanadium alloy/ liquid lithium tokamak which has some features similar to the reference reactor, the release fractions given in reference [5.21, p39] are shown in Table 5.18.

TABLE 5.18

Release fractions for the vanadium alloy/liquid lithium reactor

Mobility group	Maximum plausible release fraction
II	1.0×10^{-1}
III	5.0×10^{-2}
IV	5.0×10^{-4}
V	5.0×10^{-5}

The subsequent report [5.8] contains isotope-specific data shown in Table 5.19.

TABLE 5.19

Isotope release fractions for the vanadium alloy/liquid lithium reactor

Mobility group	Isotope	Maximum plausible release fraction
II	Ca^{45}	4.0×10^{-2}
III	Mn^{56}	1.0×10^{-3}
IV	Co^{60}	$<1.0 \times 10^{-6}$
V	Sc^{48}	4.0×10^{-5}

These data have been evaluated in a very pessimistic way. According to [5.8] there are many phenomena which would reduce these release fractions by much more than one order of magnitude (e.g. building interior clean-up and plate-out).

Considering these arguments the release fractions used for this evaluation are given in Table 5.20

5.50 For these release fractions the doses given in Table 5.21 have been calculated (according to [5.22])

These figures are rather uncertain, but probably they overestimate the consequences of the worst plausible accident in the reference reactor.

TABLE 5.20

Release fractions used in this evaluation

Mobility group	Release fraction
II	1.0×10^{-2}
III	1.0×10^{-4}
IV	1.0×10^{-7}
V	1.0×10^{-6}

TABLE 5.21

Doses calculated from the assumed release fractions

Mobility group	Effective dose for infants (Sv)	Effective dose for adults (Sv)	Limit value (Sv)
II	4.4×10^{-5}	2.3×10^{-5}	5.0×10^{-2}
III	3.9×10^{-1}	2.0×10^{-1}	5.0×10^{-2}
IV	6.1×10^{-3}	3.1×10^{-3}	5.0×10^{-2}
V	2.8×10^{-3}	1.8×10^{-3}	5.0×10^{-2}

Even under these assumptions, mobility group III is the only one exceeding the limit dose. Under realistic circumstances there is a good chance that even releases of group III also will not violate the limit value.

The doses are dominated by the long-term effects (50 years) from ground radiation and ingestion. Short term effects are insignificant.

To evaluate these results properly, the following considerations have to be remembered:

- The release fractions have been derived from a reactor which is different from the reference reactor.

- The radioactive inventory depends strongly on the composition of the structural material, which is still uncertain. So, the structural material for the EEF Reference Reactor leads to rather low long-term activity. However short and medium-term activity is relatively high for some isotopes. For instance , the activity of magnesium 27 and 28, evaluated as 10^{13} Bq for STARFIRE has been estimated to be a factor of about 10^{3} higher for the EEF standard design and 10^{4} higher for the low activity design.

5.51 For a comparison between the reference fusion reactor and a fission reactor it is reasonable to distinguish between the highly volatile elements of groups I and II and the less volatile elements of groups III to V.

In the reference fusion reactor the dominant isotope for group I is tritium, in group II only less significant isotopes exist. In a fission reactor key isotopes for group I are Kr and Xe, while group II is represented by I and Cs. These highly volatile isotopes can be released by severe accidents to a large extent. For group I a total release must be assumed, for group II release fractions above 0.1 are possible with a fission reactor under extreme circumstances.

The radiological hazard from these highly volatile isotopes is very different for a fission reactor than for the reference fusion reactor. From a release of 1% of the total tritium inventory, relevant regulations would not be violated even under pessimistic assumptions [5.22]. In contrast, the fission reactor normally contains Cs in a quantity which, on its own, would create severe radiological consequences, resulting only from inhalation and external radiation. Regulation limits could be exceeded by one or two orders of magnitude, if 1% of Cs is released. By ingestion the situation would be considerably aggravated.

For the mobility groups III to V the release fractions conceivable for the fusion reactor are lower than for a fission reactor. If only inhalation and external radiation are considered (ingestion might be avoided by appropriate measures) the doses to the maximum exposed individual are less than 10 times above the limit dose for the fusion reactor, while a fission reactor could produce doses more than two orders of magnitude above the limits.

TABLE 5.22

Release fractions for fusion and fission reactors

Mobility group	Release fraction leading to limit value doses for	
	Fusion reactor	Fission reactor
I	10^{-1} (^3H)	10^{-1} (Kr,Xe)
II	> 1	10^{-4} (I, Cs)
III	10^{-5}	10^{-4}
IV	10^{-4}	10^{-4}
V	10^{-5}	10^{-5}

Release fractions for fusion and fission reactors, which would cause limit value doses, are listed in Table 5.22.

These figures give only rough estimates. However, it can be concluded that even a total release of group II isotopes would not cause limit value doses. When comparing the figures for low mobility groups III to V it has to be borne in mind that accidental release fractions from a fusion reactor are expected to be significantly lower than from a fission reactor where rather high temperatures may be reached in a molten reactor core.

5.52 The Chernobyl accident released considerable fractions of radioactive inventory into the environment. Table 5.23 lists inventory levels ten days after the accident and estimates of release fractions for the main isotopes. In Chernobyl the near distance consequences were diminished by the strong thermal lift of the released material. Under more adverse conditions the release of 10 to 13% of Cs alone would have led to doses of several Sv up to some tens of Sv, causing early fatalities with very high probability.

5.53 Although it can be stated that the probability of severe accidents causing significant releases of radionuclides is very low both for fusion and for fission reactors (if the plants are properly designed and operated), a quantitative comparison of probabilities would be speculative.

It can be concluded that the accident-related hazard potential of a fusion reactor is significantly lower than that of a fission reactor (of actual design). This is mainly due to the large amount of highly volatile fission products in a fission reactor and to the low release fractions of less volatile elements in a fusion reactor.

TABLE 5.23
Chernobyl: radioactive inventory and release fractions

Isotope	Half-life (days)	Inventory (Bq)	Release fraction (%)
Kr 85	3.93×10^3	3.3×10^{16}	approx. 100
Xe 133	5.27	1.7×10^{18}	approx. 100
I 131	8.05	1.3×10^{18}	20
Cs 134	750	1.9×10^{17}	10
Cs 137	1.1×10^4	2.9×10^{17}	13
Sr 89	53	2.0×10^{18}	4
Sr 90	1.02×10^4	2.0×10^{17}	4
Pu 239	8.90×10^6	8.5×10^{14}	3
Pu 240	2.40×10^6	1.2×10^{15}	3

THE PROVISION OF FUEL FOR THE FUSION REACTOR

5.54 The important aspects of fuel availability are:

- cost, related to abundance and concentration in the Earth,
- distribution, which affects strategic choice,
- environmental impact of mining, milling and delivery.

Lithium

5.55 The D-T Tokamak requires deuterium and lithium fuel supply, the minimum amounts consumed per GW(e)year being approximately:

D 70 kg
Li 2600 kg

More important is the requirement for a breeder inventory of between 100 and 1000te lithium per GW(e) to meet the necessary breeding gain specification and, in some designs, to act as primary coolant. Against that background the abundance of lithium in the Earth's crust is around 30ppm, which makes it one of the more plentiful elements compared to those used to make special steels or to fuel fission reactors.

5.56 Lithium is mined in surface excavations of alumino-silicate minerals containing around 1% by weight lithium but production is currently dominated by brine sources. Brines typically contain around 100ppm of lithium, which is precipitated as carbonate after some concentration has been carried out. Proven reserves [5.11] of lithium are around 2.6Mte, of which 1.6MTe is in brines, but world resources of easily recoverable lithium ($20-30 per lb) are thought to exceed 10Mte [5.13]. Much larger quantities could be recovered at higher cost, the preference probably being to extract from more dilute brines. In the limit there is 0.2ppm of lithium in sea water. Current world production of lithium is about 80000te [5.12] mainly for use in glass and ceramics, in aluminium production and in lubricants.

5.57 The major known reserves of lithium occur in brines in Chile and in pegmatites in Australia and USA [5.12]. However, the brines which could be exploited at higher price are very widespread. In Europe there are resources in Portugal, Spain and France; in the UK, Cornish brines contain 10 to 100ppm lithium. We may reasonably conclude that, in the quantities required to sustain a large fusion reactor installation, lithium is both widespread and plentiful.

The risk to miners from lithium exploitation is low because, for the foreseeable future, a combination of brine extraction and open pit mining will meet all requirements. In terms of environmental disturbance the mining of lithium in Chile and USA today is perceived as a low impact operation. The open pit mines produce a waste rock which generates no toxic dust or gas and the brine extraction produces no toxic waste.

Deuterium

5.58 The small requirement for deuterium fuel in a D-T Tokamak would make no significant demands on either the sources of supply or the environment. Water contains deuterium at levels of 100-160ppma D in H. Current production of D_2O [5.12] is around 1000te per year and could easily be expanded.

Comparison with fission reactors

5.59 The generation of 1GW(e)year of electrical energy by nuclear fission requires the mining and purification of uranium. Unlike lithium extraction these operations incur risks of deep mining and toxic dust and gas. They also generate waste "tailings" which contain all the radioactivity associated with the decay products of ^{238}U and ^{235}U.

The quantity of natural uranium required to fuel 1GW(e)year varies from around 300te (natural U reactors) to 200te (present PWR). With further improvements in burn-up, reduction of enrichment tails and recycle of reprocessed U and Pu this figure could come down to perhaps 65te by the middle of the next century. Beyond that, the Fast Reactor would be capable of operation with less than 2te natural uranium per GW(e)year.

5.60 Bromley [5.11] has estimated that, for an ore grade of 0.1% U_3O_8, the mining and milling of 65te of uranium carries the following risks.

TABLE 5.24

Uranium mining risks

	Deaths per GW(e) year	
	Open Pit	Underground
Public risk (radon)	1.0×10^{-3}	1.0×10^{-3}
Mining risk	3.1×10^{-2}	1.74×10^{-1}

5.61 For completeness we note that Bromley [5.14] in 1986 found the risk of death in mining of coal in the UK to be 1.39 per GW(e)year. There is evidence that closure of the less safe mines in the past few years has reduced that figure but there can be no real doubt that the risk from mining of fuel increases in the sequence.

Fast Reactor
Fusion Reactor $<$ PWR $<$ Coal

with one to two orders of magnitude reduction at each step.

The provision of structural materials for the fusion reactor

5.62 Large quantities of iron and concrete are required for any power station so the environmental impact and risk associated with those materials are unlikely to show any qualitative advantage or disadvantage for fusion.

Cannon [5.15] gave ranges of the quantities of other less common materials required in the construction and 20 year operation of a conceptual 1Gw(e) fusion reactor. Table 5.25 reproduces his reference data for the "nuclear" part of a 1GW(e) fusion power station.

TABLE 5.25

Materials to build and operate a 1GW(e) fusion reactor [5.15]

Element	Tonnes for construction and 20 years operation
Al	422
B	550
Cr	1120
C	1380
Cu	1820
He	71
Mn	1580
Mo	70
Nb	80
Ni	1060
Sn	10
Si	60
Pb	320
Ta	50
Ti	1540
V	10
W	700
Zr	230

5.63 Bromley [5.11] has used Cannon's data to estimate the risk to miners in extracting these materials from typical mines. The most significant risks occur in provision of the chromium, copper, molybdenum, tantalum, titanium and tungsten. Estimates based on 1GW(e) year are given in Table 5.26 for comparison with Table 5.24.

TABLE 5.26

Risks in mining special metals for the fusion reactor

(See Table 5.25)

Element	Fatal Mining Risk per GW(e)year
Cr	8×10^{-4}
Cu	4×10^{-4}
Mo	1×10^{-3}
Ta	2×10^{-3}
Ti	3×10^{-4}
W	6×10^{-4}

5.64 Such estimates, relating to mines judged to be in operation in the middle of the next century, are necessarily very approximate but they show that the provision of structural materials for this reference reactor involves mining risks far below those for fuelling a coal fired or even a PWR power station.

