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SAFETY AND ENVIRONMENTAL IMPACT OF FUSION

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Safety and Environmental Impact of Fusion

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EXECUTIVE SUMMARY

1. Introduction

Fusion power stations would provide large amounts of base load electric energy, burning deuterium-tritium fuel. An intrinsic characteristic of them, would be the extremely low level of fuel inventory in the burning chamber, and the low levels of after burn heat power density. Obviously, fusion power stations would neither burn nor produce any fissile material. The products of the fusion process itself are benign, so that tritium and the neutron activation of materials would be the only source of potential radiological hazards. With appropriate design, these favourable inherent features can be exploited to provide substantial safety and environmental advantages.

These possibilities have been explored in a series of studies, within the European fusion programme, called the Safety and Environmental Assessments of Fusion Power (SEAFP).

The first of these studies led to the publication in 1995 of the report on the Safety and Environmental Assessment of Fusion Power (SEAFP-1). The work carried out for SEAFP-1 confirmed the attractive safety and environmental characteristics of fusion power. The independent 1996 Fusion Evaluation Board endorsed the conclusions of SEAFP-1.

The SEAFP-1 assessment also helped to identify the issues that needed further study and deeper understanding. Accordingly, a series of follow-up studies (called SEAL, SEAFP-2 and SEAFP-99) were launched that carried forward the work in this area until the end of 1999. These studies extended and improved the analyses and updated the specifications of the materials used in the designs.

This report is an integrated summary report on the work performed within all these studies, which updates and extends the original SEAFP-1 report. All the assessments have been based on the same conceptual fusion power station designs with 3,000 MW of fusion power and an output of about 1,200 MW of net electrical power. These conceptual designs are identical in their physics assumptions, based on reasonable extrapolations from the results of present experiments. They differ in their engineering and materials technology.

The two principal designs, here called “MINERVA-W” and “MINERVA-H”, were based on the two concepts for a key component (called the “blanket”) of the fusion power core of the plant, that are currently being developed in the European fusion programme. The blanket is the component of the power station where the energetic neutrons produced by the fusion process are slowed down and deliver their energy in the form of heat before being absorbed by lithium atoms to reproduce the original tritium fuel. Both of these concepts are based on the use of existing types of low-activation martensitic steel as the main structural material. MINERVA-W uses water as the heat transfer fluid; MINERVA-H uses helium. The other designs that were studied, in less detail, were advanced conceptions, introduced to obtain an indication of the further safety and environmental advantages that might be achieved by developing advanced materials, such as silicon carbide composites or vanadium alloys.

In parallel to the reported studies, detailed safety analysis have been done of the detailed engineering design of ITER. Their results confirm the safety benefits from the intrinsic characteristics of fusion within the limits from a practical implementation with the available material and technologies.

2. Inherent fusion safety characteristics

The underlying reasons for fusion’s favourable safety and environmental characteristics can be understood quite simply. There are important generic factors, which are set out below.

- There are no climate-changing emissions. The operation of a fusion power station does not involve the discharge of “greenhouse gases” to the atmosphere. There would also be no acidic emissions.
- Power excursions of the plasma are self-limited to low levels by inherent processes.
- Continuous operation of the plant is maintained by continual refuelling with the fuel mixture (deuterium and tritium), so the fuel inventory in the plasma chamber at any time is sufficient only for about one minute of operation.
- Power densities are moderate in normal operation and very small after burn termination (“low decay heat”).
- The radiotoxicity of the activated material produced by the operation of fusion power stations decays rapidly. It can be further minimised by appropriate choice of materials for the power plant components exposed to neutrons.

The first factor above is the reason for fusion’s environmental advantage over fossil fuels. The three following factors are the origin of fusion’s low accident potential. The last factor is the origin of its favourable waste management features. However, although these are generic factors, the SEAFP studies showed that the full expression of the safety and environmental advantages results from the conjunction of those generic factors with appropriate design choices, especially materials selection and radioactivity confinement system concepts.

3. Accident potential

During the burn if a total loss of active cooling were to occur, the plasma would switch off passively and any temperature increase due to decay heat cannot lead to gross melting of the structures. This holds for all the designs, with the silicon carbide based designs performing best. This result is achieved without any reliance on active safety systems or operator actions.

With appropriately designed confinement systems, no accidents driven by in-plant energies – even the most severe that could be conceived – could result in confinement failure. Resulting doses to a member of the public would be about or below 1 millisievert - well below the levels at which evacuation would be considered, and similar to, or lower than, the typical annual dose to an individual from natural sources. This result also is mostly achieved without reliance on active safety systems or operator actions.

In the event of confinement damage by an extremely rare (hypothetical) ultra-energetic ex-plant event, such as an earthquake of hitherto never experienced magnitude, an upper bound to the release of tritium is set by the vulnerable inventory, which is about one kilogram. The release of one kilogram would result in a dose to a member of the public of up to about 0.4 sieverts, in a small area close to the plant. This would give rise to health effects smaller than the typical consequences of the external hazard itself. On realistic assumptions the maximum dose would be lower, and this very hypothetical scenario could be removed by design provision: essentially, this would be an economic issue.

4. Normal Operation

Doses to the public due to tritium and other effluents were estimated to be low and significantly below internationally accepted limits.

Regarding occupational doses, those estimated for MINERVA-H were also low and below internationally accepted limits. For MINERVA-W, estimated occupational doses were higher than the current best practice in fission power stations, which points to the need, in a further design iteration, to implement design measures to reduce the mobilisation of activated steel by water corrosion. Results indicated how this could be done by appropriate engineering provision. Only a limited amount of work on occupational doses has been undertaken in the SEAFP studies. A larger and more comprehensive effort has been mounted within the ITER framework, which showed the potential for reducing doses by detailed design provision. This should be the basis for future work on these issues regarding commercial fusion power stations.

5. Management of activated material

Over their life times, fusion power stations would give rise, by component replacement and decommissioning, to activated material similar in volume to that of fission reactors, but qualitatively very different since the long-term radiotoxicity is very considerably lower.

Indices of the total radiotoxicity of all the activated materials from the fusion power stations fall, after a few decades, to levels thousand to ten thousand times lower than the value for a corresponding fission power station and broadly a factor of ten higher than the radiotoxicity of the ashes from coal-fired plants providing the same energy output.

It is estimated that virtually all – perhaps all – of the activated material could be cleared from regulatory control or recycled after about fifty years, leaving little material requiring permanent repository disposal. The heat generated by the material does not require active cooling, except possibly for a small fraction during the first few years. Broadly, about one third of the activated material could be cleared, and two thirds may be recycled with remote handling techniques. Any remaining small amounts of activated material could be disposed of as waste in shallow geological repositories.

However the technology of recycling has still to be developed, and its economic attractiveness in the future cannot be assessed (this is especially true of the silicon carbide composite considered in advanced designs).

Thus, for all the foregoing reasons, the activated material from fusion power stations would not constitute a waste management burden for future generations.

6. Other issues

In the context of proliferation, it is important that none of the materials required by a fusion power plant are subject to the provisions of the non-proliferation treaties. International movements of tritium and lithium-6 have, however, come under less formal international control arrangements and may be brought within the formal treaty system in the longer term. Even small quantities of illicit fertile or fissile material on the input or output sides of a fusion power plant could be detected with appropriate blanket exchange procedures. The fact that there should be absolutely no such material present offers a clear-cut detection criterion.

There are no significant constraints on materials availability even for an extensive use of fusion energy over centuries.

The potential for hazards from the release of chemically toxic materials, and from static magnetic fields, and electromagnetic fields, were also considered. As stated above, with appropriately designed confinement systems no accidents driven by in-plant energies could result in confinement failure: thus accidental releases of chemical toxins could be limited to insignificant levels. Any hazards to the public from electromagnetic fields would not be different from those of other forms of electric power generation, handling and transmission.

7. Principal Overall Conclusions

Fusion power stations have extremely low levels of fuel inventory in the burning chamber, their power production stops with no fuelling and they have very low levels of after burn power density. They will make no use of any fissile material, and will not emit any of the greenhouse gases. With appropriate design, these favourable inherent features can be exploited to provide substantial safety and environmental advantages.

Studies performed within the European Fusion Programme have shown that it would be possible to design commercial fusion power stations with the following features.

- The maximum radiological doses to the public arising from the most severe conceivable accident driven by in-plant energies would be well below the level at which evacuation would be considered and would be comparable to typical annual doses from natural causes.

- After a few decades, the total radiotoxic potential of the activated material arising from the operation and decommissioning of the plant will have decreased to a low value.

- Most, perhaps all, of this material, after remaining in situ for a few decades, may, if desired, be cleared or recycled, with little, or no, need for repository disposal (the remote handling technology of recycling has still to be developed and its economics assessed).

These studies have confirmed and expanded earlier findings that the safety and environmental advantages would not all accrue solely from factors inherent to the fusion process itself, but depend also upon appropriate plant design. The results and lessons learnt from these studies can form inputs to future activities to design reference attractive fusion power stations.

ACKNOWLEDGEMENTS

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CONTENTS

1 INTRODUCTION

1.1 Background and objectives

Fusion power stations have extremely low levels of fuel inventory in the burning chamber and very low levels of after burn heat power density. They will neither burn nor produce any fissile material. The products of the fusion process itself are benign, so that tritium and the neutron activation of materials will be the only sources of potential radiological hazards. The power stations will not emit any of the greenhouse gases. With appropriate design, these favourable inherent features can be exploited to provide substantial safety and environmental advantages. These possibilities have been explored in a series of studies, within the European fusion programme, called the Safety and Environmental Assessments of Fusion Power (SEAFP).

The first of these studies led to the publication in 1995 of the report [1] on the Safety and Environmental Assessment of Fusion Power (SEAFP-1). The work carried out for SEAFP-1 confirmed the attractive safety and environmental characteristics of fusion power. The independent 1996 Fusion Evaluation Board [2] endorsed the conclusions of SEAFP-1.

The SEAFP-1 assessment also helped to identify the issues that needed further study and deeper understanding. Accordingly, a series of follow-up studies (called SEAL, SEAFP-2 and SEAFP-99) were launched that carried forward the work in this area until the end of 1999. These studies extended and improved the analyses and updated the specifications of the materials used in the designs [3,4,5,6]. The detailed analyses and results have been published in the proceedings of many international conferences on fusion technology: too many to cite here. This report is an integrated report on the work performed within all these studies, which updates and extends the original SEAFP-1 report. As a consequence of improvements in data and methods of analysis, and of changes to materials specifications, the results reported here may differ in detail from those reported in the SEAFP-1 Report [1]. Broadly, the consequences of worst-case accidents are about the same, inventories of radio-toxicity are higher, occupational radiation exposures are lower, and the amount of material requiring repository disposal is lower.

1.2 Scope of this report

This report is about concepts for commercial fusion power stations, not about nearer-term fusion devices such as the proposed large burning plasma experiment ITER. Very extensive safety and environmental investigations have been performed for ITER [5,7,8], and it is necessary to bring out the differences between these and the SEAFP investigations. The differences stem from differences between ITER and future commercial power stations, and from differences in the aims of the investigations.

- Commercial fusion power stations will differ from ITER in two relevant respects:
  - They will have higher power densities, higher component temperatures, and higher neutron fluences;
  - They will use low-activation structural materials.

