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SOCIO-ECONOMIC RESEARCH ON FUSION

SERF 2 (1999-2000)

Task 1: Externalities of fusion. Exploitation and improvement of work performed under SERF 1

Prepared by CIEMAT

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FINAL REPORT

EXECUTIVE SUMMARY

Introduction

In the previous phase of the SERF project an assessment of the external costs of two conceptual models of a fusion power plant was performed, as well as a comparison with other energy options (Sáez, et al, 1999). Results obtained ranged from 1.29 mEURO/kWh to 2.71 mEURO/kWh for the two models analysed respectively, well below those obtained for fossil-fuelled power and nuclear fission power plants confirming the role of fusion as a sustainable energy source in the long term. Some elements were identified as the predominant cause of external costs. The most important of them was collective doses produced by the global dispersion of C-14.

Additional work has been carried out in the framework of the SEAFP (Safety and Environmental Assessment of Fusion Power) and SEAL projects (Cook et al, 1999) within SEAFP-2 programme. In the present phase of the SERF project the effects of all of these technological advances in the external costs of fusion power have been evaluated. An analysis of the key variables influencing the external cost aiming to set some recommendations for the design of fusion power plants with minimum external costs has been also carried out. Furthermore, the effects of a scenario of intensive use of fusion power to meet energy requirement in future have been analysed in terms of its incidence in global radiation level and global warming.

Objectives

The objectives of this Task 1 Externalities of fusion of the SERF-2 project are:

- Complete specific studies not addressed in the previous phase of SERF
- Update the assessment of externalities
- Identify key variables influencing external costs
- Carry out a sensitivity and uncertainty analysis
- Identify design criteria aiming to reduce externalities
- Set some recommendations regarding design criteria
- Define a scenario of a future fusion economy and estimate its impact on global warming and global radiation

Methodology for externalities assessment

The methodology that will be used for the assessment of the external impacts of the fusion fuel cycle is the one developed within the ExternE project. It is a bottom-up methodology, with a site-specific approach. Quantification of impacts is achieved through the damage function, or impact pathway approach that allows for a marginal, site-specific assessment. More details on the methodology in general, and on the specific methods for the valuation of each impact, may be found in the reports issued by the ExternE Project (European Commission, 1995a,b,c 1999a,b,c and Bickel et al 1999).

The previous SERF project applied the 1998 ExternE updated methodology (EC, 1999a). From then some improvements and changes have been incorporated to the methodology (Bickel et al, 1999). They have been applied in this phase of the SERF project.

Scope

The spatial scope of the assessment of externalities of the fusion fuel cycle is divided into three scales: local scale, regional scale, and global scale

Time limits are start of construction and the end of site restoration plus 100 years during which radioactive waste is kept in a repository. However, in some cases for the longest lived radionuclides longer time periods up to 100000 years have been considered.

The stages of the cycle to be considered are:

- Extraction and manufacturing of construction materials
- Construction of the plant
- Plant operation
- Waste management
- Decommissioning
- Site restoration

Results

Analysis of key variables influencing external costs

Updating of technical inputs.

In the earlier SERF study, 2 plant models were investigated: a third has now been added. The changes to the plant concepts, the more realistic materials and the switch to a stainless steel shield (which has the effect of reducing the C-14 generation but increasing other nuclides, such as Nb-94) are the main changes.

Low activation materials have been developed. There are developments in recycling opportunities that can considerably reduce waste volumes and vary with materials. The most important source of C-14 is the nitrogen in steels, and the oxygen content particularly of the water coolant in plant model 2 and the breeder materials in plant models 1 and 3. The nitrogen content of steels has been reduced by using SS-316 instead of OPSTAB. Occupational radiation exposure could be reduced to levels below 1man-Sv per year for all models. In the area of routine releases from the power plant, there has been little new work and the results available previously are still relevant.

Assessment of collective doses from the ingestion pathway.