5.65 Bromley also estimated [5.11] the environmental impact of the waste rock likely to be deposited around a mine in the provision of 1GW(e)year of electrical energy. By associating this impact with the mass of waste rock produced the result given

TABLE 5.27

Obtrusiveness of waste rock

Element	Tonnes per GW(e)year
Ta	1.7×10^5
W	1.3×10^5
U (PWR)	1.0×10^4

in Table 5.27 is obtained. For comparison the analogous result for uranium to fuel the PWR (200te) is included. We may reasonably conclude that the mining of special metals for the fusion reactor causes a larger visual impact than the mining of uranium for the PWR (or of course the Fast Reactor) but the quantities of spoil involved are similar to those which would in any event be produced in mining the iron ore to construct any type of power station. Moreover, the special materials might be recycled after use to reduce the quantities required per GW(e)/y

<u>Effect of electromagnetic fields [5.19]</u>

5.66 All electricity generation is accompanied by generation of electromagnetic fields but these local effects are not generally of any environmental significance. The Tokamak based fusion reactor deserves special consideration in this context because in Tokamak reactors the plasma will be shaped and confined by magnetic fields. Usually steady-state magnetic fields are assumed, although there will be transient fields if the pulsed-burn mode of operation is adopted. The two main sources of magnetic fields for the Tokamak are the toroidal field (TF) coils and the poloidal or equilibrium field (EF) coils. The TF coils produce large steady-state fields (typically about 10T) that are mostly contained within the coil system, so that the external fields are negligible. However, the EF coils together with the plasma current and divertor coils generate a slowly varying external dipole field that radiates vertically and horizontally relative to the torus. The strength of the magnetic fields decreases monotonically with distance from the source.

5.67 Standards or guidelines limiting human exposure to static and extremely low frequency (<300Hz) magnetic fields have been developed in a few countries, with particular emphasis on exposure from specific devices. In the UK, conditions have been specified which must be met during the operation of magnetic resonance imaging (MRI) equipment. For patients, the static field should not exceed 2.5T for the whole or a substantial portion of the body. For staff operating MRI equipment, exposure for prolonged periods to more than 0.02T for the whole body or 0.2T for the arms or hands should be avoided. These limits may be increased to 0.2T for the whole body and 2T for the arms and hands for periods totalling less than 15 minutes at a time, provided intervals of about one hour occur between such exposures. For time-varying fields, limits are based on the duration of the field changes (i.e. the time during which electric eddy currents are being induced). When the duration or exposure exceeds 10ms, exposure should not exceed root mean square rates of change of field (dB/dt) of 20T/s for patients. For durations of change of less than 10ms, higher dB/dt values are permitted as defined by the relationship $(dB/dt)^2 t < 4T^2/s$, where t is the duration of the change.

5.68 Magnetic fields may also pose a hazard by affecting the operation of electronic devices. In particular, both static and time-varying magnetic fields can interfere with the proper functioning of modern heart pacemakers. Problems can occur in the presence of fields with time rates of change above approximately 40mT/s and in static fields exceeding 1.7 to 4.7mT. Other implanted surgical devices may also be sensitive to magnetic fields to an extent which depends on their alloy composition. All persons entering magnetic field environments should therefore be screened carefully and, if necessary, prohibited from access. Paramagnetic and ferromagnetic objects subject to an intense magnetic field can cause serious damage to the reactor or injury to operators and care must also be taken to exclude these from such areas.

5.69 In general, reactor control instrumentation must be located where magnetic fields do not exceed 1mT. Thus, control room personnel will necessarily be exposed to only relatively low fields but it may not be economically feasible to reduce the magnetic field strengths to these low levels in other work areas. It was calculated for STARFIRE, a typical steady-state reactor, that except for the reactor bay area of the reactor building, where workers would not be permitted during operation, personnel would not be exposed to fields of greater than 50mT. The field was predicted to be less than 0.1mT in the reactor control room (approx. 230m from the reactor) and to fall to about the same level as the earth's natural magnetic field (i.e. 0.03mT to 0.05mT) at a distance of between 300 and 350m. Even in regions with a field of 50mT, the UK MRI dB/dt limit of 20T/s would only be exceeded by a full field change occurring in a time of less than 2.5ms, which cannot be envisaged in such a large, high energy storage system. The STARFIRE calculations may be considered conservative since the shielding provided by structural materials has been ignored.

5.70 If necessary, occupational exposure to magnetic fields beyond the main reactor buildings could be reduced in three ways; (1) active shielding (magnetic coils), (2) passive shielding (iron shell), and (3) distance (land area). Active shielding could be provided by a single coil with a diameter of 20 to 40m, excited to cancel the dipole field. Protection of all personnel at all times by reducing the fringe magnetic field would be much more costly than providing local shielding of small areas such as control rooms where personnel are more likely to be stationed. Compared to the total costs of modern power plants, the costs of magnetic shielding for employees assigned to a small control room would be insignificant at locations where the ambient fringe field was less than 10mT.

5.71 A combination of shielding design and appropriate location of plant equipment and hence operating personnel should limit exposure of workers to fringe magnetic fields in excess of the earth's natural field. The public will be exposed to no magnetic fields greater than the earth's natural background field even at the power station fence. We may conclude that the fusion reactor does not present any new environmental impact on account of its use of magnetic confinement of the plasma.

International Safeguards [5.10]

5.72 The growth of civil nuclear power has been accompanied by international concern that fissile material should not be secretly diverted by national Governments into the construction of nuclear weapons. The International Atomic Energy Agency, through the Treaty on Non-Proliferation of Nuclear Weapons, and the European Community, through the Euratom Treaty (Article 77), implement "safeguards" measures to verify that no such diversion is occurring. These measures rely upon inspectors who examine records of fissile material movement, verify records by carrying out accountancy checks, and operate containment and surveillance systems.

5.73 The feasibility of safeguards procedures depends to a large extent on the basic physics and chemistry of the nuclear fuel cycle. It is therefore important to understand whether a fusion reactor, based on a D-T burning Tokamak, would differ from the known fission reactors in any important respect in this context.

The IAEA Statute and the CEC Regulation are very clear in their definitions of "fissionable" and "source" materials. Deuterium, tritium and lithium are not categorised as being of safeguards significance. This is clearly a major advantage for the fusion fuel cycle. The D-T reactor is however a large source of neutrons. It is the feasibility of detecting the breeding of fissile material by exposure of uranium or thorium to the neutron flux which is the real "safeguards" concern.

5.74 It can be calculated that at least 100kg of ^{238}U or ^{232}Th would have to be irradiated in the blanket of a fusion reactor to produce 1kg/year of ^{239}Pu or ^{233}U. This is comparable to a LWR core but is less efficient than the blanket of a fast reactor. In principle the fertile material could be removed for processing when blanket components are removed to a shielded store every few years as part of the routine component renewal operation.

The design of a blanket/first wall renewal system could be arranged so that there is only one route for highly active components to pass from the reactor to the store. Furthermore a reactor design could be verified to ensure that no U/Pu or Th/U separation plant is built inside the facility. Under those conditions the application of a seal to the loaded casks of waste components, together with neutron and gamma sensors to detect irradiated U or Th, should ensure that fissile material removal cannot go undetected.

5.75 We may reasonably conclude that the D-T fusion reactor has a basic advantage in that the routine legitimate fuel materials do not require safeguards. This is obviously not the case with fuel discharged from fission reactors, nor with the new mixed oxide fuel loaded into PWRs or fast reactors. As a large neutron source the fusion reactor could, with suitable engineering modifications, be used to produce fissile material. The operation would be detectable by safeguards instruments and inspectors.

CONCLUSIONS

5.76 This survey of the environmental impact characteristics of a Tokamak fusion reactor has identified some qualitative features which are likely to be important in any comparison with fossil or fission energy sources.

5.77 In terms of volumes of fuel to be mined, ash to be disposed of and radio-toxic content of gaseous and liquid effluents the fusion and fission systems have by far a lesser environmental impact than coal. The characteristic feature of the fusion site releases in normal operation is likely to be the release of small amounts of tritium to the atmosphere. The exact level of this release is subject to control by engineered measures in the detailed design of a particular plant but the assumptions made in Table 5.12 lead to the conclusion that the lifetime toxic content of such emissions might be a factor fifty below that from ^{133}Xe and ^{85}Kr emissions from a PWR operated on a once-through fuel cycle, or a factor of many thousands below that from a PWR with fuel reprocessing. Annual dose to the most exposed member of the public from such releases of tritium as T_2O might be around 0.1mSv [5.18], a factor twenty or more below the natural background.

5.78 The total radioactivity and associated thermal power of the fusion reactor three days after final shutdown are less, by factors two and six respectively, than those of an equivalent PWR; this difference increases to around a factor 100 after 100 years cooling and to much larger factors at longer times. The toxic content of this radioactivity is, however, very much smaller in the fusion case. Figures 5.14 and 5.15 show that, due to the complete absence of actinides in the fusion reactor, a factor of 10 to 100 applies almost immediately on shutdown. After 100 years the toxic content of the fusion reactor has fallen to between one ten thousandth and one millionth of the PWR.

5.79 The examination of potential risk from the groundwater pathway at a deep underground disposal site shows that in comparison with PWR wastes the fusion reactor has a theoretical advantage by virtue of the absence of the long-lived fission product ^{129}I. However, that is in any event a vanishingly small risk. In qualitative terms there is an advantage in having no actinides in the fusion wastes since that avoids any need to select sites with groundwater return times of tens of thousands of years.

5.80 The inherently smaller, toxic content of the operating fusion reactor is an advantage when considering the consequences of large accidents. A part of the site tritium inventory, perhaps 1kg, will be potentially vulnerable in the most extreme accident. Other radioactive materials would be very well immobilised in the reactor structure. In comparison with the fission reactor, in which ^{131}I, ^{137}Cs and ^{90}Sr in the fuel elements present a much more toxic inventory requiring engineered containment in accident situations, the fusion reactor makes much lesser demands upon the designer. Moreover there are inherent features of the fusion reactor which reduce the probability of containment failure in an accident to almost zero. The shutdown of the fusion reaction is simple and reliable when abnormal conditions occur in the plasma and the decay heat to be removed after shutdown is smaller than in a fission reactor. Holdren et al [5.8] have shown that the thermal power from radioactive decay in the fusion reactor is one to two orders of magnitude lower at shutdown (MW per m^3 of core) than in the PWR.

5.81 The advantages to be gained from the use of "low activation" structural materials in a fusion reactor have not been fully explored in this report. They will not have any impact upon the risk from tritium release and so the case will rest upon such issues as shutdown decay power and ease of decommissioning. In the present work a fairly simple attempt to evaluate the effects of using vanadium for the first wall and blanket structures revealed order of magnitude reductions in toxic content, activity and thermal power by ten years after final shutdown.

5.82 The Tokamak fusion reactor is a low-rated machine compared to a PWR. In terms of volume of solid radioactive wastes produced it is preferable to the PWR with fuel reprocessing and recycle but produces a much larger volume than the once-through PWR due to the quantity of decommissioning waste. Taking into account the additional requirement, in the PWR case, to dispose of spent fuel there is probably little to choose between Fusion and PWR in terms of eventual cost of decommissioning.