- For these reasons, it is not possible to infer the safety and environmental impacts of a fusion power station from the results of the ITER studies. Nevertheless, the general understanding developed in the ITER studies can be deployed for the power station studies, and the methods of investigation are the same.
- In showing the safety of a near-term device like ITER, for licensing purposes, one obviously has to perform many very detailed investigations. This is possible, since ITER has a very detailed design. But in studying the safety of concepts for fusion power stations the aim is to perform rather more generic investigations to establish the key features.

2 FUSION SAFETY CONCEPTS

2.1 Fusion safety objectives

Basic safety and environmental objectives for fusion power stations originated with the findings of the 1990 independent Fusion Evaluation Board [9]. The Board found that fusion possesses “inherent environmental and safety advantages over all current alternatives for base load electricity generation”, added that a “convincing demonstration” of these advantages was necessary and emphasised two “central points”:

- “It must be clearly shown that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.”
- “Radioactive wastes from the operation of a fusion plant should not require isolation from the environment for a geological timespan and therefore should not constitute a burden for future generations.”

The Board considered that these were viable targets if supported by careful design and materials development.

These have been the guiding objectives of the SEAFP studies.

2.2 Fusion safety characteristics

This section offers a brief overview of the safety and environmental characteristics of fusion power, for the reader’s general orientation, before the report goes into more detail.

Fusion potentially offers the following three areas of safety and environmental advantage.

- No climate-changing emissions
  The operation of a fusion power station does not involve the discharge of “greenhouse gases” to the atmosphere. There would also be no acidic emissions. The fabrication of the components of a fusion power station, as with most industrial processes, might involve some greenhouse gas production.
- Low consequences of worst-case accidents

This potential feature stems from some key favourable safety characteristics of fusion, which constitute qualitative differences from fission:

- Power excursions of the plasma are self-limited by inherent processes.
- Continuous operation of the power station is maintained by continual refuelling with the fuel mixture (deuterium and tritium), so the fuel inventory in the plasma chamber at any time is sufficient only for about one minute of operation.
- Power densities are moderate in normal operation and very small after burn termination ("low decay heat").

- No waste management burden on future generations

  This potential feature arises because the activated material produced by the operation of fusion power stations is quite unlike the actinides or fission products present in the waste from fission power reactors: its radiotoxicity decays much more rapidly than in the fission case, and can be further minimised by appropriate choice of materials for the power plant components.

The first of the above advantages is a generic feature of fusion. The SEAFP studies have shown that the full expression of the second and third safety and environmental advantages results from the conjunction of generic features of fusion with appropriate design choices, especially materials development and selection and confinement system concepts.

2.3 Fusion safety approach

Throughout, favourable inherent properties of fusion systems, and passive features of the plant designs, were emphasised. In practice, a fusion power station would have active safety systems, partly for investment protection and partly to further enhance safety performance, but these systems were not emphasised or credited in the SEAFP studies.

With regard to the management of activated materials, the main principle followed was to optimise the compositions of the materials used in the plant, so as to minimise (or, if possible, eliminate) any requirement for repository disposal of activated materials.

With regard to accidents, two main principles were followed.

- Firstly, to ensure that the design and material choices were such that temperature excursions were moderate, even in the most severe accidents.
- Secondly, to choose confinement arrangements which ensure that confinement integrity is maintained in all cases.

By following these principles, it was ensured that, even in the worst case accident, doses to the public would be low.

3 FUSION POWER STATION CONCEPTUAL DESIGNS

In this Chapter brief descriptions are provided of the power station conceptual designs which formed the basis of the studies.

3.1 Basic choices

A schematic diagram showing the basic principles of a fusion power station, based on the "tokamak" magnetic configuration, is given in Figure 1.

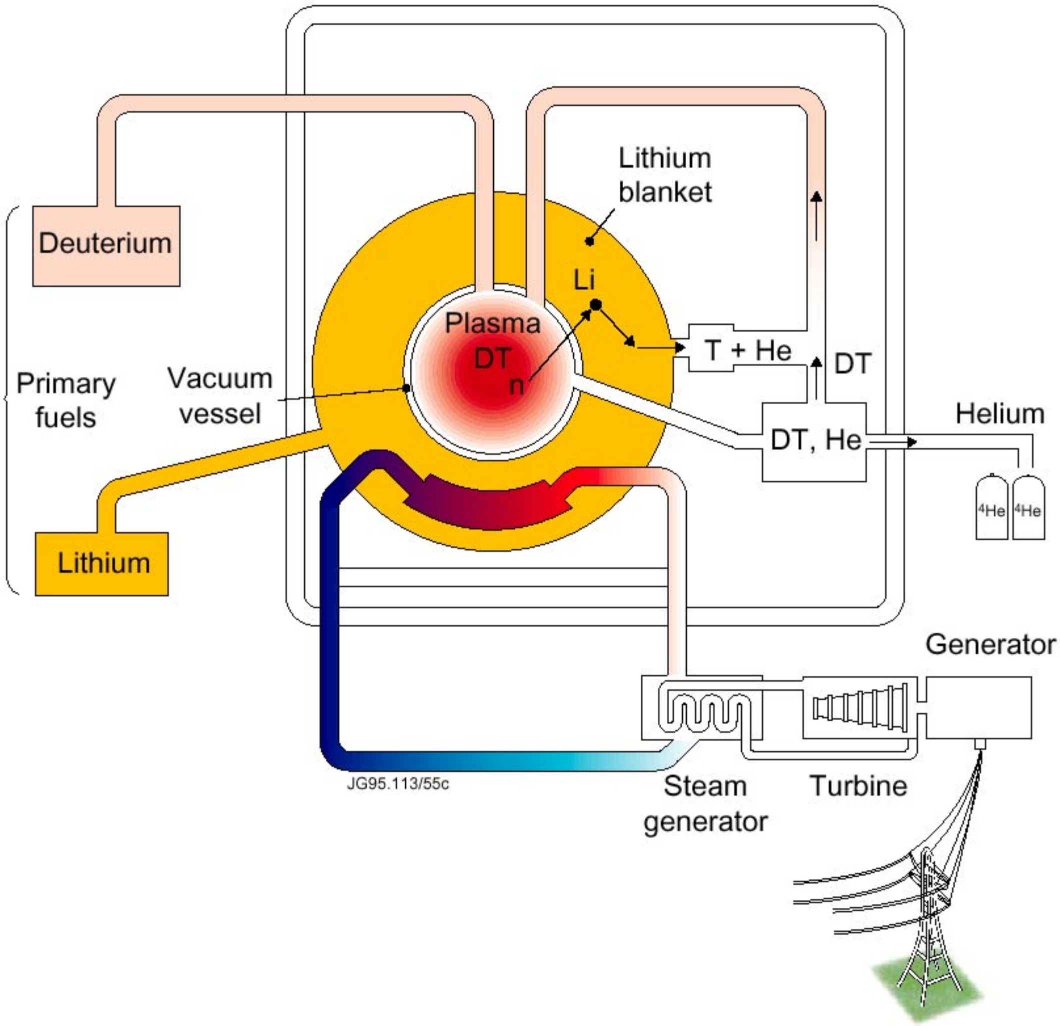

Figure 1: Schematic diagram of a fusion power station

In such a power station, energy is released when nuclei of deuterium and tritium fuse to form helium nuclei. Each such act of fusion sets free an energy of 17.6 MeV, of which 14.1MeV appears as the kinetic energy of a neutron and 3.5 MeV appears as the kinetic energy of a helium nucleus. These events occur in a very high temperature ionised gas, known as a plasma, of deuterium and tritium. The hot plasma is held thermally insulated from the material surroundings by magnetic fields. It is heated, in part by the kinetic energy of the helium nuclei, in part by an electric current carried by the plasma, and in part by auxiliary heating systems such as radio frequency sources or beams of particles. The energy carried away by the neutrons is absorbed in a surrounding structure called the "blanket". The energy is removed from the blanket, by a flow of coolant fluid to steam generators, and used to produce electricity in the conventional way.

The fuels for fusion are deuterium and lithium. Compounds of lithium (not lithium itself) are in the blanket. They interact with the neutrons from the plasma to generate tritium, which is extracted from the blanket and injected, together with deuterium, into the plasma to sustain the fusion process.

There are several basic concepts for the practical implementation of fusion power. Of these, the "tokamak" concept has been developed furthest, and has produced 16 MW of fusion power in the European JET experiment. The SEAFP power stations were based on the tokamak concept. In such a power station, the plasma is held by the magnetic fields in a torus-shaped vacuum chamber. Thus the blanket surrounding the plasma is also toroidal. Between the blanket and the vacuum vessel is another toroidal structure, the shield. This serves to reduce the neutron flux to the vacuum vessel and the ex-vessel structures. The magnetic fields are created in part by electric currents in the plasma, and in part by currents in coils surrounding the vacuum vessel. To minimise dissipation of energy, these coils are superconducting.

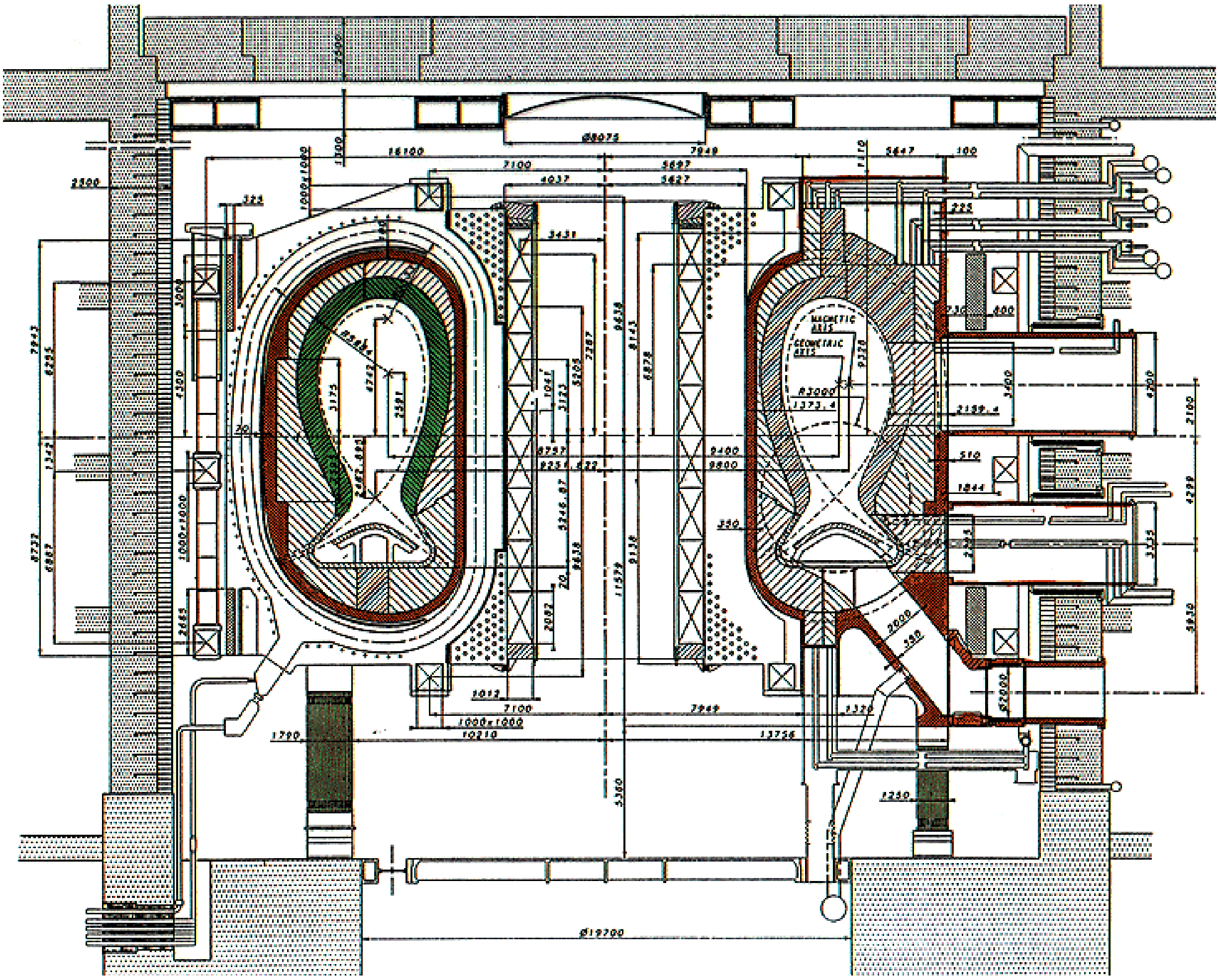

Figure 2: Vertical section of the fusion power core of the designs of fusion power station considered in these studies