In the present phase of the SERF project an analysis of the relative importance of the ingestion pathway in the total external costs produced was performed. The analysis was limited to the radionuclides identified as causing the most important part of collective doses. The resulting external costs estimated were 2.29e-09 mEURO/kWh for plant models 1 and 3 due to tritium only and 2.87e-02 mEURO/kWh for plant model 2 due mainly to Mn-54 and Co-60.

Assessment of the consequences of the four different combinations of armour materials and shroud gases.

In the SEAFP project (Raeder et al, 1995) different armour materials, Beryllium or Tungsten and shroud gases, Argon or Nitrogen, were investigated. In SERF1 the Argon-Tungsten combination was selected as the base for assessment of external costs. Differences in the inventory of atmospheric emissions between the four possible combinations are more evident in plant models 1 and 3, while in plant model 2 no appreciable differences exist.

The analysis of local effects revealed that the combination selected produced the highest external costs. For global effects, differences up to nine orders of magnitude were found in C-14 emissions in plant models 1 and 3. However, the estimation of the external costs associated revealed that although the differences are important, they are not going to affect significantly the final value of the external cost of the fusion fuel cycle.

Recalculation of externalities in all the fusion fuel cycle stages considering new activated materials.

Total values considering the present practice (PP) scenario amount for 1.61, 3.79 and 1.51 mEuro/kWh for plant models 1, 2 and 3 respectively. For plant models 1 and 3 external cost are dominated by the effect of waste disposal and followed by occupational impacts in the construction and decommissioning of the power plant. Effects of routine radioactive emissions are very reduced even considering global dispersion of C-14 and H-3 nuclides. For plant model 2, external costs are dominated by the effect of the global dispersion of C-14. For detailed results see table 6.

Results obtained in this phase of the SERF project are fairly similar to those obtained in the previous SERF although slightly increased (see figure 6). The new plant model 3 shows a better performance in terms of external costs than the other two previous models.

An impact of choosing helium as coolant in the case of plant model 3 relates to the higher thermodynamic efficiency of the plant. The change in net electrical power due to increased efficiency would primarily affect plant model 3 which would have a net electrical power of approximately 1300 MW.

The resulting external cost of plant model 3 considering this increased efficiency is 1.16 mEURO/kWh, confirming the better characteristics of this plant model in terms of external costs.

Review and improvement of the methodology to calculate uncertainties

For the SERF studies, it is proposed to use the PRISM code [Gardner *et al*, 1983] for these analyses, which is specifically developed in order to perform effective error propagation studies. By using effective error propagation methods it is easy to perform a thorough investigation of the models, such as sensitivity and uncertainty analyses.

An uncertainty analysis gives the confidence in results due to the uncertainties coupled to the parameter values. A sensitivity analysis implies that all parameter values are changed in the same manner. The results of such analysis give information about the parameters for which the model is most sensitive.

The basis for the analyses is the model parameters. By specifying them, and their distribution, it is possible to generate an ensemble of input data files. Running a model with these produces a set of output data files, which can be analysed subsequently, yielding distributions of result variables. Regression analysis provides information about which parameters contribute most to the uncertainty of the results.

When analysing the results from the various models in the SERF studies it is proposed to use the median and the 5-% and 95-% percentiles as best estimate and range of results, respectively.

Evaluation of radiological and economic consequences associated with an accident of a fusion power plant.

The accidental situation considered refers to a release of a few tens of g of H-3, with a probability of occurrence lower than 10^{-7} per year. Such an accidental environmental release leads to a cumulated collective dose integrated on 50 years of about 60 man-Sv for the local population, while the collective dose of the population located between 100 and 1000 km around the power plant is in the range of 130 man-Sv. In this larger area, the individual dose is reduced by a factor 10 compared with the individual dose of the local population.

Restrictions on food trade and consumption, if any, should be rather limited to a small area (less than 10 km), for a short duration (less than a week) and only for a few products (mainly milk and cow meat).

Disturbances of the local economy are rather limited as far as there is no need to relocate people according to the estimated level of individual doses. The indirect costs represent less than 5% of the direct external costs of the accident.