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FIGURE 5.2
Activities of components of EEF Reference Reactor (ferritic) after final shutdown. 1200MW(e)

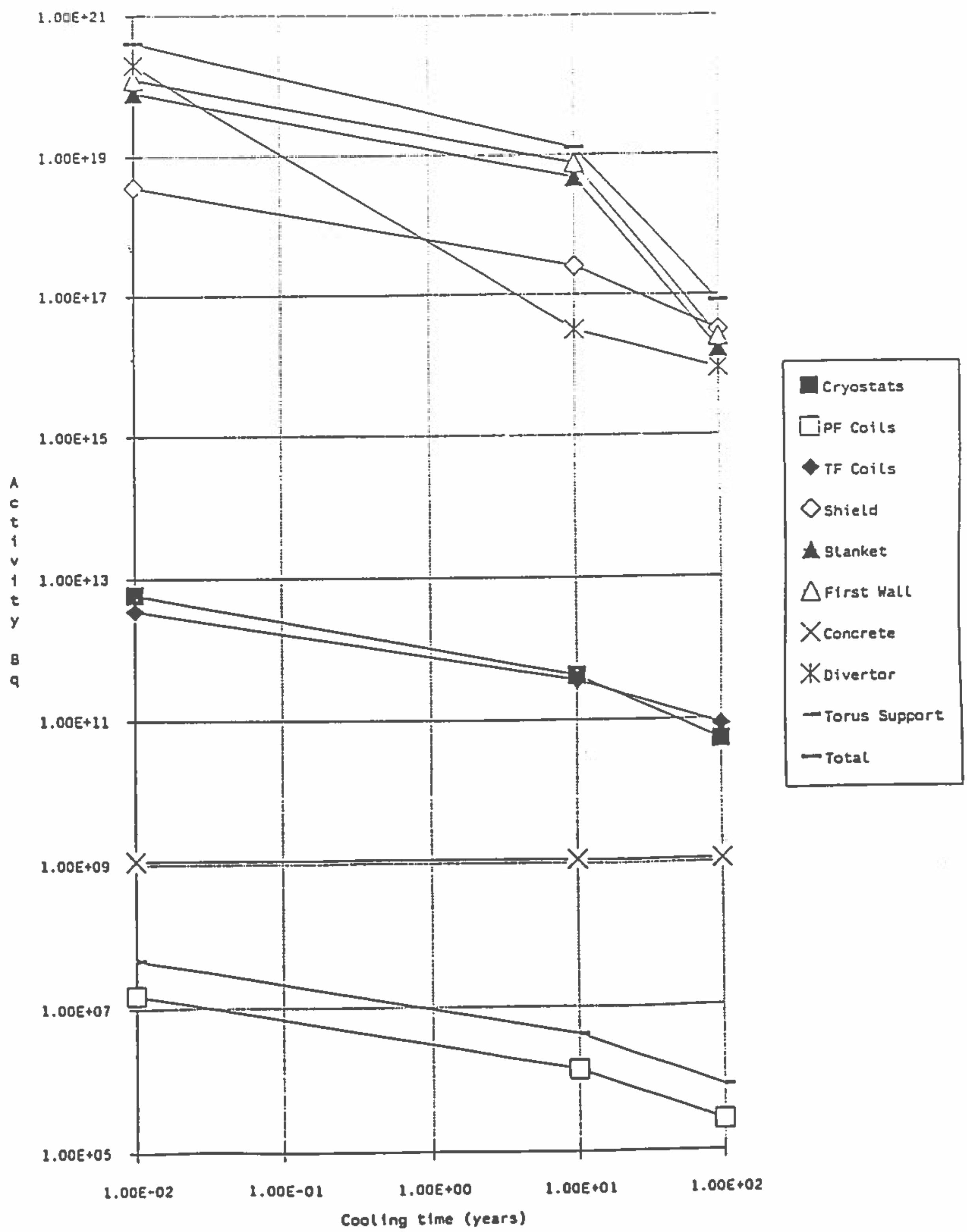


FIGURE 5.3

Thermal power of components of EEF Reference Reactor (ferritic) after final shutdown. 1200MW(e)

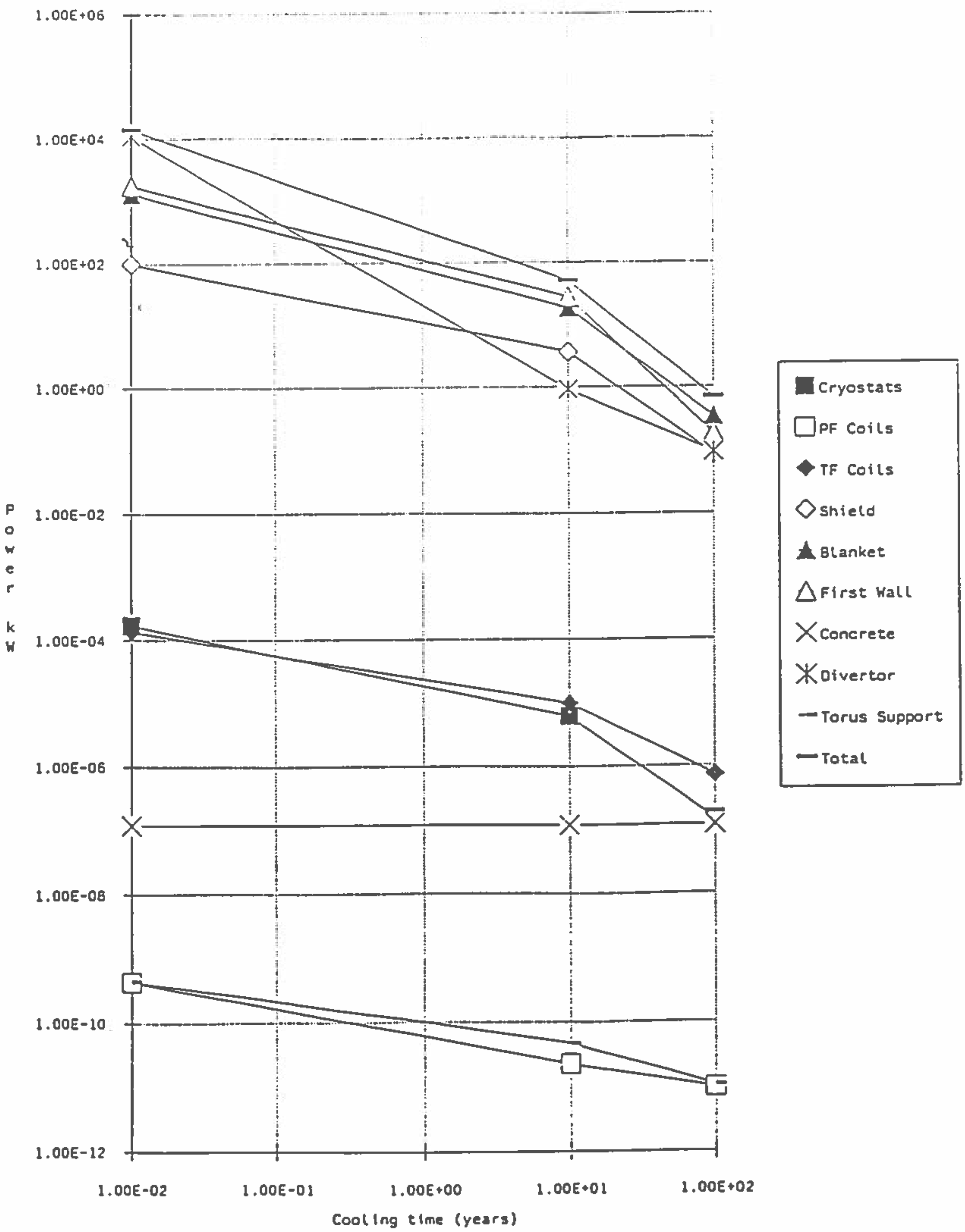


FIGURE 5.4
Dose rate from components of EEF Reference Reactor (ferritic) after final shutdown. 1200MW(e)

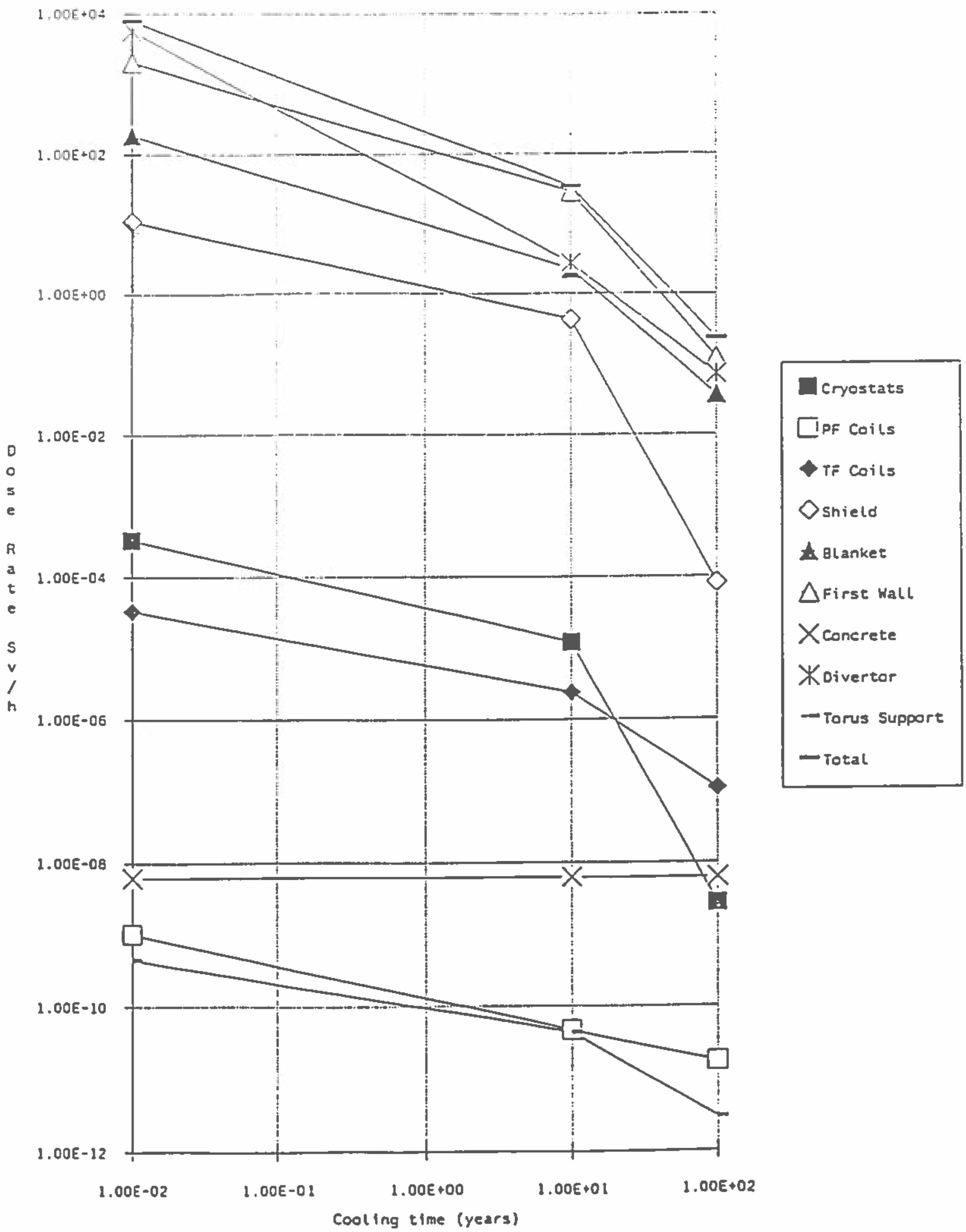


FIGURE 5.5
Inhalation toxic content of components of EEF Reference Reactor (ferritic) after final shutdown 1200MW(e)