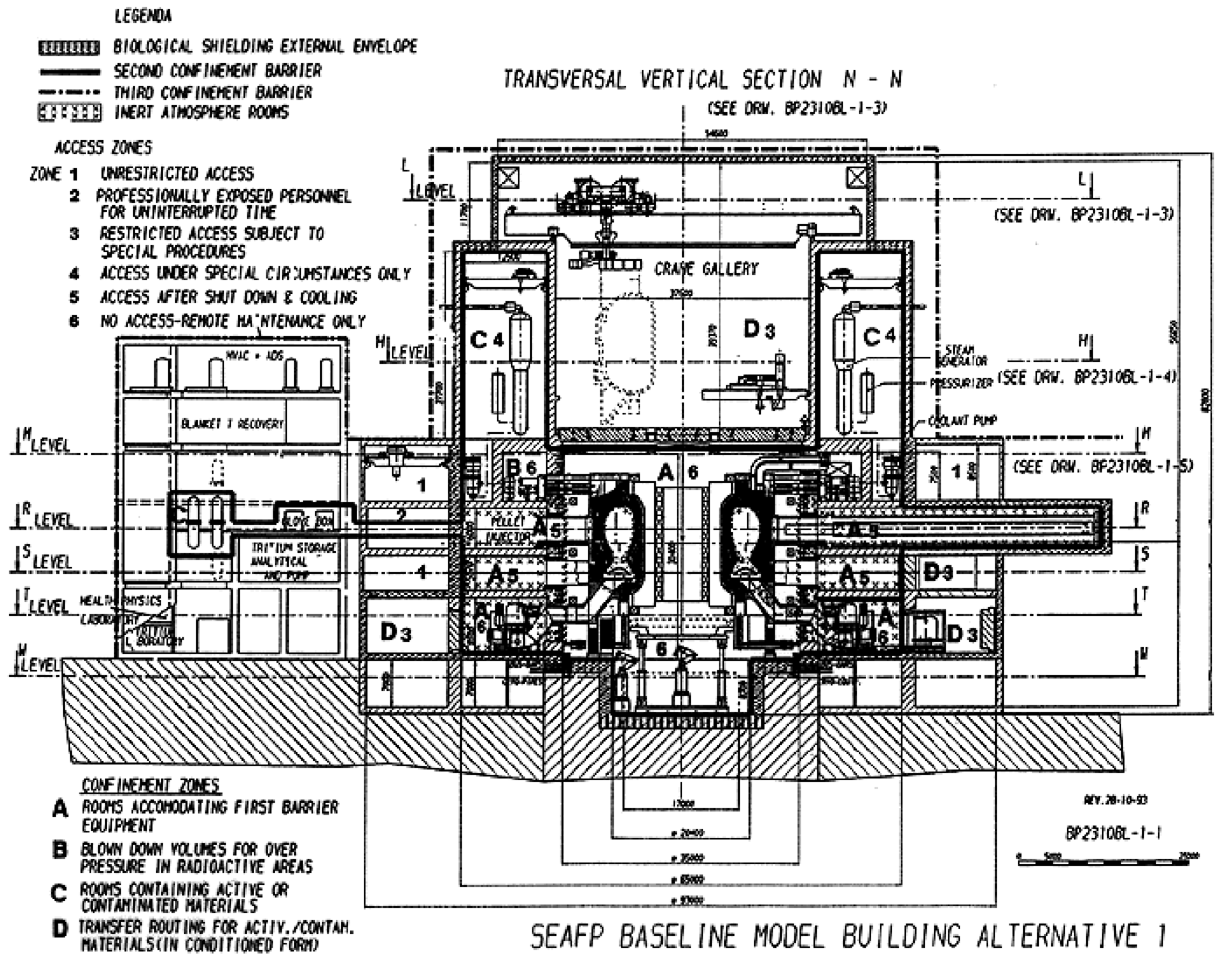

Figure 3: Vertical section of the core, surrounding buildings, and tritium plant of the designs of fusion power stations considered in these studies

A vertical section of the fusion power core of the power stations considered in these studies is shown in Figure 2, and of the core, surrounding building and tritium plant, in Figure 3. An additional component shown in Figure 2, but not yet referred to, is the divertor. The divertor is located in the vacuum vessel below the plasma: its function is to evacuate the flow of hot gases (helium, and unburned deuterium and tritium) exhausting from the plasma. The fuel (deuterium and tritium) burning in the plasma is continually replenished during operation.

Further details are given below, for those aspects of the designs especially pertinent to the assessment of safety and environmental impacts. However, for most aspects of the design, which are essentially those common to all the designs, more details can be found in the first SEAFP-1 report [1]: these details are not repeated here.

The designs differ from one another in the following respects: the blanket concepts, and consequential changes; material specifications; containment arrangements. These are summarised in the appropriate sections below.

3.2 Basic parameters

The fusion power cores of all the designs share the same overall geometry and plasma characteristics. The principal parameters are listed below.

Plasma major radius	:	9.4 metres
Plasma minor radius	:	2.1 metres
Plasma current	:	10.4 MA
Plasma temperature	:	10 keV
Fusion power	:	3,000 MW
Blanket life	:	5 full power years

The average flux of energy carried to the surrounding structures by the neutrons (called the average "wall load") is 2.1 MW/m^2.

Details are given in the original SEAFP-1 report [1]. The plasma parameters were chosen in 1992 as reasonable extrapolations of then-existing experimental performance, and were not changed in the course of the SEAFP studies. Since 1992 there have been enormous advances in the practise and understanding of fusion plasma physics. These would change the details [1] of the SEAFP plasma physics characteristics, but would not change the main parameters in a way that could have significant effect on safety or environmental impacts.

3.3 Materials strategy and resources

In the SEAFP studies, the principal strategic materials issues were related to the choices of blanket. The two reference designs, MINERVA-W and MINERVA-H, specified a low-activation martensitic steel (with nominal composition 0.1C-9Cr-2W-0.2V-0.07Ta) as the structural material of their blankets. As well as having expected desirable physical properties in fusion conditions, the activation of these steels by fusion neutrons is much lower than that of conventional steels. These steels have been developed and extensively tested in recent years, though not, of course, in fusion-specific conditions. The blanket concepts of MINERVA-W and MINERVA-H are based on the blankets that have been successfully developed within the European fusion programme.

In addition to MINERVA-W and MINERVA-H, other conceptual designs, distinguished by blankets based on advanced materials, were studied at a lower level of detail in order to assess their potential merits. The structural material employed for one of these blankets was a vanadium alloy with composition V-4Cr-4Ti. The remaining blanket concepts made use of silicon carbide composite, either as structural material or as thermal insulation. Vanadium alloys and silicon carbide composites are presently available, but would need additional development and characterisation to become suited for fusion power plants.

The assumed compositions of the blanket structural materials varied at different stages during the SEAFP series of studies, reflecting the substantial progress being made, both within and outside the world fusion programme, on material development. Results appropriate to the most recent compositions are normally reported here.

For reasons related to the physics of plasma-surface compatibility, plasma-facing surfaces of the blankets and divertors are covered with a thin layer of an “armour” material. Both beryllium and tungsten were considered and assessed as alternatives for this role.

Another materials variant concerned the composition of the steel/water in-vessel shield and the vacuum vessel: stainless steel 316 and a low activation, manganese-based, alternative austenitic steel, OPTSTAB, were used as alternates.

The availability at acceptable cost of an abundant supply of fuels and materials for a future extensive fusion power economy is, in principle, an important strategic consideration. For the fuel deuterium, many studies have shown that there are no conceivable resource problems. Existing known resources of lithium are sufficient for about a thousand years of a fusion power economy (say a thousand SEAFP-type power stations at any time). Economic analyses show that, at present prices, the cost of lithium procurement would contribute only about 0.1% of the cost of electricity from fusion, so a very large increase in lithium prices could be tolerated, which would make much larger resources available. All these considerations ignore the additional vast resources of lithium in seawater. The German Institute of Geological Sciences investigated the future availability of materials required for fusion power stations [10]. There are no significant constraints on resource availability for any of the designs even for an extensive use of fusion energy over centuries. Moreover, as is shown in Chapter 7, virtually all components of a fusion power station could be recycled.

The use of low-activation materials has the consequence that the calculated activation can be dominated by that arising from impurities in the materials. A detailed analysis was made of the extent to which, in practical terms, the deleterious impurities could be minimised, so further reducing the calculated activation. The optimised compositions resulting from this analysis were used as the basis of the activation analysis (see Chapter 4).

3.4 In-vessel components

The main components inside the vacuum vessel are the blanket, divertor and shield.

The blankets for MINERVA-W and MINERVA-H were slight adaptations, to the SEAFP geometry, of the two blankets that have been developed successfully in the European fusion programme. These are the water-cooled lithium-lead blanket (MINERVA-W) and the helium-cooled pebble-bed blanket (MINERVA-H). Four other blanket concepts were also assessed: these are more advanced concepts, which have not been so well developed, but may have potential for higher thermodynamic efficiency and safety. The main features of all six blankets are shown in Table 1. (Note that MINERVA-W and MINERVA-H were originally called Plant Model 2 and Plant Model 3.) The armour materials were, as noted above, chosen to be either beryllium or tungsten; however the silicon carbide blankets (Models 4 and 5) were assumed to need no armour.

The optimisation of divertor physics and technology is still an active research topic, and no attempt was made to contribute to this within the SEAFP studies. A divertor concept was used only to the extent needed to serve as a basis for safety and environmental analysis. For MINERVA-W, the divertor concept uses a copper heat sink structure, coated by either beryllium or tungsten, and cooled by water. A sophisticated version of this concept has been

Table 1: The main features of the six SEAFP blanket concepts

Plant Model	FW/blanket structure	Tritium-generating material	Neutron multiplier	FW/blanket coolant
1	vanadium alloy	Li_2O ceramic pebble bed	none	helium
MINERVA-W	low activation martensitic steel	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	water
MINERVA-H	low activation martensitic steel	Li_4SiO_4 ceramic pebble bed	beryllium	helium
4	SiC/SiC	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	liquid $Li_{17}Pb_{83}$
5	Low Activation martensitic steel with SiC/SiC insulators	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	helium and liquid $Li_{17}Pb_{83}$
6	SiC/SiC	Li_4SiO_4 ceramic pebble bed	beryllium	helium

developed, in the European fusion programme, for ITER. For MINERVA-H, a helium-cooled divertor was posited. For Model 1 the divertor concept was based on a vanadium alloy. No particular divertor concepts were assumed for Models 4-6.