As far as the risk aversion of public is concerned the initial external costs of the accident have to be multiplied by a factor ranging from 8 to 25, according to the selected discount rate. According to these different components, the external costs of the fusion accident is in the range of 10^{-6} to 10^{-4} mEURO / kWh while the total external costs for fusion are estimated in the range of a few mEURO / kWh.

Identification of key variables in different stages of the fusion fuel cycle.

Manufacturing of materials, power plant construction and power plant operation

- ✓ C-14 and H-3 emissions in the normal operation of the power plant.
- ✓ Occupational accidents in the construction and operation of the plant.
- ✓ Energy use and emissions in the manufacturing of the materials.
- ✓ Occupational exposure and local population exposure to routine radioactive emissions.

Decommissioning and site restoration

- ✓ Occupational accidents and diseases during decommissioning.

Waste disposal

- ✓ Amount of C-14 in waste.
- ✓ Retention of releases, especially C-14, in geosphere (in repository).
- ✓ Global transfer of C-14 in the environment and the integration time.

Two cost component groups, global C-14 impacts and occupational accidents, have been identified as contributing more than 90% to the total external costs.

Uncertainty ranges of key inputs

Because the use of the three different conceptual designs is intended to give an idea of the range of possibilities, it is considered here that this represents the range of uncertainties in the analysis.

- ✓ Effluents: Overall the variation in effluents among the three plant models is approximately a factor of 2, however the variation in C-14 release is much larger, varying by orders of magnitude.
- ✓ Occupational Radiation Exposure: This is higher in the water-cooled plant by a factor of approximately 5.
- ✓ Activated Materials in waste: The variation in the plant models is approximately 20%. A similar consideration applies to the activation of the tritium generating material. The use of a tritium generating material that does not include oxygen effectively removes this externality.
- ✓ Accidents: In terms of release of activated materials, the plant models vary by up to an order of magnitude.

Sensitivity analysis with key variables.

Considering sensitivity analysis for waste transports, the distance to recycling or repository gives the largest influence to the variability of the calculated costs. In recycling models, plant parameters are of great importance for the calculated results, as well as the amount of waste. The parameters concerning construction costs, upon which costs for decommissioning have been calculated, influences the variation in the calculated external costs the most as well as parameters concerning occupational accidents. The decommissioning phase is the dominating contributor to the calculated external costs for decommissioning and site restoration. For the model calculating external costs of site restoration, distance to recycling (conventional) gives the largest influence on the variability of the calculated results. The sensitivity analysis for the model calculating routine release of activation products into a river, the length of one compartment and velocity, which determines the dilution of a contaminant is of importance as well as the source term.

Sensitivity of the impacts associated with the power plant localisation

The calculations were performed for two site locations. One site is inland (Marcoule, France) and the other one is coastal (Flamanville, France). Results were also compared with those obtained for the Lauffen site (inland site).

The results show that the site location does not strongly affect the impacts at the local scale, nor the fact that liquid releases may occur into a river rather than into the marine environment. Furthermore, in the long term, the impacts are largely dominated by the global impacts of C-14. For local and short-term impacts, results obtained for the 3 sites remain in the same order of magnitude.

Identification of design criteria pursuing externalities minimization.

Identification of design criteria.

Coolant

The most obvious conclusion of the externalities work is that power plants using water coolant are much less favourable than those that use helium. This is essentially because of the generation of C-14 in the oxygen of the cooling water.

Another impact of choosing helium as coolant relates to the thermodynamic efficiency of the plant. The overall conversion efficiency of a helium cooled plant (from fusion power to electrical power) could be up to 50% higher than a water cooled plant.

Materials Selection

In optimising materials for a fusion power plant, careful consideration is given to the potential harm of the nuclides that make up the activated structure at the end of the life of the power plant. In the externalities assessment, collective dose pathways analysis plays an important, additional, role which gives strong weight to nuclides that enter the global carbon cycle specially C-14.