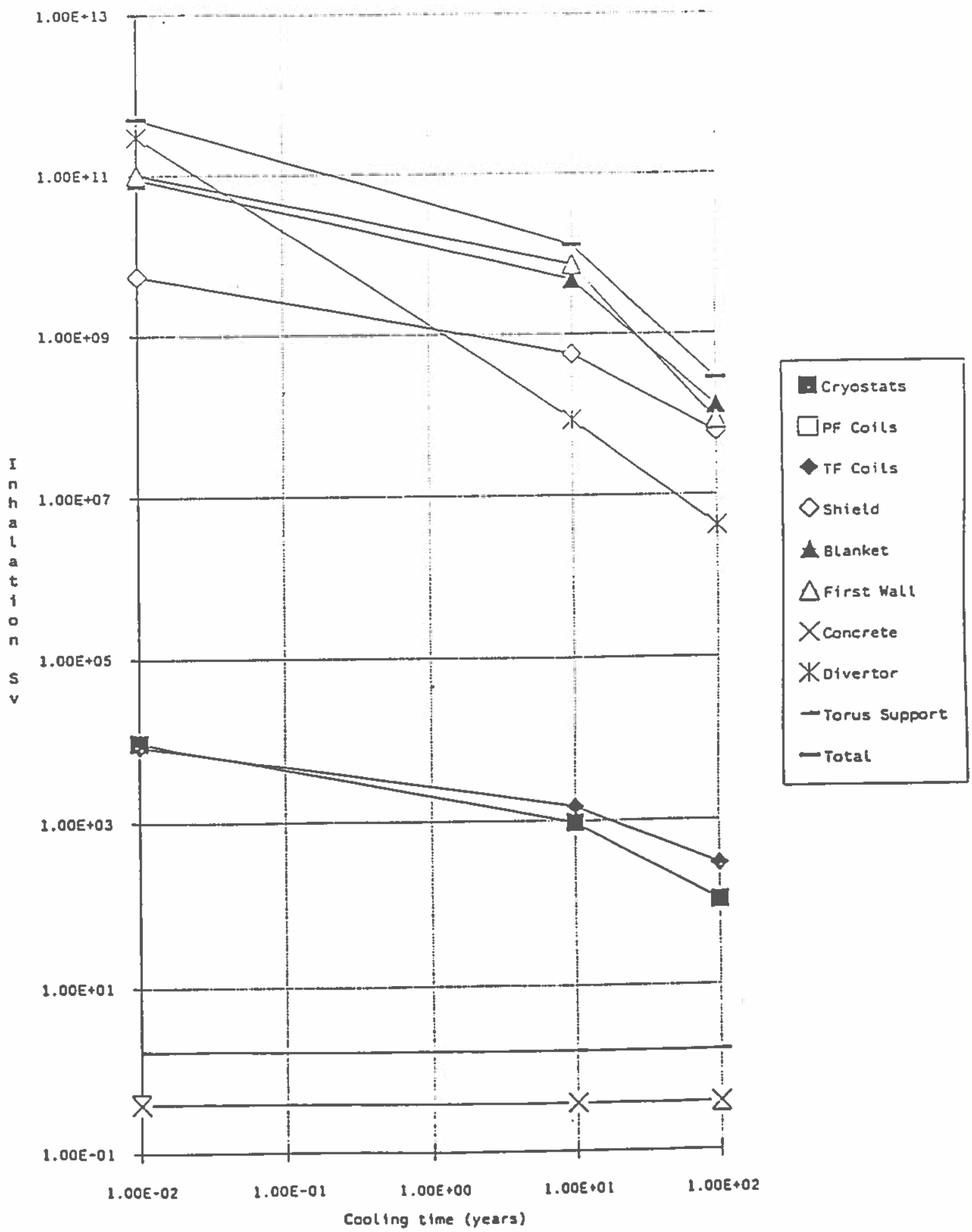


FIGURE 5.6
Ingestion toxic content of components of EEF Reference Reactor (ferritic) after final shutdown. 1200MW(e)

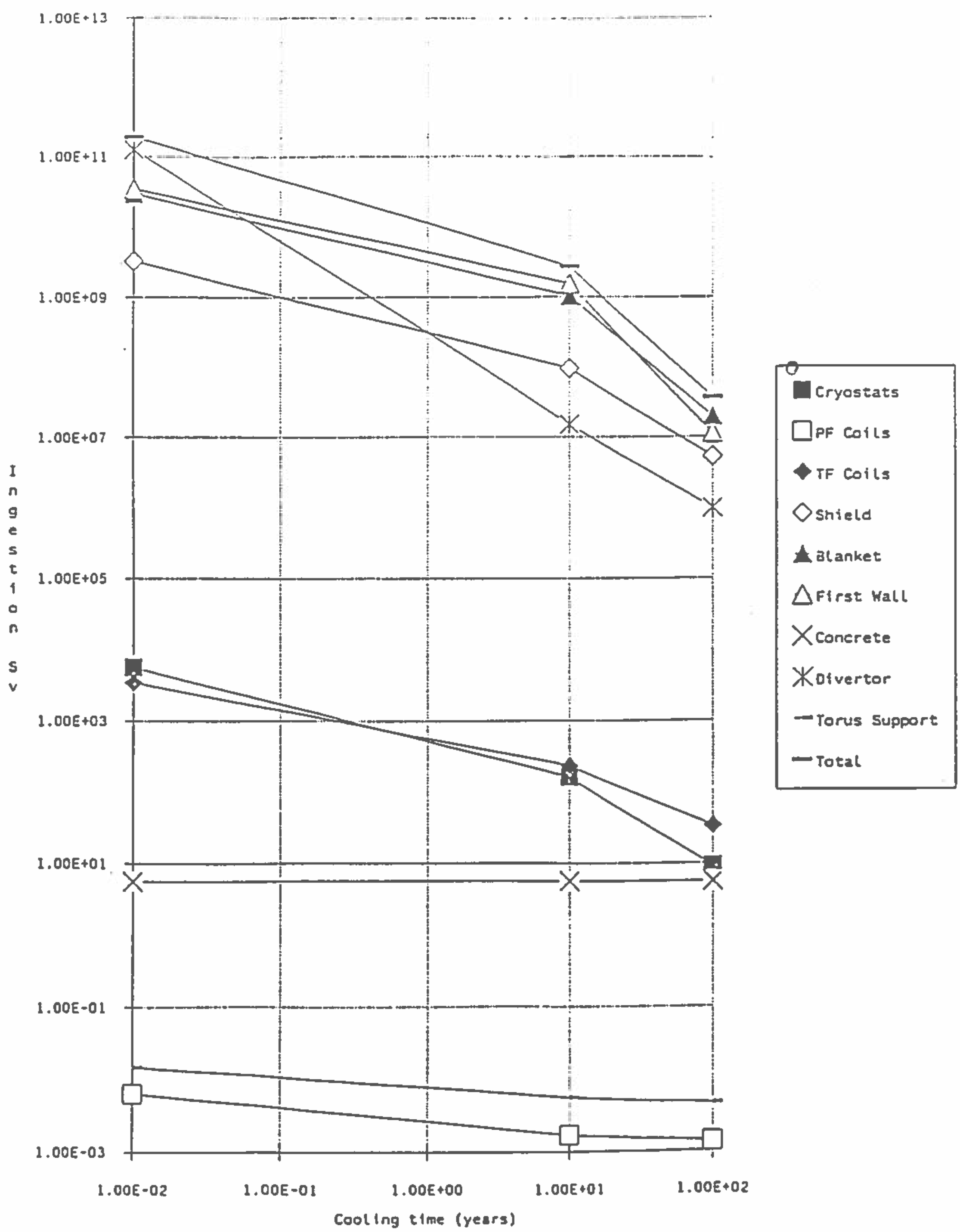


FIGURE 5.7

Activities of components of EEF Reference Reactor (low activation) after final shutdown 1200MW(e)

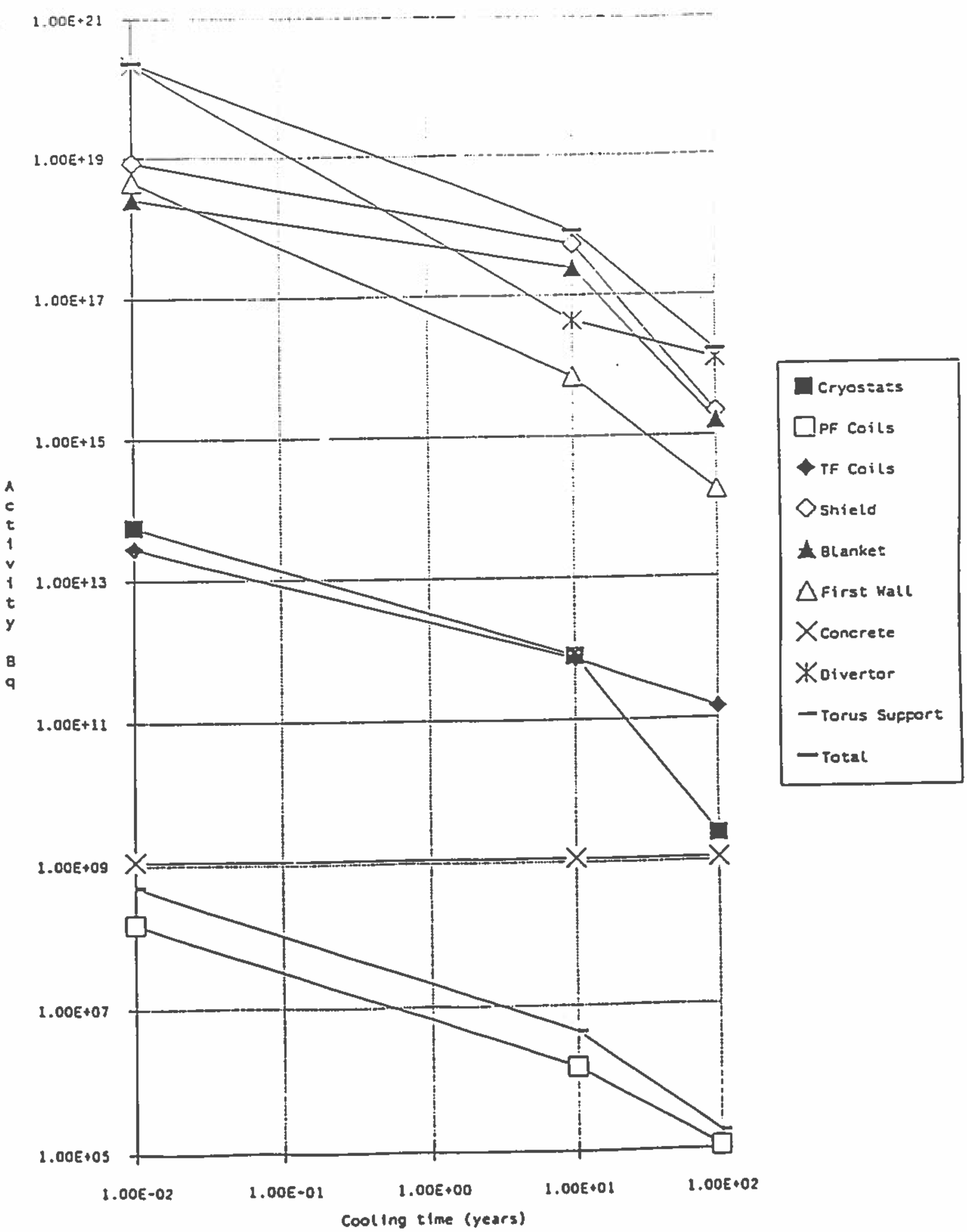


FIGURE 5.8

Thermal power of components of EEF Reference Reactor (low activation) after final shutdown 1200MW(e)

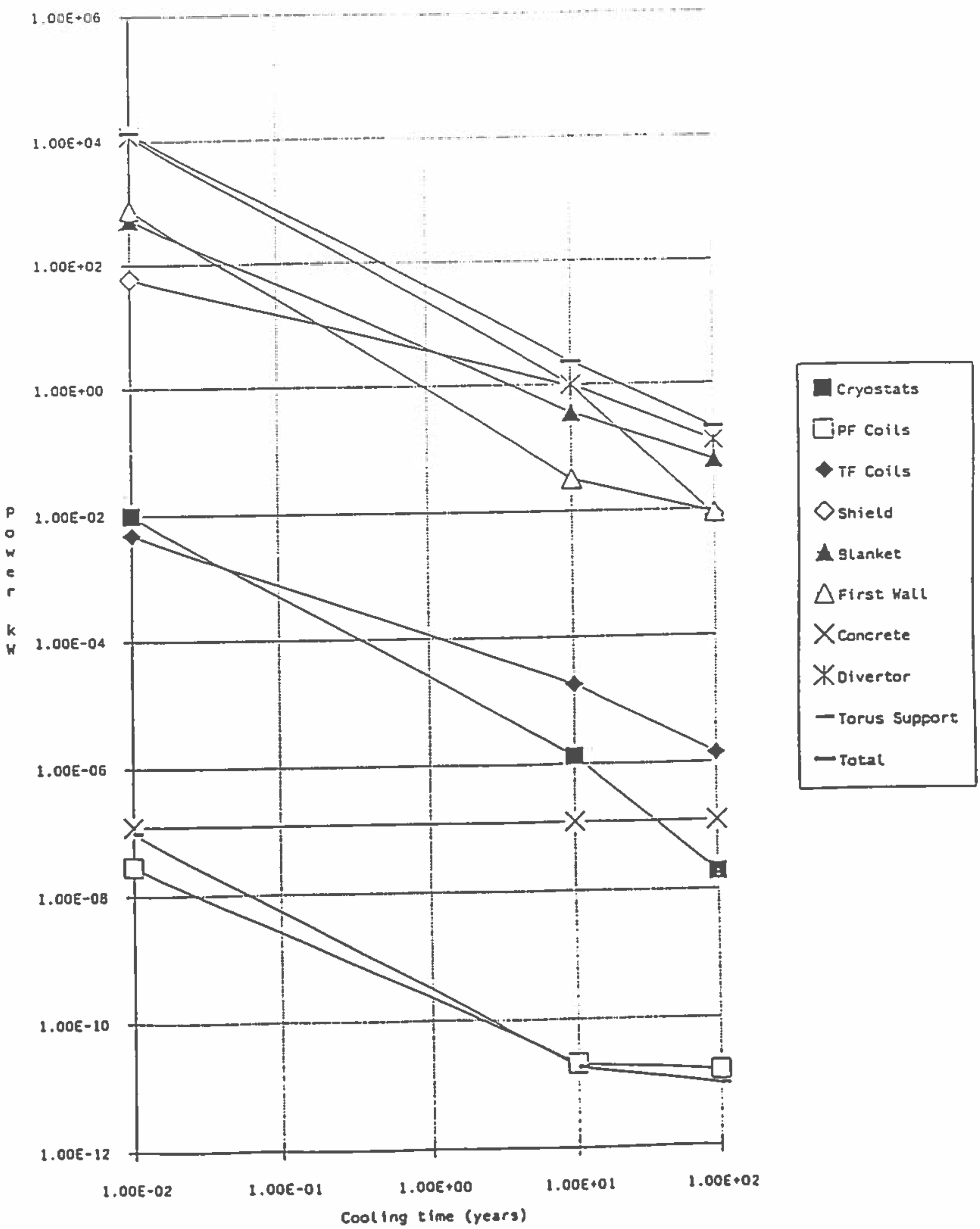


FIGURE 5.9

Dose rate from components of EEF Reference Reactor (low activation) after final shutdown 1200MW(e)