The shield is a structure between the blanket and the vacuum vessel, designed to protect the vacuum vessel and the coils from the damaging effect of residual neutron flux. The choice of steel for the shield and vacuum vessel is noted in section 3.3.

3.5 Ex-vessel components

This section summarises the remaining components of the fusion power core as shown in Figure 2. Apart from changes consequent on the choice of blanket, these components are the same in each design.

The ex-vessel components begin with the toroidal and poloidal field coils consist of 316L steel casing, a ceramic insulator and a copper stabilised superconducting winding pack. The inboard side also has a solid lead gamma ray shield and a boron carbide neutron shield to protect the coils from damaging effects. To maintain the superconducting coils at very low temperature, a cryostat vessel surrounds the magnets and vacuum vessel. This comprises a reinforced concrete cylinder with an inner liner of AISI 304L steel.

Decay heat removal from the inner fusion power core can be provided using natural convection to back up a major loss of active cooling.

3.6 Balance of plant and confinement systems

The remainder of the plant includes auxiliary systems, the plasma exhaust and fuel handling systems, the heat transport systems, the confinement systems, and the conventional electricity generation systems. The confinement systems, which are directly relevant to safety, are summarised here. The remaining systems are described in the SEAFP-1 [1] report.

Several different types of confinement system were considered. They all are based at minimum on two strong and leak-tight barriers. Overpressure due to loss of coolant are managed by rupture disk or safety valves connected with filters or scrubbers. Figure 4 is a schematic diagram of a confinement system constituted by a single large building containing the vessel and the primary cooling systems.

Several arrangements have been studied, depending on the coolant (helium or water) and the size and volume of the building main volume. The scrubber system is particularly efficient in the case of a water cooled power station; it retains most of the tritiated water and particles.

The performance of these arrangements has been scrutinised on the basis of the safety assessment presented in Chapter 6 of this report. They all provide an effective system of largely passive confinement (in some cases atmospheric detritiation may be needed before exhaust venting). The cost differences are estimated to be small. Therefore, the choice of confinement scheme can be made on other considerations, such as occupational hazards and plant availability.

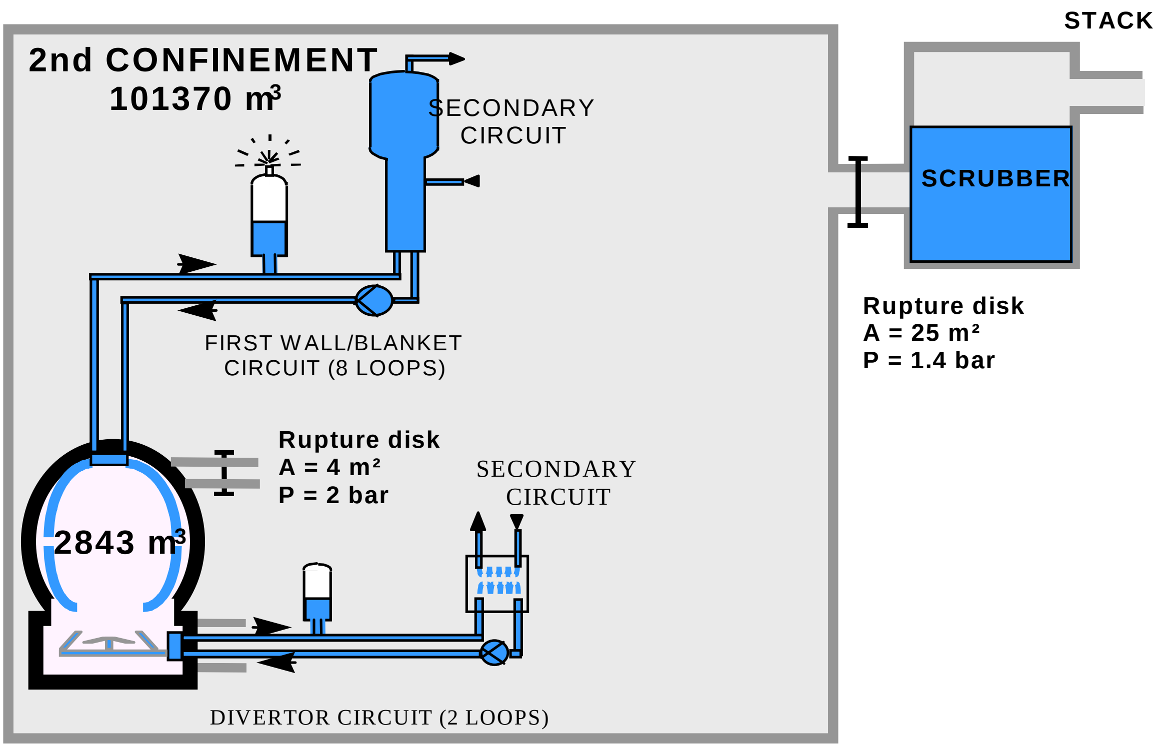

Figure 4: Schematic diagram of a containment system

4 ENERGIES, POWERS AND POTENTIAL HAZARDS

This Chapter reports the determination of the inventories of potentially hazardous materials, and the free energies and processes that could be conceived to have potential to mobilise those materials or challenge the integrity of possible confinement systems. The results were used as the basis for the analyses of safety issues and environmental impacts summarised in later Chapters.

This Chapter deals with the following energies and/or hazards:

- Fusion and plasma energy;
- Other energies;
- Decay heat power;
- Activation;
- Chemical and other hazards;

4.1 Fusion and plasma energy

Once the inflow of deuterium and tritium fuel mixture to the reaction chamber is stopped, the fusion energy potentially contained is only enough for about one minute of operation. This can be compared with a fission reactor, where the potential energy in the in-vessel fuel is enough for months or years of operation.

The thermal energy of the plasma is only about 1 GJ, and the plasma magnetic energy is only 0.3 GJ.

Table 2: Summary of energy inventories of MINERVA-W and MINERVA-H

MINERVA-W and MINERVA-H	
In-vessel fuel (DT)	325 GJ
Plasma-facing beryllium (Be-air reaction)	485 GJ
Toroidal field coils	170 GJ
Poloidal field coils	48 GJ
Plasma thermal energy	1 GJ
Plasma magnetic energy	0.3 GJ
MINERVA-W only	
Primary coolant water (enthalpy)	410 GJ
MINERVA-H only	
Primary coolant helium (enthalpy)	30 GJ

4.2 Other energies

The enthalpy of the primary circuit coolants is 410 GJ for MINERVA-W (water) and 30 GJ for MINERVA-H (helium). The energy associated with postulated chemical interactions between beryllium armour material, covering the plasma-facing wall of the plasma chamber, and air is 485 GJ. The energy associated with postulated chemical interactions between beryllium armour and water from the cooling circuits (in MINERVA-W only) is 295 GJ. This neglects the possibility, for MINERVA-H, of interactions between the neutron multiplier beryllium and water from either the shield or the secondary circuits. If necessary, this possibility could be minimised by design provision. The energy associated with the magnetic field coils total about 220 GJ.

Table 2 summarises the energy inventories of MINERVA-W and MINERVA-H. The inventories of the other Models do not show a significantly different picture.

None of this entails that the energies could actually be mobilised in a real accident sequence. Accident analyses have shown that these energies are too small to breach the confinement.

4.3 Decay heat power

A qualitatively distinct type of energy, which can only be released at a fixed and measured pace, is decay heat. This is the energy released by the decay of activated material. If the density of decay heat power is sufficiently high, it can cause temperature excursions in the aftermath of loss of cooling events. The decay heat power is calculated from knowledge of the activation inventories. The calculation of the activation inventories is described in section 4.4. The calculated densities of decay heat power, averaged over the blankets, are shown in Figure 5 for all the Plant Models.

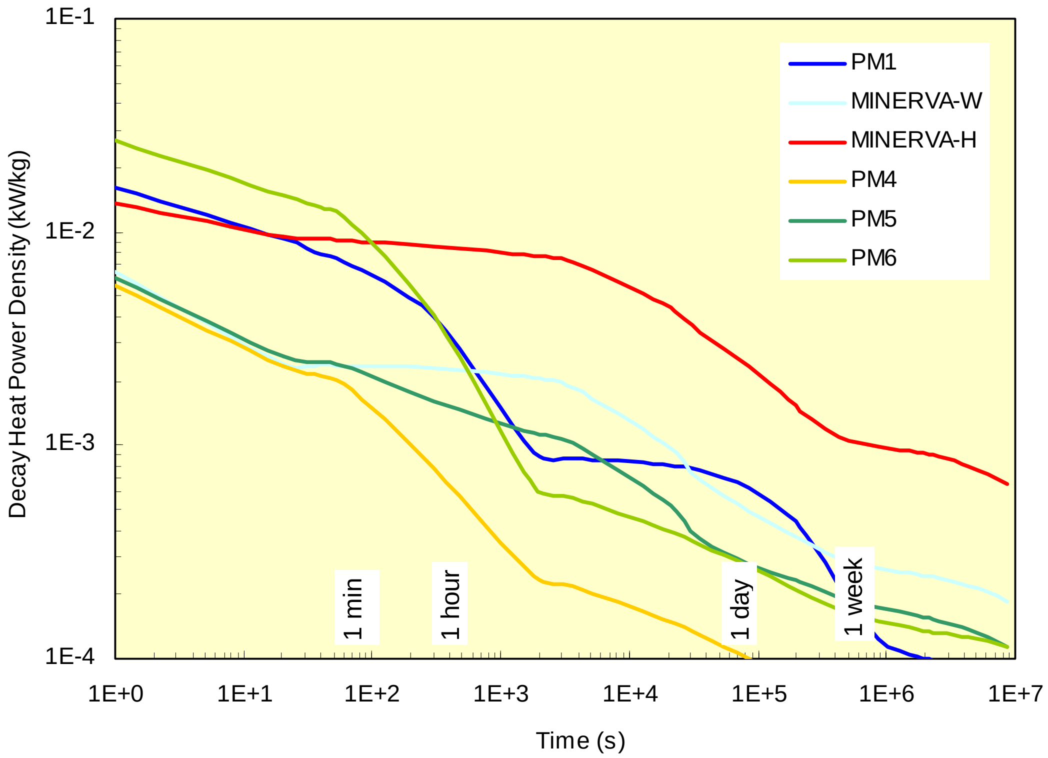

Figure 5: Decay heat power density, averaged over the blanket, for the six SEAFP blankets.

Overall (taking into account also the decay heat power in the first wall, shield and other components) the decay heat power densities for MINERVA-W, MINERVA-H and the other Models are about a hundred times lower than the corresponding numbers for a fission reactor. As is shown in section 6.4, the low decay heat power densities imply that no dangerous temperature excursions of the structure of the plant could occur, even in the event of a complete and indefinitely prolonged loss of all active cooling.

4.4 Activation

There are two distinct sources of activation: tritium and materials activated as a result of exposure to neutrons.