The main sources of C-14 are the nitrogen in the steels and Vanadium alloy, and the oxygen content of the model 1 and 3 tritium generating material. It is believed that the nitrogen in steel could be reduced, for instance to 0.01%, which would reduce the steel contents by approximately a factor of 5. In the case of plant model 2, this allows a reduction of the C-14 to 20% of its present level, however plant models 1 and 3 would remain at 40% or higher of their existing levels. Given that plant model 2 structures produce lower C-14 anyway, at about 70% of the others, this is a substantial benefit for plant model 2, arising primarily because of the lack of oxygen in the tritium generating material.

SS-316 has been chosen instead of OPTSTAB as shield material here specifically because the C-14 generation of OPTSTAB is particularly high. However if we wished to reduce the C-14 content further, it would be necessary to reduce the nitrogen content even further. If one wished to avoid the need for a repository storage of materials whilst affecting background radiation by less than a few percent, lithium oxide and lithium orthosilicate should not be used.

Analysis of interdependences and consequences of changes

Construction and Operational Phases

The most significant feature is the domination of global radiation effects, because of global collective doses due to release of H-3 and C-14. The obvious conclusion would be not to use water as coolant, which would reduce the (already low) external costs with a factor 5 for PM 2. Steels with a low content of Nitrogen would also be favourable.

The contribution from external costs due to occupational accidents and diseases are also significant. An effort to reduce these costs could consist of:

- ✓ use of well-trained personnel,
- ✓ proper measures to ensure safety,
- ✓ well-planned and well-managed construction,
- ✓ design of components that facilitates the above,

Decommissioning and Site Restoration Phases

The external costs due to occupational accidents and diseases dominate. An effort to reduce these costs could consist of those given in the previous section, and in addition a design that facilitates replacement during the Operational Phase. Disregarding external costs due to occupational accidents and diseases the release of dust during recycling exhibits the highest external costs.

Possible actions to minimise the external costs are:

- ✓ reduce particle concentration around the recycling plant(s):
  - ✓ minimise the amount of waste material
  - ✓ use highly efficient filters
- ✓ use a high chimney stack
- ✓ locate the recycling plant(s) in a not densely populated area

Waste Disposal

Only disposal of radioactive waste was considered in this study. The waste consists of contaminated (mostly steel) components from the fusion reactor, and if recycling is employed, the slag from the melting process.

The global effects tend to dominate, and also here C-14 causes the highest collective doses. To lower the dose, it is important that a long time passes until nuclides may expose the population. Using geological repositories is a common way of achieving this. A reduction in external costs with one order of magnitude was found in [Korhonen, 2000a], when the assumed time until exposure was increased from 20 000 years to 50 000 years. One way of achieving this is recycling, the residues of which will be more difficult to dissolve that the pure metal. Recycling also reduces the volumes that need to be kept in the repository.

Design criteria and recommendations

Based on the above considerations some recommendations have been proposed in order to optimise a fusion power plant on the basis of the present understanding of the external costs, and combining different aspects of the plant models studied so far.

Future fusion economy escenario

In the following three different approaches to the question on the impact of an intense fusion economy are presented.

The ability of fusion to mitigate greenhouse gas emissions

Fusion is usually not considered a helpful CO2-mitigation technology, because it is not expected to be economically available before the second half of the 21st century. Intermediate solutions like the substitution of coal by natural gas will help to reduce the greenhouse gas emissions in the short and medium term. Fusion will be available when a replacement of these technologies is necessary.

In the framework of the Socio-Economic Studies on Fusion (SERF1), two different scenarios were explored which differ in the discount rates, level of energy demand, availability of fossil fuels and energy price projections. Both scenarios assume that the capacity of nuclear fission never exceeds the current level and is expected to phase out at 2100. In both cases neither new renewables nor fusion will win considerable market shares until the year 2100. Fossil fuels remain the most important primary energy sources. The picture changes drastically, however, if future CO_2 emissions are to be restricted in order to reduce the risk of climate changes. In this case fusion and new renewables like wind and solar win considerable market shares.