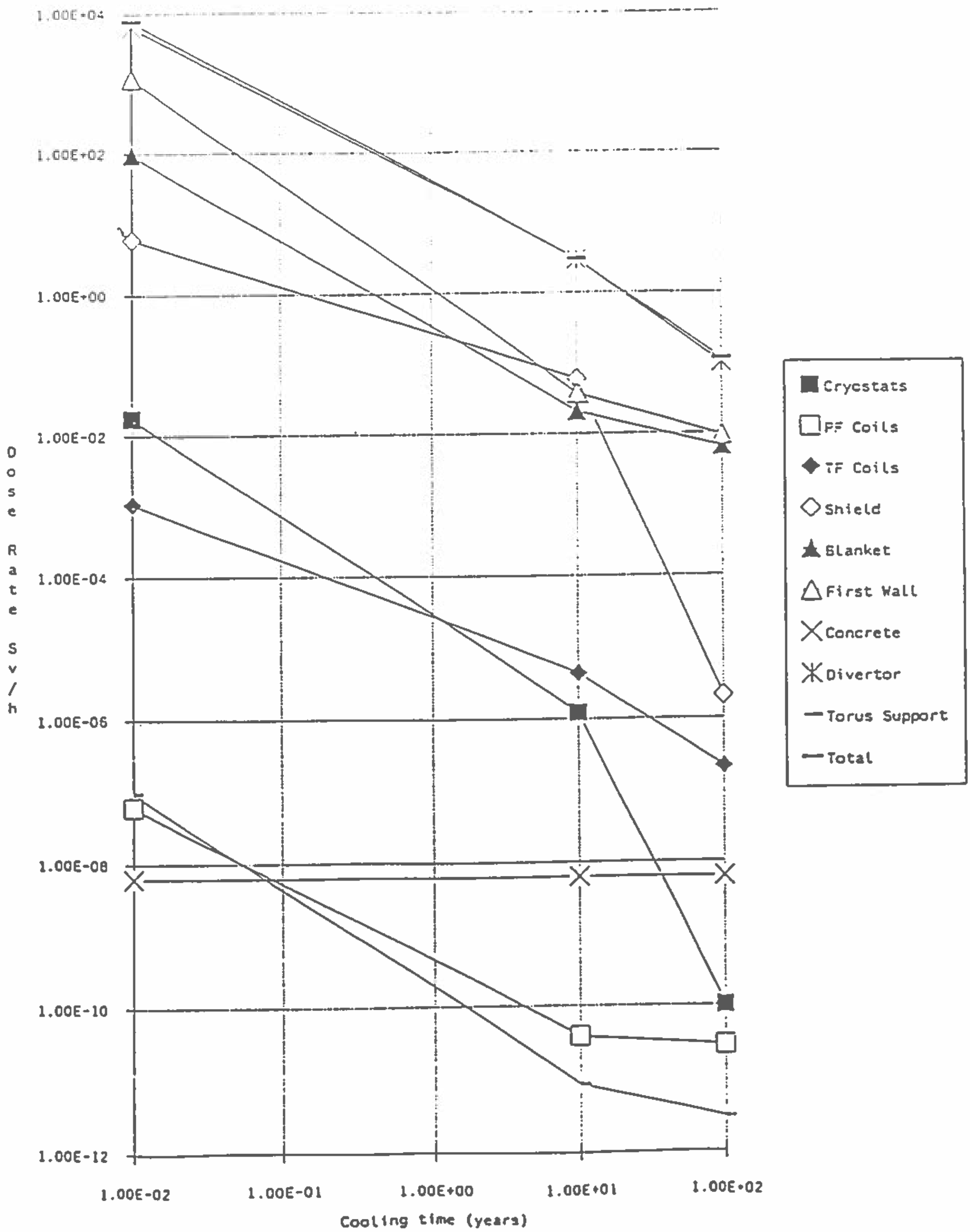


Figure 5.10
Inhalation toxic content of components of EEF Reference Reactor (low activation) after final shutdown. 1200MW(e)

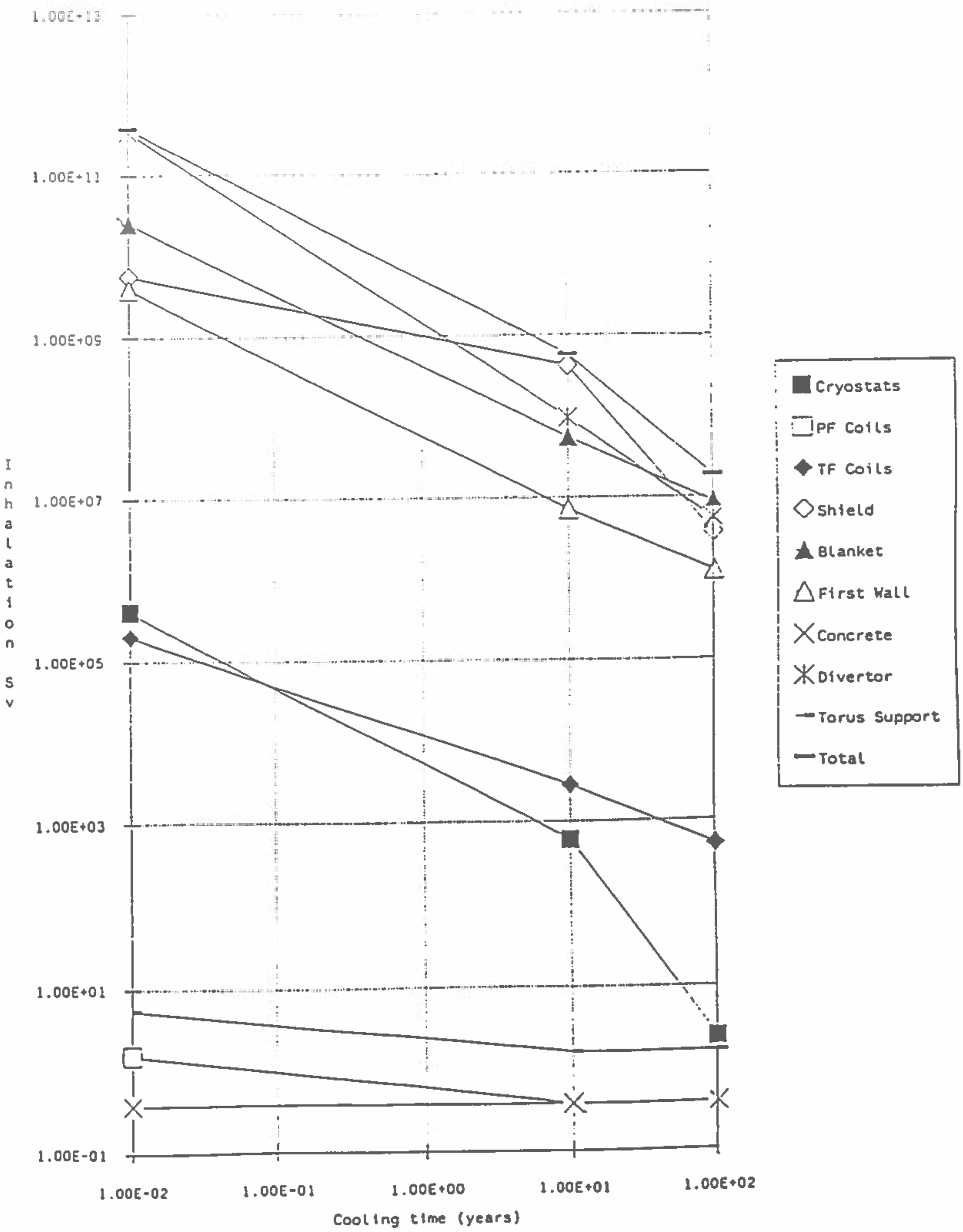


FIGURE 5.11

Ingestion toxic content of components of EEF Reference Reactor (low activation) after final shutdown 1200MW(e)

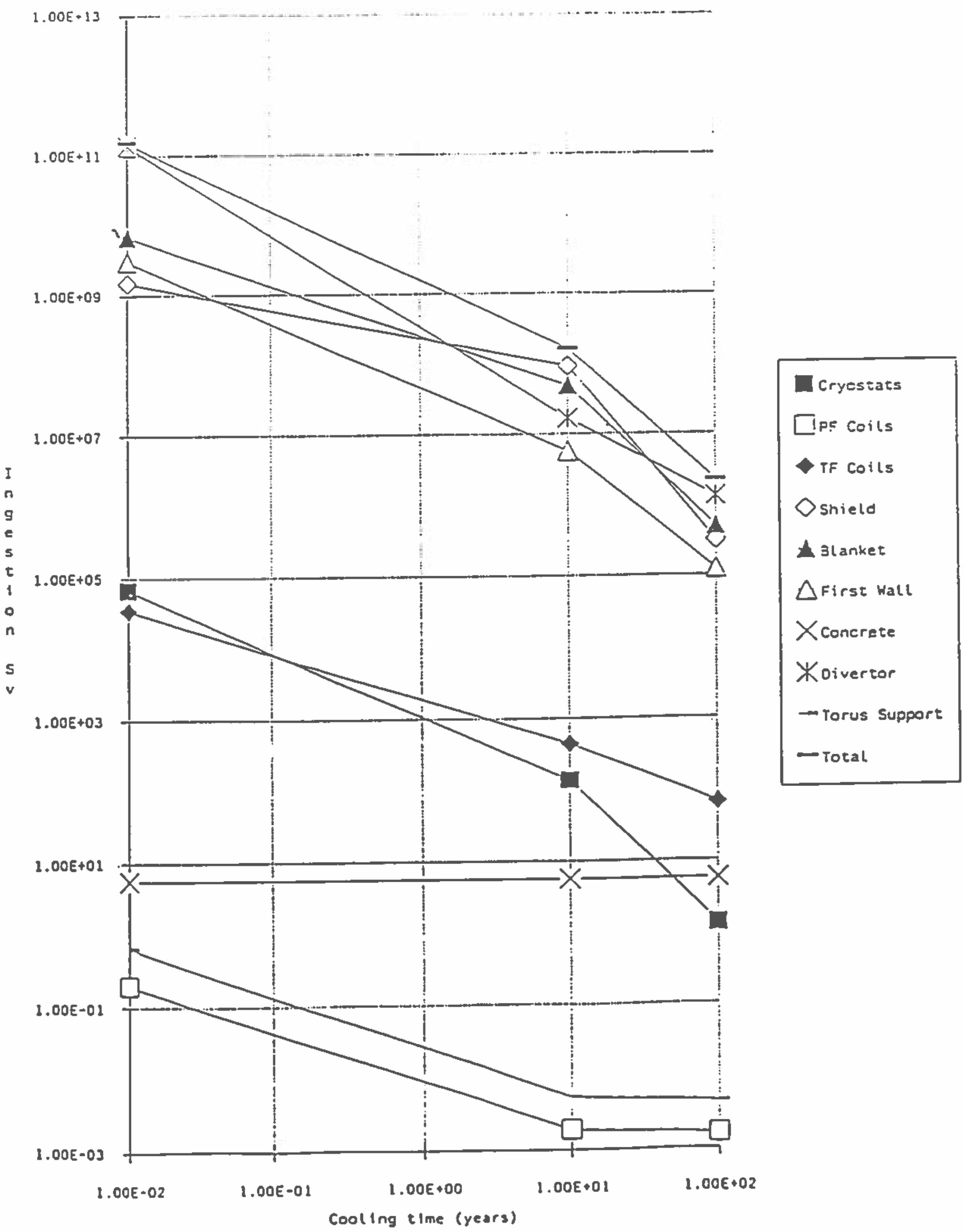


FIGURE 5.12
Comparison of activity of PWR with both variants of EEF 1000MW(e)