Tritium inventories come about in two main ways. Firstly, tritium accumulates in the armour as a result of interactions with the plasma. In SEAFP, this inventory was estimated to be one kilogram if the armour material is beryllium and fifty grams if the armour is tungsten. These estimates are uncertain, owing to the limited present understanding of the processes involved, which are the subject of investigation in present experiments, in particular JET. Secondly, tritium is generated in the blanket, removed by various dedicated systems to a processing plant, then put back into the plasma. An important objective of the design process was to minimise these inventories and other, minor, inventories. These inventories were estimated to be about 1.5 kg.

In order to calculate inventories of activation products, neutronics and activation modelling was performed in detail for all the designs, using well-validated sophisticated computer codes. Neutronics calculations were performed with two independent Monte Carlo codes in the framework of a one-dimensional representation of the radial build in the mid-plane of each of the designs. Particular care was taken to correctly account for the effects of resonance self-shielding in tungsten. Then, based on the neutron flux spectra and the most comprehensively validated activation database in the world, complete activation product nuclide inventories were calculated for every region in each design out to the magnetic field coils. These inventories, and their characteristics on a nuclide-by-nuclide basis, are used in the detailed analyses of safety and environmental impacts reported in the Chapters below. A broad summary of their essential character is given in Figures 6 and 7 by means of radiotoxicity indices. These indices are measures of total potential biological hazard. They comprise the total calculated number of sievert, related either to ingestion or inhalation, of the activated materials deriving from each of the fusion power station plant models, at times up to 500 years after the shutdown of the power station. The equivalent information for a fast reactor (with two different fuel cycles), a pressurised water reactor, and the ashes from a coal-fired power station, are also shown. (Coal wastes contain small quantities of uranium, thorium, and their daughter products.) The data for the fusion and fission plants includes replaced components accumulated over the whole plant lifetime. All the numbers are normalised so that the value for a fast reactor at shutdown is unity.

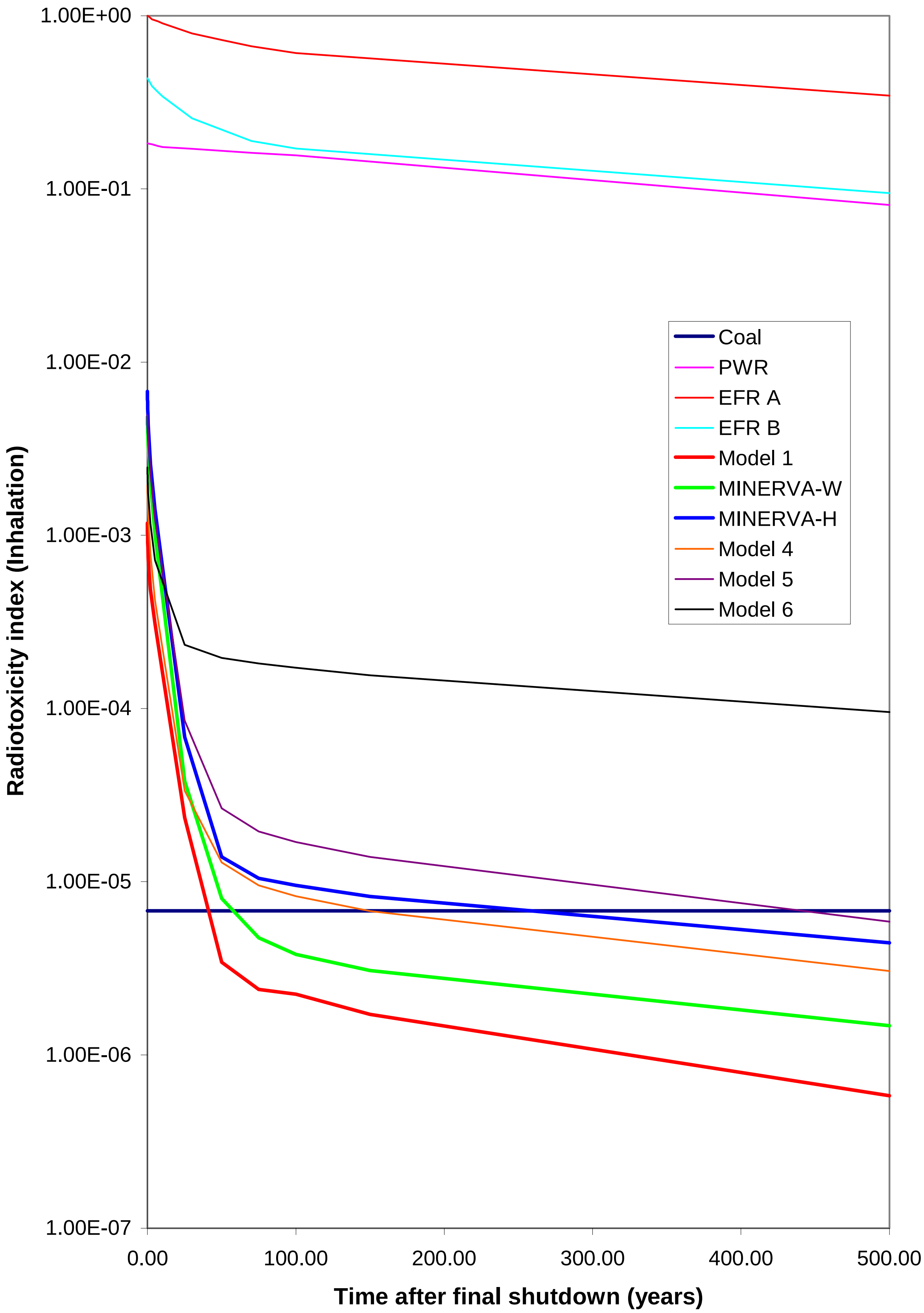

Figure 6: Radiotoxicity indices for inhalation. SEAFP (MINERVA-W, MINERVA-H, Models 1 and 4-6), European Fast Reactor project (EFRA and EFRB), Pressurised Water Reactor (PWR), and coal-fired plant, all for the same total electric energy generation.

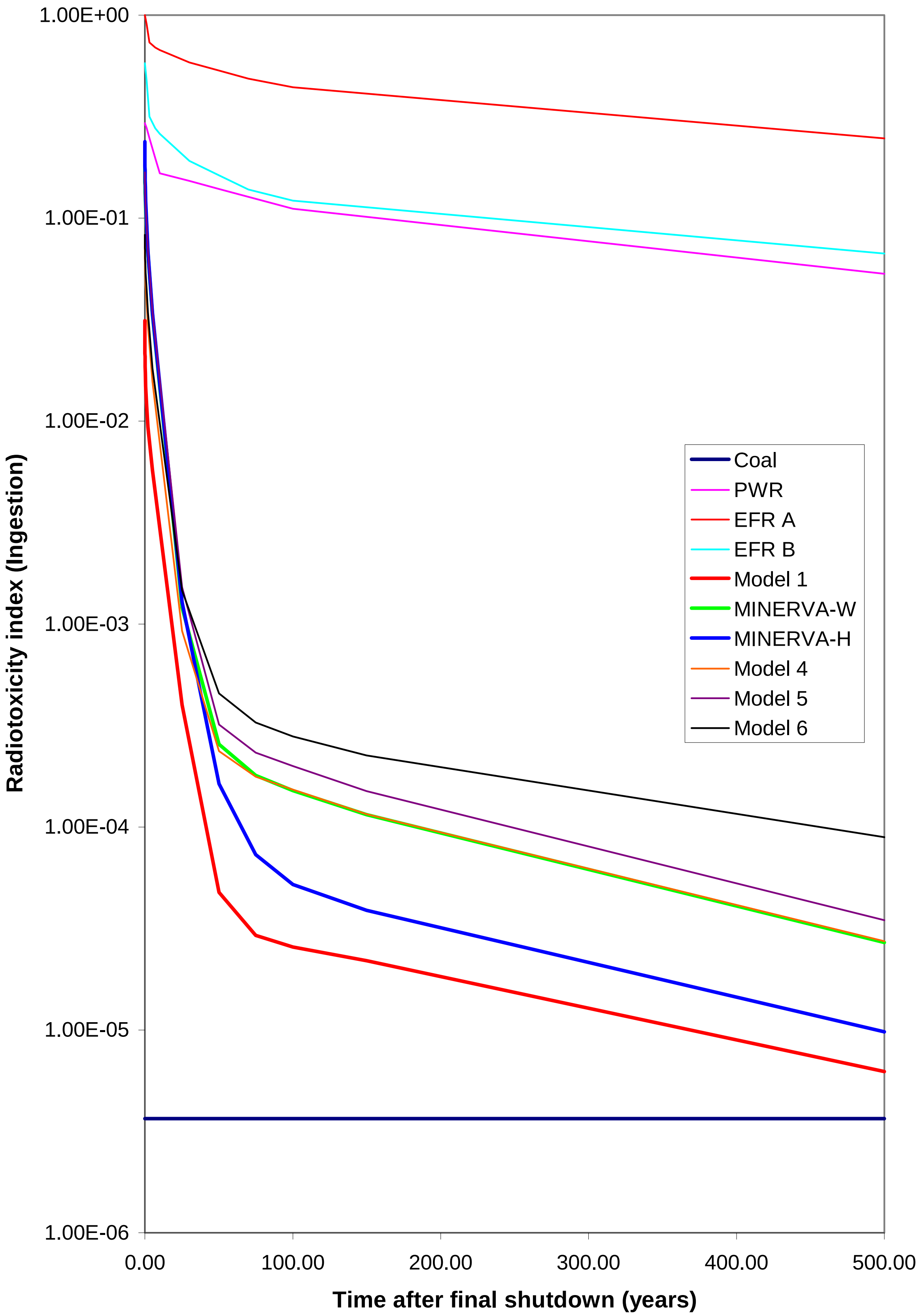

Figure 7: Radiotoxicity indices for ingestion. SEAFP (MINERVA-W, MINERVA-H, Models 1 and 4-6), European Fast Reactor project (EFRA and EFRB), Pressurised Water Reactor (PWR), and coal-fired plant, all for the same total electric energy generation.

It is apparent from Figures 6 and 7 that, after a few decades, indices of the total radiotoxicity of all the activated materials from the fusion power stations fall to levels one thousand to ten thousand times lower than that of the corresponding material from a fission power station. This feature arises because the indices for fission power stations are dominated by the contributions from the fissile fuel and cladding in the reactor cores, and fusion power stations do not use these materials. After a few decades, the total fusion radiotoxicities are broadly a factor ten greater than the corresponding numbers for the total radiotoxicity of the coal ash. In the cases where they can be compared, these fusion radiotoxicity indices are higher than those reported in the SEAFP-1 Report [1], because of more accurate modelling.

4.5 Chemical and other possible hazards

Two other categories of potential hazard were identified: chemical toxins and electromagnetic fields. An initial survey developed a short-list of the elements most likely to have some potential to give rise to hazard. The short-listed elements were the following: lithium, beryllium, vanadium, chromium, zirconium, tin, and lead. These were included in the accident analysis, as described in section 8.2. An assessment of the possible hazards from electromagnetic fields is described in section 5.2.

5 SAFETY ASSESSMENT: NORMAL OPERATION

This chapter summarises the results of the assessments of potential hazards to the plant operators and public from normal operation of a fusion power station. Sections 5.1 and 5.2 relate to operators; section 5.3 relates to the public. All these effects are very dependent on fine details of design and operating practices. In the SEAFP studies they have been estimated broadly but conservatively: if it were necessary, they could be reduced further by design measures.