Technological change is described by two phases, the first phase is the phase of invention. In case of fusion invention would be the point in time when the first power plant operates. Then follows for a technology the time of diffusion.

Fusion can only hold considerable market shares at the end of this century since the time of invention is expected to happen between 2030 and 2040. Therefore fusion will not play a role as greenhouse gas mitigation technology before that time. The primary energy carrier, natural gas, would lead to a specific reduction of greenhouse gas emissions anyhow. The time when the share of natural gas will pass its maximum roughly coincides with the invention (the technological and economic proof of principle) of fusion.

Electricity consumption will increase considerably even after 2050, leaving enough space for fusion, even without replacing older technologies although alternative low-GHG electricity generating techniques might compete for the same potential market as fusion.

The radiological impact of an intense fusion economy

The investigation has concentrated on a few radioisotopes which are of global impact: tritium and C-14. It is assumed that fusion contributes to the world wide electricity demand with a steady capacity of 1000 GWe. The intense fusion economy should operate 1000 years. Assuming an availability of 75 % requires the installation of 1334 fusion plants of 1 GWe capacity at each time. In total 33334 power plants need to be constructed, operated, decommissioned and the radioactive waste needs to be stored. The plant model followed the models developed for the series of SEAFP studies.

Obtained results shown that individual doses due to tritium are much below the doses associated with natural background radiation level and that, only for scenario 3 the individual doses due to C-14 would reach the extreme case with 0,035 mSv/a a value, roughly 1 % of the natural background radiation.

In conclusion, C-14 releases would lead, in the case of an intense fusion economy, to significant collective doses, however the individual doses would be orders of magnitude below the natural background radiation. This result needs to be put into perspective with the general discussion on the impacts of very low levels of exposure for large population cumulated over a very long time period.

Fusion, even in an intense fusion economy, will definitely not change the global environment significantly. The changes are in the worst case a few percent to the natural background radiation, but in most cases much below this.

Impacts of a future nuclear fusion economy to global warming and global ionizing radiation

In this study some basic evaluations for the estimation of global transfer of radiocarbon and carbon dioxide is presented. In a first scenario a single 1 000 MW fusion plant is assumed to start to operate in 2050 and in the second scenario 20 new plants are assumed to start operating annually after 2050 during a period of fifty years.

Two kind of global impacts are considered: the impacts of radioactive C-14 emissions and the impacts of avoided carbon dioxide emissions assuming fusion power will be used instead of especially fossil energy.

Only C-14 emissions due to normal operations are considered. Water-cooled plants are assumed. It is assumed that an emission of 580g CO_2/kWh would be avoided due to the production of fusion power.

Global impacts of a fusion plant (Scenario 1) to the carbon balance are small when compared to global background concentrations. About 5 TBq C-14 is estimated to accumulate maximally in atmosphere in case of studied Scenario 1. In 2150 about 1.5 TBq is left in atmosphere. In the case of avoided carbon dioxide emissions maximally 12 ppb could be avoided due to a fusion power plant. In the long term (in 2150) about 7 ppb could be avoided. The impacts can be compared with the natural background. For both concentrations maximal contribution has been estimated to be 0.004%.

Radiological health impacts are estimated by using simple impact factors. Also global warming most probably causes health impacts (deaths). From the assumption that doubled CO_2 concentration would cause 138 000 deaths/a (IPCC 1996b, Fankhauser 1995) a factor of about 500 deaths/a per ppm (or 500 deaths per ppm-year) is estimated. For C-14 in atmosphere a factor 0.05 deaths/a per TBq in atmosphere is used. About 10 deaths are caused during period 2050–2150 due to C-14 and about 400 deaths would be avoided due to avoided CO_2 concentration.

For scenario 2, total impact to CO_2 concentration due to operation of 1 000 fusion plants is about 10 ppm (9.5 ppm) soon after 2100. This is 4% from the additional concentration ceiling about 280 ppm in the case of stabilisation at 550 ppm (or equivalently from the preindustrial background). Concentrations of C-14 might increase also by about 4% from the natural background. Total radiation impacts would be about 200 000 deaths. Avoided health impacts due to decrease in global warming during 2050–2150 would probably be much greater.