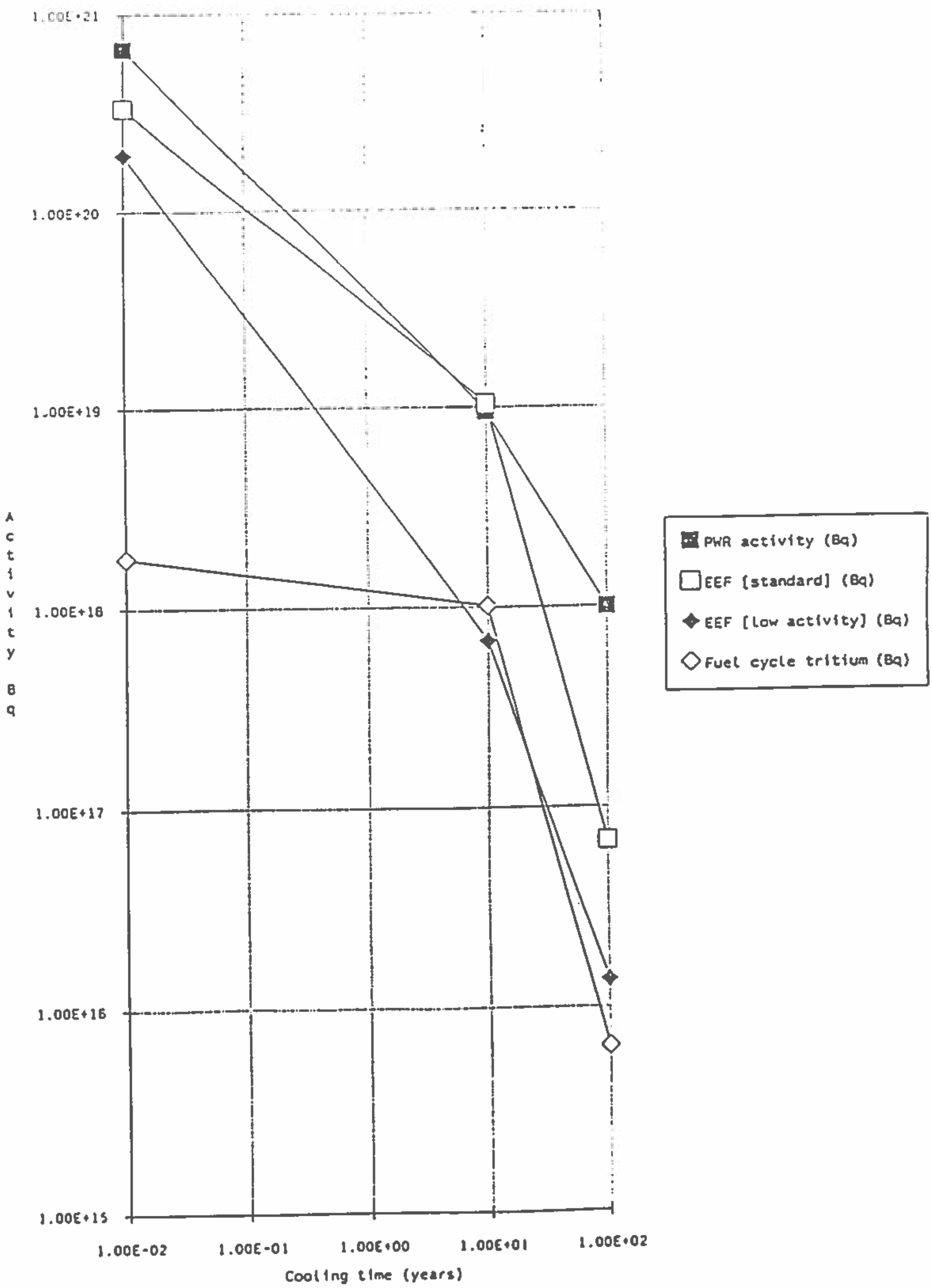


FIGURE 5.13

Comparison of thermal decay power of PWR with both variants of EEF 1000MW(e)

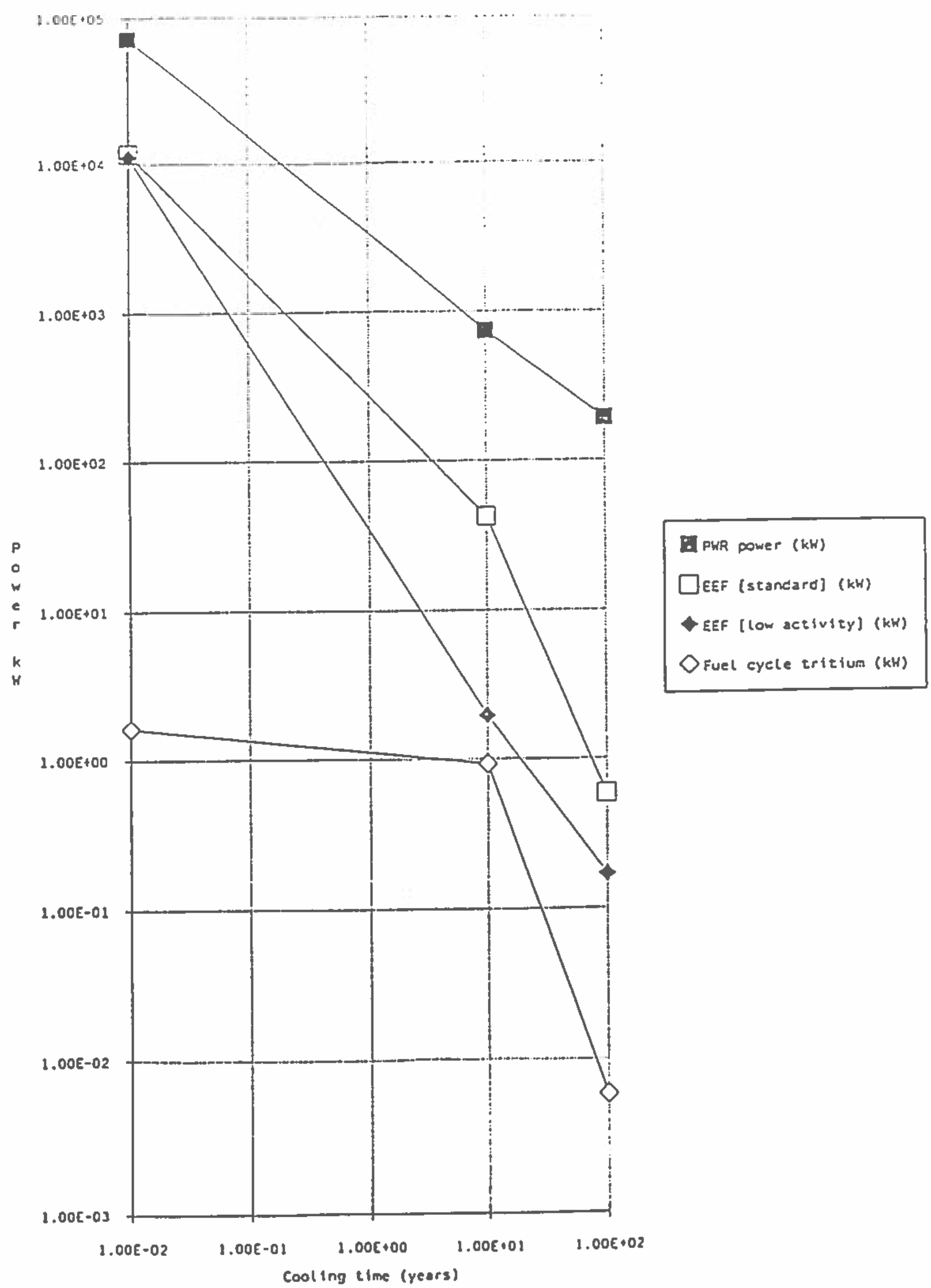


FIGURE 5.14

Comparison of toxic content (ingestion) of PWR with both variants of EEF 1000MW(e)

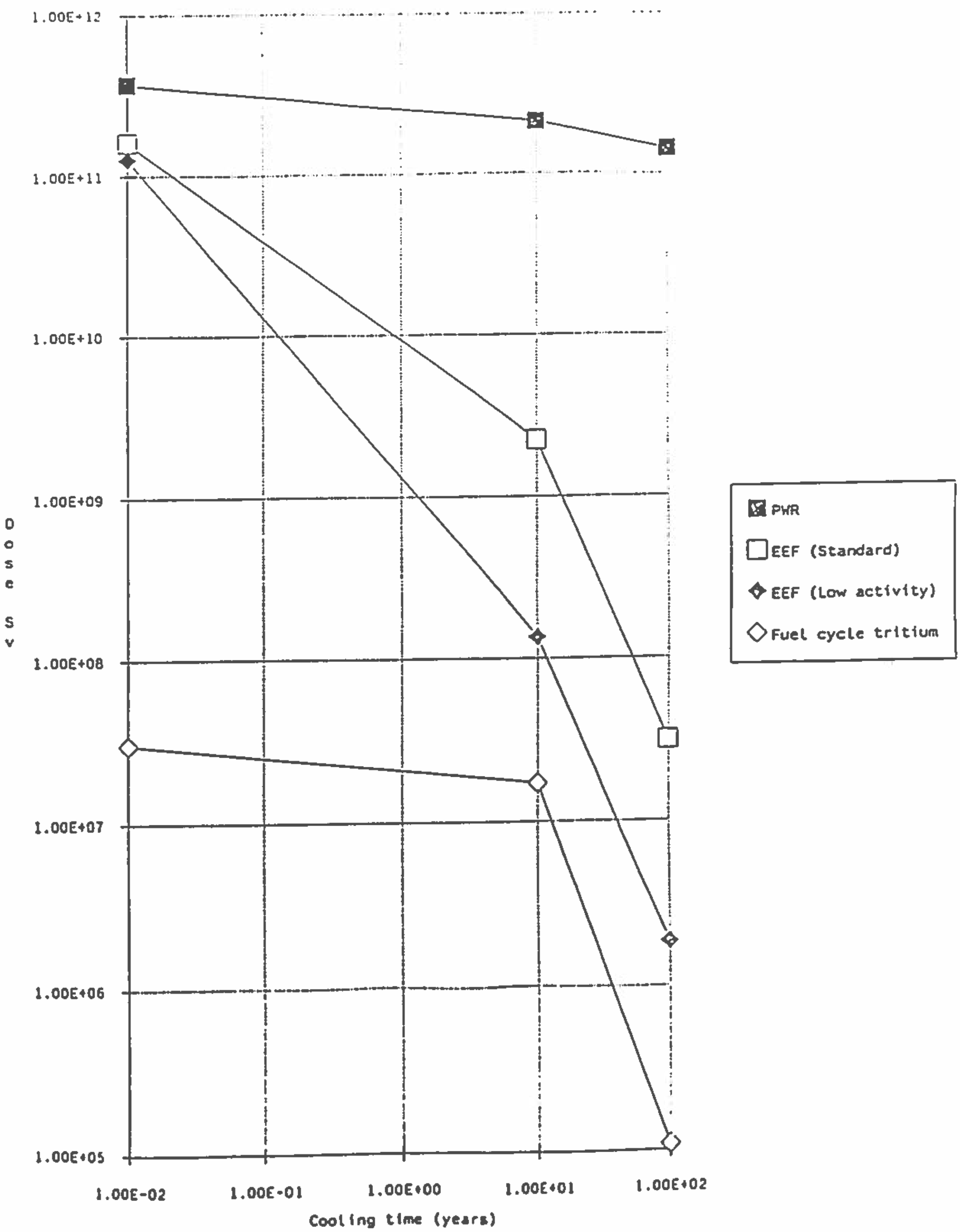


FIGURE 5.15

Comparison of toxic content (inhalation) of PWR with both variants of EEF 1000MW(e)