5.1 Operational radiation exposure

Occupational doses were estimated for MINERVA-W, MINERVA-H and Plant Model 1. These were estimated on the basis of doses from activated components during maintenance and other operations. For the helium-cooled models, the estimated collective doses were low - about 0.2 man-sieverts/year. This is similar to the best performance of modern PWRs optimised over decades of experience. For the water-cooled MINERVA-W, most of the estimated doses arose from activation products in coolant loops. Modelling the underlying phenomena, with due account of water- chemistry measures, led to estimated doses about 2 man-sieverts/year. Additional studies indicated that the doses could be reduced to lower levels by employing engineered cooling circuit clean-up systems similar to those used in certain existing power plants. Only a limited amount of work on the estimation of occupational doses was undertaken within the SEAFP studies. A larger and more comprehensive effort has been mounted within the ITER framework [5,7], which showed the potential for reducing estimated doses by detailed design provision. This should be the basis for future work on these issues regarding commercial fusion power stations.

5.2 Exposure to electromagnetic fields

Any hazards to members of the public from electromagnetic fields would not be different from those (if any) arising from other forms of electric power generation handling and transmission.

Nevertheless, as fusion power stations use large magnetic fields in the power core, a study on occupational exposure to magnetic fields was undertaken. This study was carried out in two parts. The first part of the study surveyed the literature concerning the effects of magnetic fields on humans. The (non-conclusive) evidence is that there are no adverse or irreversible health effects attributable to occasional exposures to strong fields (up to 2 Tesla); at about 4 Tesla and above there is significant evidence of detrimental effects on health. Accordingly, the second part of the study was concerned with the development of a framework for managing the control of field hazards in the design of a fusion power station. It was concluded that adequate control of exposure should be reasonably straightforward to achieve.

5.3 Tritium and activation product effluents

Detailed assessments of effluent releases, and of resulting doses via both atmospheric and aqueous pathways were performed for MINERVA-W and Plant Model 1. No study was made for MINERVA-H: however, based on our general understanding and the trends in the analyses, it is expected to be similar to Plant Model 1. The assessments made were conservative.

The possible effluents are conveniently divided into tritium and activation products, and into gaseous or liquid effluents. These differ in their origin and nature according to whether the power station is water-cooled or helium-cooled. Considerable details of the analyses and results were presented in the SEAFP-1 report [1]: only the main points are summarised here.

Tritium effluents could originate from the cooling loops and the tritium handling and processing systems. Tritium in cooling loops could originate from permeation from the tritium-generating parts of the blanket, direct generation in the coolant, and minor sources. These were calculated conservatively. Tritium inventories in the tritium handling and processing systems were calculated as part of the design process. Gaseous and liquid leakage of tritium to the environment was calculated conservatively and from experienced gained with the Darlington Tritium Removal Facility in Canada. Gaseous activation product effluents could originate from activation products in the coolant, erosion dust in the vacuum vessel, activation of the inert shroud gas adjacent to the cryostat, and minor sources. The related inventories were estimated as summarised in chapter 4: the leakage rates were estimated using conservative assumptions. No liquid effluents of significance could be identified for Plant Model 1. For MINERVA-W they could arise from the activation of the cooling loops. The activation of the loops was calculated as part of the calculation of occupational doses summarised in section 5.1. The magnitude of liquid effluents may be dominated by the details of operational practices that are difficult to anticipate, and human errors which are difficult to model. Accordingly, the effluents were estimated by simple conservative modelling of coolant escapes from the loops and the collection, treatment and discharge of activity as part of the waste streams.

From the gaseous effluent release rates estimated as described above, doses to the most exposed member of the public from the atmospheric pathway were calculated using standard pathways models, in the presence of conservative weather sequences. Similarly, doses from aqueous pathways were determined, on the assumption that the discharge was to a lake or a relatively enclosed arm of the sea. Doses due to tritium were calculated based on exposure to elemental tritium and tritiated water. The calculated doses, which are conservative upper bounds, are shown in Table 3.

The total upper-bound doses from gaseous effluents, shown in Table 3, are very low, not exceeding 1 microsievert/year, and are significantly below internationally accepted limits. The upper-bound doses from liquid effluents are much lower still.

Table 3: Conservatively calculated upper bounds to doses arising from effluents

	Dose to the most exposed member of the public from gaseous effluents [μSv/y]	Dose to the most exposed member of the public from liquid effluents [μSv/y]
Model 1		
Tritium	0.28	0.003
Activation products	0.002	Insignificant
Total	0.28	0.003
MINERVA-W		
Tritium	0.37	0.04
Activation products	0.58	0.07
Total	0.95	0.11

6 SAFETY ASSESSMENT: ACCIDENTS

6.1 Objectives and methodology

Chapters 2 and 4 have set out the key favourable safety characteristics of fusion, in particular, the limited inventories of energies and powers able to drive accidents, and the low radiotoxic inventories. They open up the prospects of: achieving low consequences of worst-case accidents; achieving this without taking credit for the operation of active safety systems or operator actions.

Figure 8 displays the overall logic of the physics of fusion safety and of the accident analysis, showing the factors that limit potential doses to low levels.

Based on this logic, two main principles were followed.

- Firstly: to ensure that the design and material choices were such that temperature excursions would be moderate even in the most severe accidents.
- Secondly, to choose confinement arrangements which ensure that confinement integrity is maintained in all cases.

Moderate temperature excursions eliminate all possibility of a whole spectrum of accident sequences associated with melting of structural or confinement components that dominate in the safety analysis of fission reactors, and they guarantee the avoidance of significant mobilisation of activation products. Confinement integrity ensures that releases of internally mobilised material are low, and that the maximum possible resulting doses are very low.

The SEAFP studies focused their efforts on worst-case accidents, in order to make sure that overriding safety principles were satisfied. However, this does not, of course, exhaust the safety issues. In addition, commercial fusion power stations must be designed so as to lower the consequences and frequencies of lesser accidents. Some of these issues were addressed in the SEAFP studies but are not reported here: they have been thoroughly and successfully addressed in the ITER safety studies [6,7].

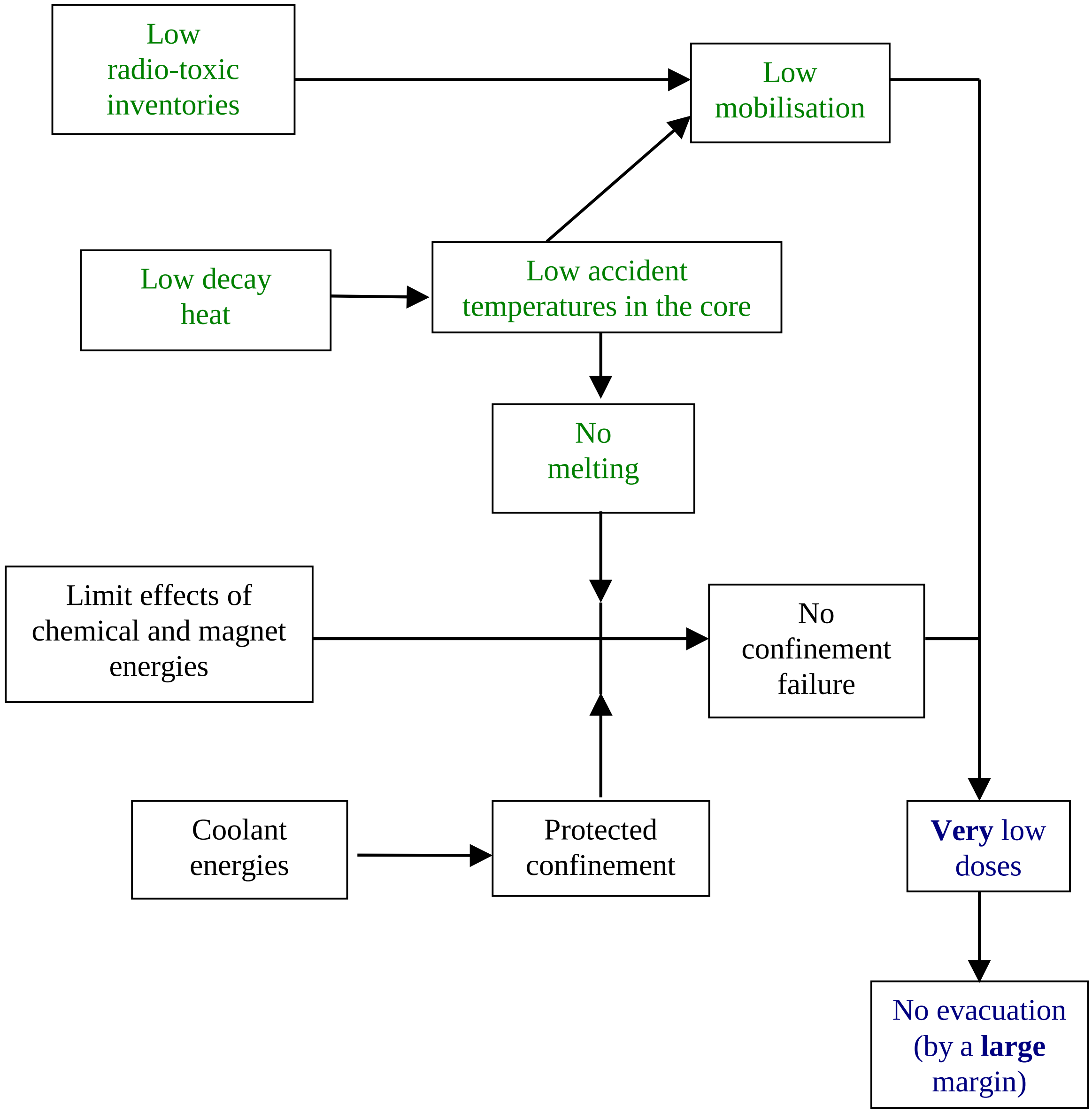

Figure 8: Overview of the physics of fusion's inherent safety characteristics

6.2 Accident identification

Logically, the first step in safety analysis is to systematically identify, and provisionally rank, the potential accident sequences.

This was done several times during the SEAFP studies, with increasing detail and rigour. The methods used were standard: HAZOP; Master Logic Diagrams; Functional Failure Modes and Effects Analysis. As well as identifying the potential accident sequences, these exercises also selected short-lists of the accidents that most merited analysis in detail. These are described in the following sections.

6.3 Accident analyses

For the short-listed accident sequences, and for certain identified key phenomena, detailed and extensive mathematical modelling was performed [1,3]. The sequences and phenomena modelled included the following:

- Accidents initiated by loss of primary circuit coolant inside the vacuum vessel;
- Accidents initiated by loss of primary circuit coolant outside the vacuum vessel;
- Accidents initiated by loss of site electric power;
- Accidents initiated by loss of the flow of the primary circuit coolant;
- Accidents initiated by loss of heat rejection from the secondary circuit;
- Accidents initiated by break in the secondary circuit, with multiple steam generator tube rupture;
- Accidents initiated by breach of the vacuum vessel;
- Accidents initiated by loss of the cryogenic helium.
- Hydrogen production and potential accidental consequences;
- Releases of magnet energy.

These many and extensive analyses are not described here. Rather, the key points relating to the relatively more serious sequences are summarised in the following sections. These key points relate to either the mobilisation of activated material or the potential for challenges to the integrity of the containment.

6.4 Mobilisation source terms and temperature excursions

Analyses showed that the most significant inventories are the following:
- Tritium in the armour material.
- Activated dust (arising from the armour material) in the vacuum vessel.
- Activation products fixed in structural materials.

With respect to their potential mobility in accidents, these inventories fall into two categories. The first two inventories are potentially very mobile. Their mobility was treated conservatively in the SEAFP studies: they were treated as wholly mobile. Thus the assumed mobility is independent of the accident sequence. The third inventory is much the largest, but could only be mobilised by very high temperatures. Thus the issue for mobilisation analysis is to calculate temperature excursions in accidents and the resulting evolution of activation products.

In the SEAFP studies, the temperatures and associated mobilisation were also calculated conservatively. The calculations hypothetically assumed a complete and instantaneous loss of all coolant in all the primary circuit loops, with no mitigation. In the modelling, the only mechanisms for removing decay heat were radiation and conduction. The results are displayed in Figure 9, for all the Plant Models.

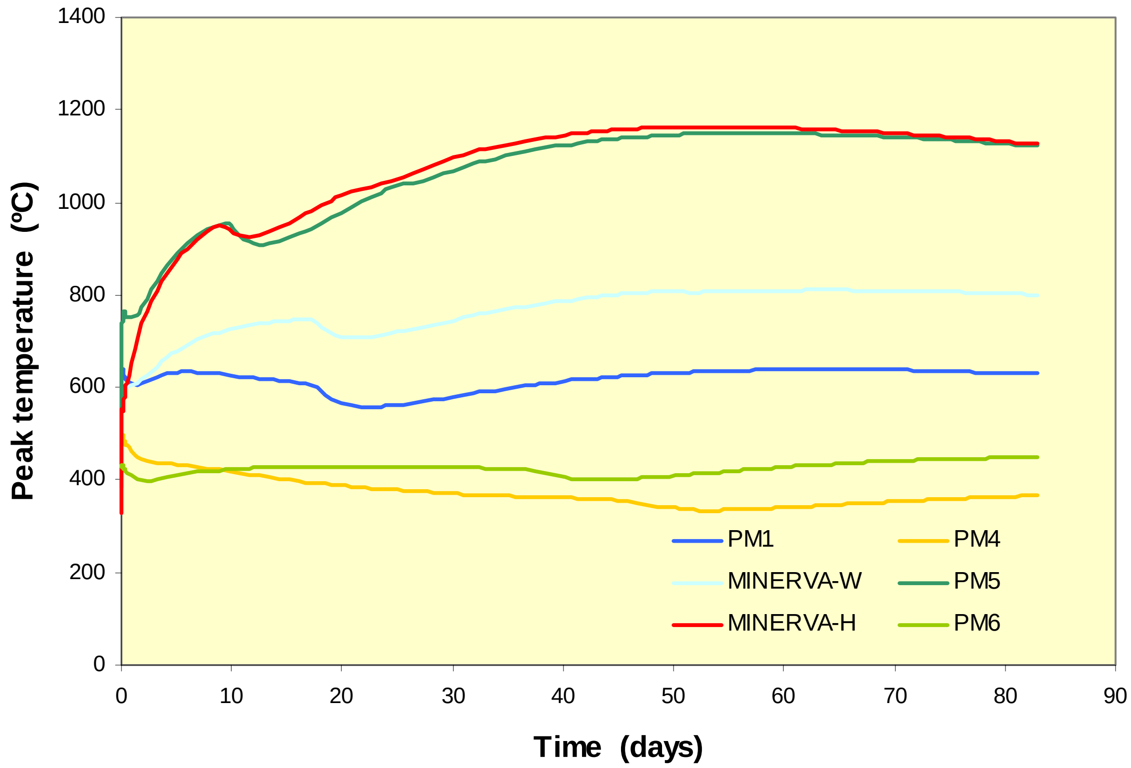

Figure 9: Conservatively calculated peak temperatures following hypothesised loss of all coolant, and no credit taken for any safety system or mitigative action, for the six SEAFP designs.

For MINERVA-W and MINERVA-H, limited temperature rises are shown for the hottest component, the first wall , peaking at times typically 50 days after the accident initiation. These temperatures are below the melting temperatures of the materials even on this conservative basis of modelling, and taking no credit for any heat removal by in-blanket thermo-fluid processes, active safety features or interventions. More realistic modelling or the inclusion of realistic accident features would lead to lower calculated temperatures. The temperatures could be further reduced by passive design provision. The more “futuristic” Plant Models with blankets based on vanadium alloy or silicon carbide structure show even lower calculated temperatures. Indeed, the temperatures in Plant Models 4 and 6 fall.

Because of the much higher decay heat of tungsten (even with correct treatment of the self-shielding effect), peak temperatures differ according to whether the armour material is beryllium or tungsten. (They also depend upon the choice of SS-316 or OPTSTAB for the shield.) Table 4 shows the long-term peak temperatures of the outboard plasma-facing side of the blanket, for MINERVA-W and MINERVA-H, with either tungsten or beryllium armour.

Table 4: Conservatively calculated upper bounds to long-term peak temperatures of the outboard first wall following hypothesised loss of all coolant, and no credit taken for any safety system or mitigative action

	With tungsten armour	With beryllium armour
MINERVA-W	934 °C	797 °C
MINERVA-H	1357 °C	1167 °C

The mobilisation of the activation products fixed in structures was then calculated from the temperature histories by using temperature-dependent, nuclide-specific, empirical data from volatility tests. This was only carried out for MINERVA-W and MINERVA-H: it was clear that mobilisation would be lower for Plant Models 1, 4 and 6. The mobilised inventories were carried forward to the next stage of the analysis.

6.5 Confinement strategies and analysis

Section 3.6 mentioned different types of confinement system studied. It was impracticable to study every significant accident sequence with every type of confinement system. Rather, a sufficient, and sufficiently varied, set of sequence/confinement combinations was analysed, using the worst kinds of accident sequence. In addition, there was analysis of particular pertinent phenomena: hydrogen production and magnet energy releases. Together with the rankings produced by the accident identification studies, and our general understanding supplemented by the large mass of related ITER work, this is a good basis for the overall conclusions.

Releases of magnet energy could be conceived to challenge containment integrity in two ways: acceleration of loose objects and arcing phenomena. Modelling of major arcing phenomena, with the potential to lead to confinement degradation, was performed. This analysis pointed to the need for design changes to eliminate this scenario. Such design provision should be included in any future detailed power plant study. Modelling of the acceleration of detached objects by magnetic fields showed that any major threat to containment integrity could be discounted. The co-existence of beryllium (as armour or, in MINERVA-H and Plant Model 6, as a neutron multiplier in the blanket) with water (as primary circuit coolant, secondary circuit coolant, or a component of the shield) entails the possibility of hydrogen production from chemical reactions in accident conditions. The possibility of subsequent combustion would be a hazard for the further evolution of the accident. Parametric studies of hydrogen phenomena identified design measures that would accommodate the associated risks. Inerting of sufficient rooms is a very efficient system, but has the great drawback of being difficult to manage in operational practice. It would be best combined with systems for hydrogen removal. The studies performed were not definitive. In any future power plant study, if the co-existence of water and beryllium is not ruled out in the design, more detailed studies should be performed.

The following initiated accident sequences have been analysed in detail: in-vessel loss of coolant, loss of heat rejection from the secondary loop, break in the secondary loop with multiple steam generator tube rupture.

The analyses of these accident sequences comprised thermo-fluid-dynamics modelling that computed the flows of coolant fluid and energy through the various compartments of the system, calculating the pressures, temperatures, densities, forces, and rates of release to the environment. The main points arising, relating to confinement integrity and releases, are summarised below.

The results show clearly that a filter-vented confinement strategy can be devised, (with in some cases an added atmospheric detritiation) that would ensure the maintenance of confinement integrity and low releases, even for the most challenging accident sequences. The results also show that the same outcome could be obtained with a closed confinement arrangement, with a rather big expansion volume of about 200,000 cubic metres. Economic studies showed that the cost differences between the different types of containment system are small. Therefore, the choice of confinement scheme can be made on other considerations, such as occupational hazards and plant availability.

Two particular accident sequences are presented in the following with their possible releases of tritium and dust. Figure 10 shows calculated releases of dust as a function of time for the accident initiated by a secondary circuit break in MINERVA-W, with confinement system Type C shown in Figure 4 (the labels C2, C3, and C4 refer to slightly different assumptions made in the modelling). In this accident sequence it is conservatively hypothesised that a break in the secondary circuit leads to multiple failure of the steam generator tube and that this in turn leads to an in-vessel break of the primary circuit. This hypothetically opens up a pathway from inside the vacuum vessel to the outermost confinement.

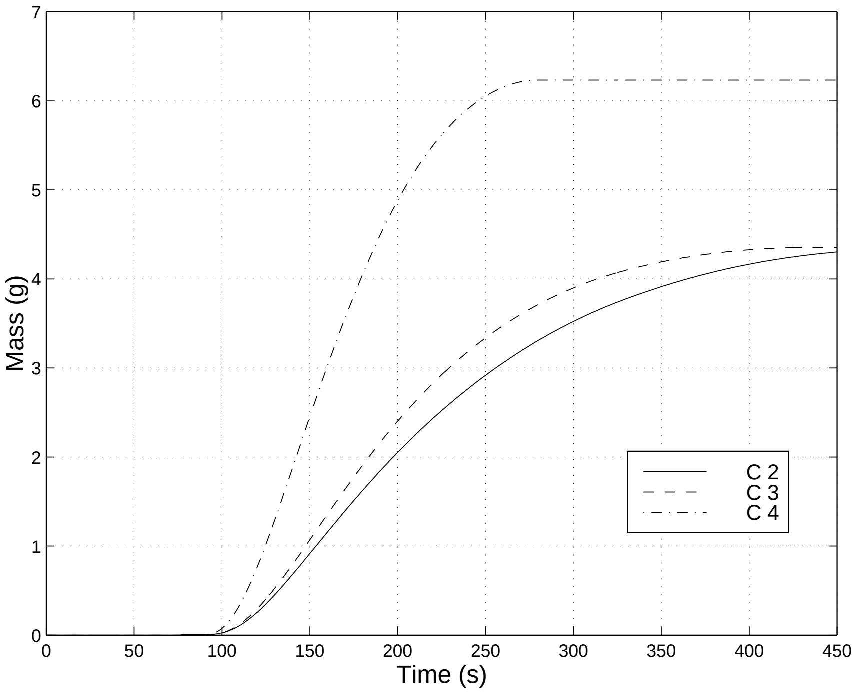

Figure 10: Calculated releases of dust to the environment for an accident in MINERVA-W, with Type C containment system

Figure 10 shows that a maximum of 6 grams of dust is released, out of ten kilograms taken to be mobilised. Less than one thousandth of the mobilised material is released. A similar calculation for other types of confinement system showed much smaller releases.

Very conservative modelling of accidents, in MINERVA-W and MINERVA-H, initiated by an in-vessel loss of coolant event, also led to low release fractions. In these calculations 1kg of tritium (as tritiated water vapour, the least benign form) and 10 kg of dust were assessed mobilised. The activation products fixed in structures were mobilised according to the very conservative prescription described in section 6.4, above. It was conservatively assumed that all mobilised material was transported to the outermost volume. Modelling of aerosol dynamics was undertaken, to estimate retention fractions. Release rates were calculated, based on the estimate that the confinement leaks in proportion to the square root of the overpressure and by one percent per day at an overpressure of 0.1 kilopascals. These release fractions were applied to the mobilised inventories stated above, to calculate the masses of each nuclide released. The calculated nuclide masses released were carried forward to the calculation of the resulting doses to the public.