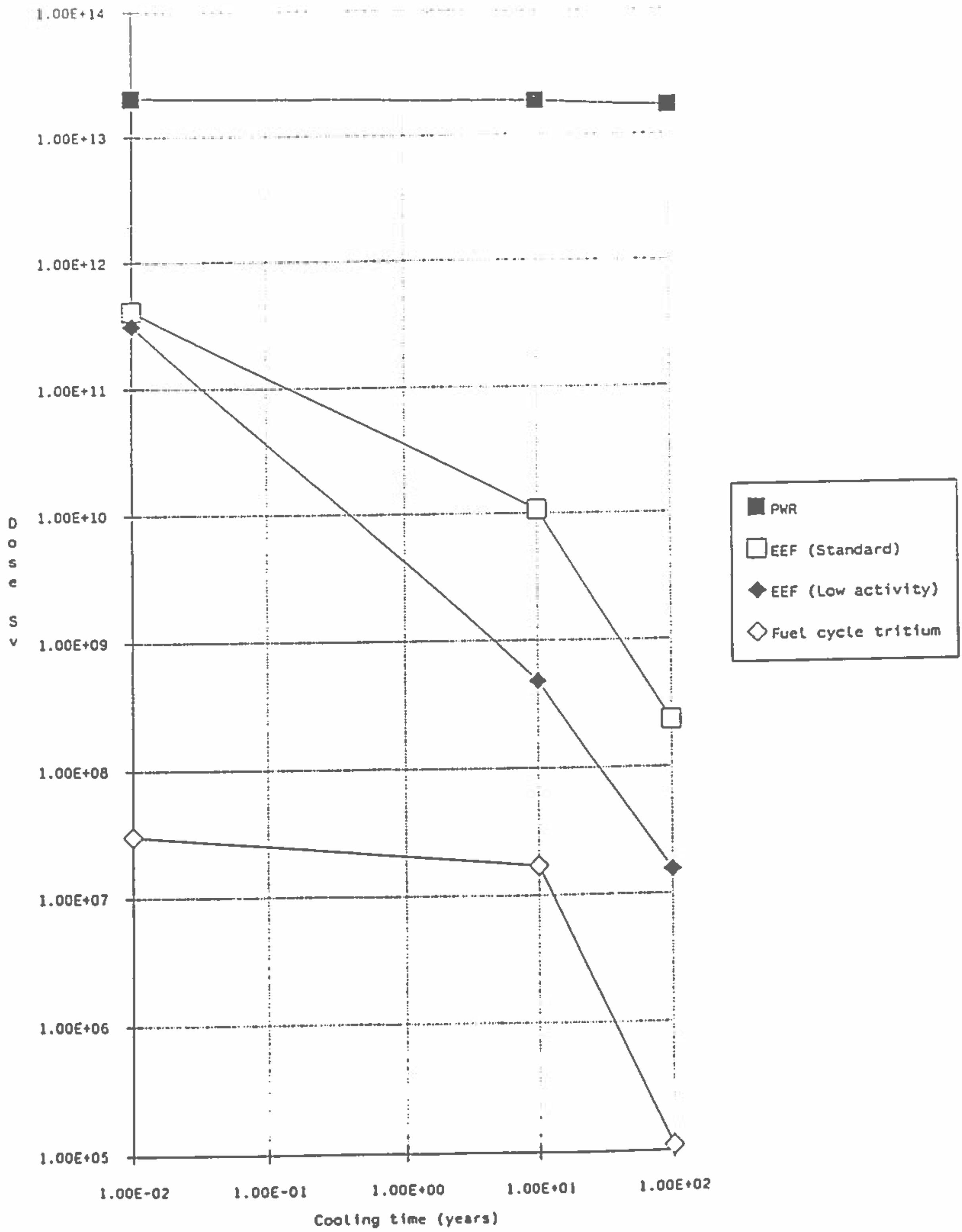
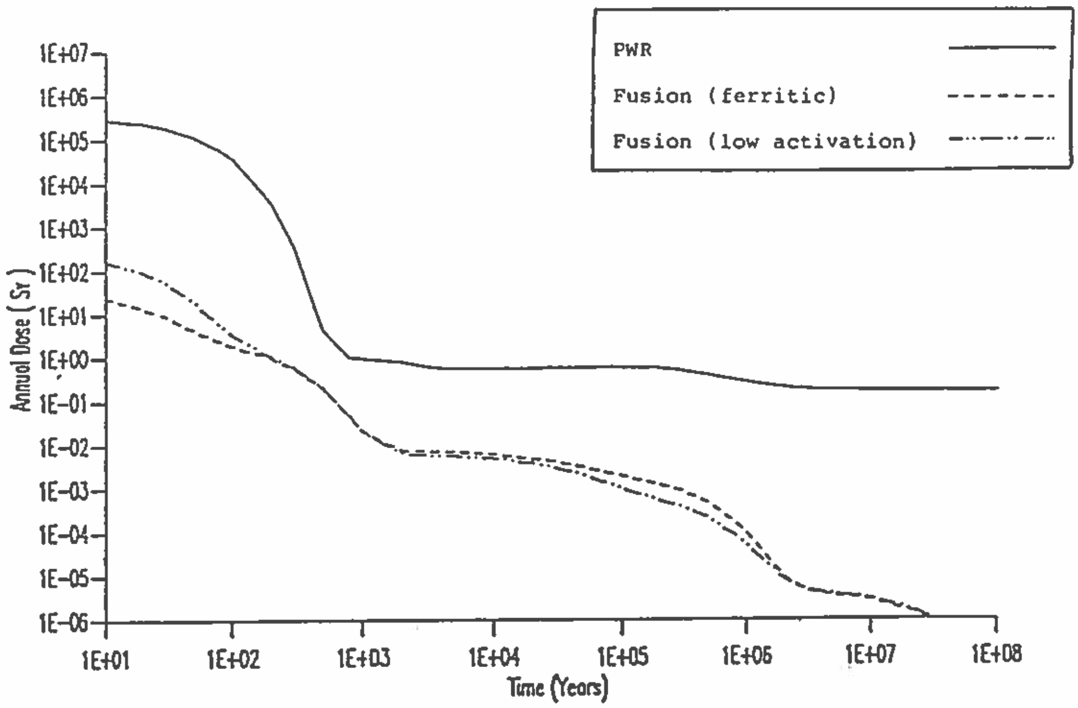


FIGURE 5.16

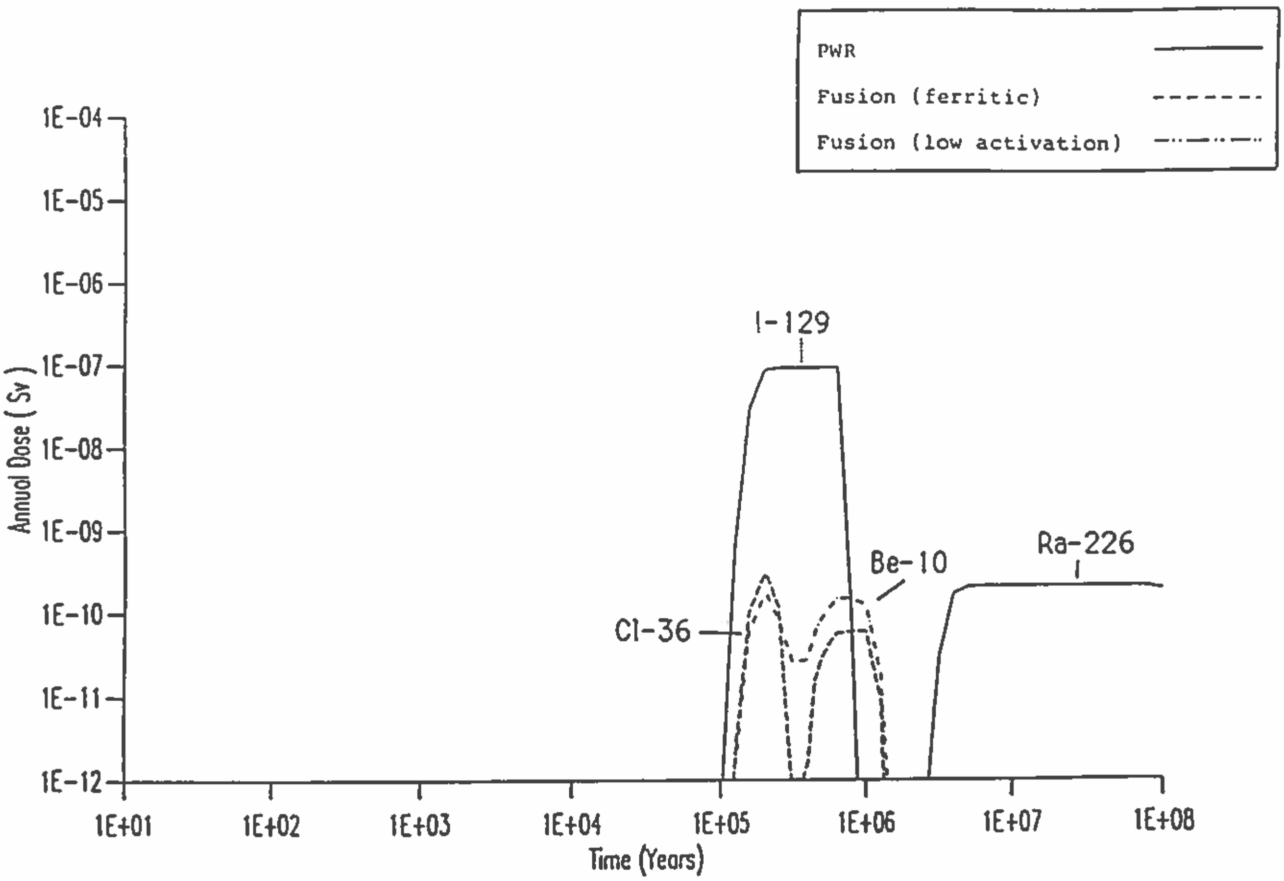
The toxicity of "near-field" repository groundwater. Comparison of reactor types 1000MW(e)



Near-field toxicity, best estimate parameters

FIGURE 5.17

The toxicity of stream water due to waste repository, Comparison of reactor types. 1000MW(e)



Chapter 6

CONCLUSIONS

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CONCLUSIONS

6.1 This report discusses the potential economic and environmental benefits of the Community's Fusion Research Programme, on the basis of conceptual outlines of fusion reactors provided to us by that programme and by the USA programmes of fusion reactor studies (para. 1.1 to 1.16).

6.2 Because the fusion programme is still in the physics research stage, our analyses involve many uncertainties, so that the results constitute a contribution to the wider European discussion on the benefits of fusion (e.g. the European Parliament's STOA analysis) rather than conclusive arguments (para.1.8, 1.9, 1.14).

THE MARKET FOR FUSION ENERGY

6.3 The main application we consider for fusion energy is base-load electricity generation in Western Europe. A successful outcome of the Community's fusion research programme would of course also have world-wide implication for electricity generation, but we have not attempted to assess the wider geographical benefits. Likewise we have neither pursued in any depth nor taken into account alternative uses of fusion energy; nor have we considered spin-off from the research programme (para. 1.11).

6.4 We consider that the potential benefits of fusion could become commercialised in the mid-21st century (para. 1.7) , by which time the base-load electricity capacity in Western Europe might be in the range 250 GW(e) to 1000 GW(e) and the corresponding investment in new and replacement power station plant would then require construction of over 10 GW(e) per year (para. 2.3 to 2.12).

6.5 The figures are speculative and the outturns will be affected by fluctuations and shocks, by developments in the rest of the world and by environmental pressure to reduce energy consumption. However, we think it most unlikely that Western Europe will wish to forego large-scale interconnected electricity supply, so that at least the lower part of the range of required investment postulated seems plausible (para. 2.13 to 2.18).