6.6 Accident consequence assessment

The doses to the most exposed individual (MEI) at the site boundary (assumed to be one kilometre from the plant) were calculated using dispersion and dose conversion factors appropriate to the worst-case assumption of ground-level release in weather conditions that lead to the highest doses. The results are shown in Table 5. It is plain from the list of conservative assumptions made that actual maximum doses would be lower.

Table 5: Conservatively calculated doses, to the most exposed individual, from worst-case accidents.

	with tungsten armour	**with beryllium armour**
MINERVA-W	1.6 mSv	0.445 mSv
MINERVA-H	2.6 mSv	0.207 mSv

Even on this very conservative basis, all the calculated doses are at the millisievert level: well below the level at which evacuation would be considered and comparable to typical annual doses from natural causes.

6.7 External events and human factors

In the SEAFP studies, only preliminary consideration was given to the role of external events in accidents. For example, in the event of confinement damage by a very rare or hypothetical ultra-energetic ex-plant event, such as an earthquake of hitherto never experienced magnitude, an upper bound to the release of tritium is set by the vulnerable inventory, which is about one kilogram. If calculated on very conservative assumptions, the release of one kilogram would result in a dose to a member of the public of up to about 0.4 sievert, in a small area close to the plant. This would give rise to health effects smaller than the typical consequences of the external hazard itself. On realistic assumptions the maximum dose would be lower, and this very hypothetical scenario could be removed by design provision. Essentially, such external hazards are an economic issue, for consideration in any future fusion power plant study.

The fundamentals of fusion safety demonstrated in the SEAFP studies, that low consequences of worst case accidents are guaranteed by inherent characteristics and passive features of design, suggest that a fusion power station would be very resistant to adverse human factors. The conservative analysis of worst case accidents presented above was independent of the details of accident initiation and progression, such as might be caused by human factors. Some preliminary work was done in the SEAFP studies, but detailed consideration must await a further study.

7 MANAGEMENT OF ACTIVATED MATERIALS

Section 4.4 describes how the activation of the components of the fusion power station designs was calculated. Section 4.5 describes the calculations of decay heat power density. It emerges from these calculations that, over their lifetimes, fusion power stations would give rise, by component replacement and decommissioning, to volumes of activated material similar to the corresponding volumes from fission reactors. However, the fusion material is qualitatively very different, since the maximum decay heat density is about a hundred times lower and the long-term radiotoxicity is very considerably lower. The heat generated by the material does not require active cooling, except possibly for a small fraction of the material during the first few years. Figures 6 and 7 compare the total radiotoxicity of the activated material produced by fusion power stations with that produced by nuclear fission or coal-fired power stations and show its rapid decrease in a few decades after shut down of the plant.

This opens up the possibility that after a moderate decay time most, or all, of the activated fusion material could be cleared from regulatory control or recycled, by remote handling methods, into the next generation of fusion power stations, leaving little or no waste requiring permanent repository disposal. Exploration of these possibilities was the main thrust of the studies reported below. In addition, studies of intrusion scenarios were performed, for the first time for fusion.

7.1 Activation inventory and materials analysis

As summarised in section 4.4, a systematic methodology was developed and implemented to optimise the impurity compositions of the materials, but only to realistic levels. In addition to this process, it was noted that the replacement of the stainless steel SS-316, initially specified as the structural material of the ex-blanket components, with an alternative, manganese-based, austenitic steel, OPTSTAB, led to improved results for the purposes of activated materials management. Table 6 shows the components that were subject to the optimisation process, for MINERVA-W, MINERVA-H and Plant Model 1.

A similar exercise was undertaken for the other Plant Models. Using the realistic optimised compositions, a full set of activation calculations, for all materials, components, and Plant Models, were performed.

Table 6: Components subjected to material optimisation

Location	Plant Model 1	MINERVA-W	MINERVA-H
Armour	Be or W	Be or W	Be or W
FW structure	V-4Cr-4Ti	martensitic steel	martensitic steel
BL structure	V-4Cr-4Ti	martensitic steel	martensitic steel
BL tritium generator	Li_2O	LiPb	Li_4SiO_4
BL multiplier	none	LiPb	Be
backplate	V-4Cr-4Ti	martensitic steel	martensitic steel
shield	SS-316 or OPTSTAB	SS-316 or OPTSTAB	SS-316 or OPTSTAB
divertor armour	Be or W	Be or W	Be or W
divertor heat sink	V-4Cr-4Ti	Cu	Cu
divertor structure	V-4Cr-4Ti	martensitic steel	martensitic steel
vacuum vessel	SS-316 or OPTSTAB	SS-316 or OPTSTAB	SS-316 or OPTSTAB
neutron shield	B_4C	B_4C	B_4C
gamma shield	Pb	Pb	Pb
magnet insulator	complex	complex	complex
magnet winding	complex	complex	complex
magnet coil case	SS-316 or OPTSTAB	SS-316 or OPTSTAB	SS-316 or OPTSTAB

7.2 Recycling and clearance possibilities

Table 7 shows the classification of fusion activated materials for the purposes of recycling and clearance analysis. It is based on limits on the contact dose rate and on a clearance index proposed by the International Atomic Energy Agency (IAEA). The IAEA clearance index [11] is a weighted average of the specific activity of the nuclides in the material. The weights are derived from safety analyses of waste stores, in such a manner that, provided the value of the index is less than one, a maximum individual dose of ten microsieverts/year could arise from all possible pathways of exposure. In applying this in the SEAFP studies, some additional factors of conservatism were imposed. An alternative clearance criterion was also analysed, allowing reuse of the material for any purpose: this was the European Commission (EC) recommendation for the unconditional recycling of metal scrap [12]. The results were similar. It should be noted that publication of the IAEA and EC recommendations has not yet led to their adoption in national regulations. The criteria for recycling, by remote-handling techniques, have been set at levels a thousand times higher than the widely accepted levels for "hands-on" recycling. Though somewhat arbitrary, this is judged to be conservative, pending a detailed investigation.

Compliance with these limits was assessed after an interim storage period. This was taken to be fifty years apart from a few cases, concerning some blanket and shield zones, in which longer storage periods, never exceeding a hundred years, were assumed.

Table 7: Classification of fusion activated materials for the purposes of recycling and clearance analysis

Activated material classifications	**Contact dose rate, mSv/h**	**Decay heat power density, W/m^3**	**IAEA Clearance index**
PDW = Permanent Disposal Waste	> 20	> 10	
CRM = Complex Recycle Material	2 - 20	1 - 10	
SRM = Simple Recycle Material	< 2	< 1	
NAW = Non Active Waste (can be cleared)			< 1

7.3 Waste management

Table 8 shows the results for MINERVA-W, MINERVA-H and Plant Model 1.

Table 8: Management options for the activated materials of Plant Model 1, MINERVA-W and MINERVA-H

Management option	Plant Model 1	MINERVA-W	MINERVA-H
PDW	0.0 (+)	0.0 (+)	0.0 (+)
CRM	0.0%	1.9%	11.9%
SRM	60.7%	70.5%	47.4%
NAW	39.3%	27.5%	40.7%
Weight, tonnes	66,800	95,300	64,500

(+) A few tens of tonnes of armour material may possibly need to be disposed of as permanent disposal waste.

It can be seen that most (possibly all) of the material could be cleared from regulatory control, or recycled, leaving little (possibly none) that would require permanent repository disposal. This is so regardless of whether vanadium alloy or low-activation martensitic steel is used as the blanket structural material. These results are an improvement on those of SEAFP-1 [1], as a result of better specification of materials. Calculations were performed to check that the re-use of re-cycled material in another fusion power station does not lead to a significant build-up of activation. No significant problem was found.

The same analyses were performed for Plant Models 4 and 6, which use silicon carbide composite (with realistic, though optimised, impurity composition) as the blanket structural material. The results show that the especially low short-term activation of silicon carbide leads to low dose rates on the timescale important for maintenance operations and initial dismantling, up to a few years after end-of-life. Thereafter the activation advantages of silicon carbide diminish with time. Overall, however, the advantages of using silicon carbide are marginal: it may be more difficult to recycle in practice, and its greater transparency to neutrons leads to higher activation levels in the vacuum vessel material and plant components outside the vessel.

7.4 Repository analysis

The technology of recycling has still to be developed, and its economic attractiveness in the future cannot be assessed. So, despite the option to clear and recycle, it might be decided to consign the activated material to a repository. For this reason, analyses were made of the hazards of intrusion into a fusion repository. Using a conservative model and scenario for intrusion, that had been developed for analysis of fission repositories, doses to the most exposed individual from a fusion repository were calculated. (These were found to be about a thousand times lower than for intrusion into a fission repository).

8 OTHER ISSUES

8.1 Proliferation aspects

It is significant that none of the materials required by a fusion power station are subject to the provisions of the Treaty on the Non-Proliferation of Nuclear Weapons or the Euratom Treaty.

However, this does not mean that fusion is free of non-proliferation issues. The issues divide into two categories: other restrictions on materials legitimately present; the use of fusion power stations for illegitimate purposes.

International movements of tritium and lithium-6 have, more recently, come under looser and less formal international control arrangements. It is possible that these may be brought within the formal treaty system in the longer term. Tritium can, of course, be produced in nuclear fission reactors by rather simple methods.

In theory it would be possible to produce fissile material by exposing fertile material to neutron bombardment in a modified blanket of fusion power plants. However, for this purpose a specific blanket would have to be developed and used, which would be easily identifiable. In addition, even small quantities of illicit fertile or fissile material on the input or output sides of a fusion power plant could be detected with appropriate blanket exchange procedures. The fact that there should be absolutely no such material present would offer a clear-cut detection criterion.

8.2 Non-nuclear hazards

The potential for hazards from the release of chemically toxic materials was also studied. The elements short-listed in section 4.5 were considered in detail. The air concentrations, of these elements, likely to pose health hazards were derived from current regulatory approaches. These were converted to maximum permissible release rates using a standard conservative atmospheric dispersion model. Release rates for these elements in worst possible accidents were calculated conservatively in the course of the calculations described in sections 6.5 and 6.6. The conservatively calculated release rates were found to be several orders of magnitude lower than the conservatively calculated maximum permissible release rates, indicating that any health risk would be insignificant.

9 CONCLUSIONS

The extensive studies that have been performed within the European SEAFP Programmes have confirmed the attractive safety and environmental characteristics of fusion power station concepts. The studies make it clear both that major favourable safety and environmental features derive from inherent properties of fusion power and that the fullest expression of the safety and environmental advantages of fusion depends also upon appropriate material specifications and plant design. It would be possible to design commercial fusion power stations with the following features.

- The maximum radiological doses to the public arising from the most severe conceivable accident driven by in-plant energies would be well below the level at which evacuation would be considered and comparable to typical annual doses from natural causes.

- After a few decades, the total radiotoxic potential of the activated material arising from the operation and decommissioning of the fusion plant will decrease to a low value. Most – perhaps all – of this material could, if desired, be cleared or recycled by remote handling techniques, with little – or no – need for repository disposal. Activated fusion material would not constitute a waste burden for future generations.

The results supporting these and other, detailed, conclusions are summarised in this report. The detailed lessons learnt will be input to future European studies of commercial fusion power stations, which will update and improve the conceptual designs to reflect the most recent advances in fusion physics and technology research and development.

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