6.6 Taking account of the possible electricity needs, of the huge potential global demand for fuel and energy, and of the associated threats to the environment, Europe has a strong interest in developing a new energy source, such as fusion, which if successful could satisfy foreseeable demand, which uses indigenous resources, and which could provide energy in a way that meets major environmental concerns (para. 2.14 - 2.26).

6.7 The evaluation of fusion R&D expenditure as an investment for the European Community should concern social profitability as well as commercial profitability, i.e. it should not be based solely on private returns such as royalties for patents on fusion reactors; it should also take into account "external effects" which would not accrue directly to a private investor in fusion R&D, such as environmental advantages (para. 2.27 to 2.28).

6.8 Fusion research can be profitable even if it requires some decades to bring it to fruition, provided that the electricity generated by fusion turns out to be competitive with that generated by other methods, and that fusion energy is used for a sufficient time (para. 2.29 to 2.33).

6.9 This analysis illustrates also how valuable it is to have effective international collaboration, which shares the research costs with other parts of the world and which can speed up the research as compared to what Europe would do alone (para. 2.34).

FUSION REACTOR CONCEPTS

6.10 The fusion research programme of the European Community and its partners is making excellent progress. Fusion energy outputs have now reached tens of kW (thermal) in pure deuterium gas. The extrapolation of the key physical parameter to the value needed in an envisaged power producing D-T reactor is about a factor of ten. Nonetheless the reactor outlines used for our studies are hypothetical because they depend on the extrapolation of physics and engineering knowledge beyond present experience (para. 3.12 to 3.21).

6.11 All the outline concepts considered here assume that the fuel comprises deuterium and lithium, with actual fusion reactions occurring between deuterium and tritium, the latter being derived from the lithium. We believe the prospects for pure deuterium fuel and for more advanced fuels such as deuterium plus ^{3}He are too speculative to require us to add to the United States ESECOM studies (para. 3.31 to 3.34).

6.12 The outline concepts used here are all based on the confinement of high temperature gas by magnetic fields in a Tokamak system, because this is the most advanced in the research. Three parameter sets have been used for cost analysis: a concept PCSR-E from the previous (1986) report on fusion costs [1.2], an EEF Reference concept, and an advanced concept AMTR-3 which is used to illustrate the benefits of possible advances in physics and engineering. For accident and environmental analysis we have used the STARFIRE design and two versions of the EEF Reference design, one using ferritic steel and the other vanadium alloy as the structural material. Note that other major components are of unchanged material (para. 3.1 to 3.11 and Table 3.4).

ECONOMIC POTENTIAL

6.13 Costs of baseload electricity in the 21st century are assumed for our studies to be set by imported coal fired stations and by nuclear fission reactor power stations. We have considered (para. 4.1,4.2,and 4.15, and fig. A2.2) two cases, namely, that:

(i) The cost of electricity is unchanged in real terms;

(ii) The cost of electricity is assumed to be 20% more than in case (i) because of a rise in fuel or fuel cycle costs.

6.14 The cost of fusion electricity will be dominated by the capital cost of the plant; it is possible, therefore, to simplify the problem of comparison and refer only to capital costs (para. 4.13); Ref [3.2].

6.15 The capital cost of a prototype fusion reactor is estimated to be between 2.2 and 2.5 times the cost of a series production reactor (the learning curve effect) (para. 4.10).

6.16 The capital cost of a prototype fusion reactor must then be less than 3.6 to 4.2 times the capital cost of a series PWR reactor if fusion is to stand a good chance of being economically competitive (para. 4.16).

6.17 Today the European estimates of the capital cost of this prototype are between 3 and 6 times the capital cost of a current PWR, depending on the model prototype considered (para. 4.21 to 4.25, and Table 4.8).

6.18 It must be emphasized that these cost calculations take into account only the factors which are normally quantified and exclude other major aspects (independence & environment), which are considered separately (para. 4.29).

6.19 In the same way, uncertainties in capital cost of the fusion prototype are large and cannot be assessed. For instance, we could not safely estimate the link between today's capital cost estimates and the real capital cost of the prototype in 2020 (para.4.31).

6.20 The results of the ESECOM studies, using US conventions for both fusion and fission PWR and the European learning curve figure for the capital costs, fall within the same range as those found for our European studies (para. 4.18, 4.19, 4.20, 4.25).

6.21 The major lesson for the European programme is the need to define cheaper structures before the moment of decision for a fusion prototype. The time allowed makes this quite possible, given the improvements expected during the research stage (para.4.32).

ENVIRONMENTAL POTENTIAL

Provision of materials

6.22 The fuel for fusion reactors (Li and D) is abundant and widely distributed in nature at rather low concentrations (30ppmw). Compared to fossil fuels, small quantities are needed, 0.5 to 5 tonnes per GW(e) year depending on the efficiency of using the lithium. An investment of several hundred tonnes of lithium per GW(e) is also required. Practically speaking, D-T fusion fuel is an inexhaustible energy source for conceivable global energy requirements and duration. (para. 5.54 to 5.58).

6.23 The environmental disturbance of extracting lithium from brines and deuterium from water is small and the risks in mining operations for lithium also are small. Fusion compares very favourably in both respects with the mining operations for fossil fuel and for PWR fission reactors (para. 5.59 to 5.61).

6.24 Provision of other materials special to fusion reactors appears to present no special difficulty or environmental impact above that of providing ordinary construction materials for generating plant (para. 5.62 to 5.65).

The power plant

6.25 A fusion-based electricity generating station is envisaged to consist of large concrete buildings enclosing the plant, whose visual impact and land usage is comparable to that of other large central power stations (para. 3.8).

6.26 Waste heat is rejected at the end of the conventional thermodynamic cycle using water, vapour or dry air coolant. No greenhouse gases or other significant gaseous or liquid effluents are envisaged. The helium produced by the fusion reactions (about 0.5 tonnes per GW(e) year) is entirely harmless and will be either vented or used within the plant (para.5.2 to 5.3).

Radioactive Inventory

6.27 In a fusion reactor there is substantial radioactivity arising from the intermediate product tritium and the neutron-activated components of the structure.(para.5.3 to 5.10; Tables 5.5 to 5.8).

6.28 Tritium is volatile and it is envisaged that about 5kg is on site at any one time, but only a fraction is vulnerable to release under accident conditions. We have adopted 1kg as an upper estimate for the accident vulnerable inventory (para.5.7,5.44).

6.29 Neutron activation of the main structure produces a radioactive inventory whose quantity, measured in becquerels is, on shut-down, comparable to that of a PWR (about 10^8TBq). The size and longevity are a strong function of the material used in the structure. It is embedded in non-volatile structural materials and coolant. The inhalation hazard potential is at least ten times less than that of the equivalent PWR inventory. With the appropriate materials the inventory of a fusion reactor can be made smaller, and made to have a rapid decay (para. 5.6 to 5.14; Tables 5.7 , 5.18).

6.30 The radioactivity, even with the most optimistic choice of structural materials, makes remote handling mandatory for all maintenance and servicing operations on the plant within the biological shield (Fig 5.14; Table 5.6).

6.31 The pure fusion plant will contain no uranium, plutonium or other actinide elements capable of fission or of alpha radio-activity other than those present as (unwelcome) impurities (para. 5.5, 5.6, Ref.[5.18]).

6.32 Losses from this radioactive inventory to the environment, other than potential tritium losses, would be limited to any losses of activated atmosphere in the reactor hall, and would be much smaller than routine emissions of radioactivity from coal plant and PWR plant. However no analysis of the transport of corrosion products by the coolant is available and, prima facie, this could lead to small losses comparable to those from PWR plant (para.5.8 and 5.17 to 5.20)

6.33 Routine losses as T_2O have to be less than 5 to 10 TBq/day (about 0.02g of T) to satisfy regulatory guidelines Ref.[5.9]. A number of studies have expressed confidence that this can be achieved, but it has yet to be demonstrated. The releases estimated for routine operations of STARFIRE are 0.5 TBq/day (para.5.19 to 5.20).

Waste disposal and decommissioning

6.34 The volume of radioactive material produced in maintenance operations and in decommissioning would, it appears, be larger in volume than that of an equivalent PWR with a once-through fuel cycle. The toxicity is far less, and there is of course no criticality problem and fewer cooling problems. The volumes requiring disposal are dominated by the lower level wastes which come in the PWR case (without reprocessing) from the steam cycle plant; whereas in the fusion case, it comes from the whole reactor core (para 5.21 to 5.31, Tables 5.13 to 5.15).

6.35 The mitigation of the volume of waste disposal by use of low activation elements or by recycling used material is a significant issue if the potential superiority of fusion over fission in this respect is to be realised. Ref.[5.5].

6.36 The potential hazard of wastes from fusion plant, stored over many hundreds of years, is many orders of magnitude less than that of fission waste (para. 5.32 to 5.41).

SAFETY ISSUES

6.37 Fusion reactors are envisaged to be enclosed in a containment building which will prevent the release of tritium to the environment arising from accidents to the plant (para. 5.46).

6.38 Accident releases of the 1kg tritium into the atmosphere could not, even with pessimistic assumptions cause severe acute health effects outside the site 1km boundary. The release of, and consequent health hazards from activated structural materials would, it appears, have very limited radiological consequences even for the worst plausible accident (para. 5.48 to 5.51).

6.39 It seems possible that no energy source within the fusion plant will be capable of disrupting the envisaged containment. There are only some ten seconds-worth of fuel in the hot gas, and the magnetic confinement method ensures that normal power cannot be exceeded by more than some tens of %. There is no possibility of a criticality accident involving for example, six months fuel supply and a thousandfold increase of power output. The possibility of disrupting the containment building by meltdown due to after heat can be further reduced or eliminated with a fusion reactor by use of appropriate materials (para. 5.46, 5.47, 5.15, 5.16).

6.40 Some reactor concepts (but not European ones) contemplate using liquid lithium in the reactor. If most of the lithium were to catch fire in an uncontrolled way, then, in addition to tritium release, some of the structural material might be volatilised and discharged to the environment. The careful studies carried out by ESECOM in the USA show a hazard potential (radiation dose received) at least ten times less for fusion than for fission reactors in this hypothetical case. Ref.[5.8].

6.41 Fusion cannot have criticality accidents in spent fuel disposal ponds or in any reprocessing plant. Any waste product has low specific residual power (table 5.8).

6.42 The electromagnetic fields inherent in magnetic fusion reactors could pose a modest potential exposure to operating staff, none at all to the public (para. 5.66 to 5.71).

6.43 None of the materials in routine operation requires Non-Proliferation Treaty safeguards. However the neutron flux could be used, given engineering modification, to produce plutonium or U^{233} by irradiation of uranium or thorium. Clandestine breeding could be detected by surveillance and neutron monitoring measures (para. 5.72 to 5.75).

6.44 Tritium is toxic (because of its radioactivity) and is a valuable material, so that on-site quantity control of the fuel cycle will be needed. Ref.[5.9].

GENERAL CONCLUSIONS

6.45 Base-load electricity generation will continue to be of central importance to Western Europe throughout the 21st century, when fusion research could come to fruition and could meet part or all of the large market for central power stations.

6.46 Our analysis indicates a potential for cost and societally economic competitive fusion power, and offers a simple target for the capital cost of a prototype reactor by which to test this potential.

6.47 Fusion offers clear environmental benefits compared to coal-fired power (no gaseous carbon dioxide emission, no major mining and transport operations), and to fission (no fission products, no plutonium production, no criticality accidents).

6.48 The study group therefore concludes that the European fusion research programme should continue to be vigorously supported.

6.49 Not least to provide a real physics and engineering basis for cost and environmental analyses, priority should continue to be given to establishing (preferably by demonstration) at the earliest date that net thermal power can be generated by fusion reactions in the way envisaged in power reactors.

6.50 We reiterate the advice already submitted by us to the Commission in January 1989 that engineering designs of commercial reactors should be developed and analysed much more thoroughly as part of the Euratom fusion programme in order to explore ways of developing the economic and environmental potential of fusion.

6.51 The research and development programme needs to be conducted with an awareness of the importance of reducing capital and operating costs of the ultimate plant.

6.52 We believe that the research programme should develop more strongly means of improving and demonstrating the environmental potential of fusion, especially in reducing the volume and longevity of radioactive material produced parasitically by fusion neutrons, and by confirming the low consequence of any accident to the envisaged plant.