In conclusion, avoided global warming impacts are in the production of fusion power much more important than caused radiation impacts.

Conclusions

Analysis of key variables influencing external costs

In this phase of the SERF project the input to the externalities assessment of fusion power has been updated to take account of developments in power plant design. The changes to the plant concepts, the more realistic materials and the switch to a stainless steel shield are the main changes over the assumptions underlying earlier SERF work. Main conclusions are summarised below:

- Collective doses produced by the ingestion of contaminated foodstuff and water are low compared to other impacts of the fuel cycle in the three models.
- The influence of different combinations of armour materials and shroud gases in the external costs produced by a fusion power, although important, do not affect the final figure of external cost.
- The recalculation of externalities of the fusion fuel cycle performed yielded the following results: 1.61, 3.76 and 1.51 mEuro/kWh for plant models 1, 2

and 3 respectively. These values are well below the values obtained in SERF1 for fossil fuels and nuclear fission.

For plant models 1 and 3 external cost are dominated by the effect of waste disposal followed by occupational impacts in the construction and decommissioning of the power plant. Effects of routine radioactive emissions other than the global dispersion of C-14 and H-3 are very reduced. For plant model 2, external costs are dominated by the effect of the global dispersion of C-14.

- Results obtained in this phase of the SERF project are fairly similar to those obtained in the previous SERF although slightly increased mainly due to the following reasons:
  - ✓ External costs due to occupational accidents updated to EURO 2000 values are somehow higher.
  - ✓ C-14 collective global doses have been integrated over 100,000 years instead of 10,000 years as it was done in the previous SERF.
  - ✓ Waste disposal external costs are higher due to the different retention time considered as well as the extension of the integration time to 100,000 years.
- The new plant model 3 shows a better performance in terms of external costs than the other two previous models as well as much more feasible characteristics, especially in terms of materials and a higher efficiency.
- The methodology to calculate uncertainties has been reviewed and applied to some of the stages of the fuel cycle. The use of the PRISM code is proposed.
- The external costs of the fusion accident are in the range of 10^{-6} to 10^{-4} mEURO/kWh. Even with the integration of risk aversion, these external costs still remain quite limited.
- Key variables in the external costs are factors contributing to C-14 emissions or to the impacts due to transfer of C-14 emissions, and factors contributing to occupational accidents. Integration period of impacts is especially important.
- Parameters identified having large influence on the calculated results for external costs are: for waste transport, the distance to repository and/or recycling plant; for recycling, plant parameters and the amount of waste, and for decommissioning, parameters concerning construction costs. In the routine release of radioactivity into the river the largest influence is due to the source term and the length of river compartments.
- The results of the sensitivity analysis of site location show that this factor does not strongly affect the impacts at the local scale. In the long term, the impacts are largely dominated by the global impacts of C-14 which are independent from the location.

Identification of design criteria pursuing externalities minimisation

An important part of the process of determining the external costs of fusion power is to identify the areas where improvement is both possible and beneficial. In the choice of coolant the externalities assessment strongly supports the use of helium rather than water, due to the lower C-14 production. Furthermore, the overall plant efficiency is higher in the plant models using. In the choice of plant materials, the external cost assessment suggests that the use of the stainless steel SS-316 as shield material is better.

Summarising, the following recommendations should be followed in order to optimise a fusion power plant on the basis of the present understanding of the external costs, and combining different aspects of the plant models studied so far:

- ♦ Related to the design of the fusion power plant
  - ✓ helium cooled reactor
  - ✓ tritium breeding material with no oxygen (for instance using lithium-lead)
  - ✓ shield made of a reduced nitrogen steel (not OPTSTAB).
  - ✓ Recycle fusion plant components
  - ✓ Dispose the waste in geological repositories
- ♦ Related to conventional activities:
  - ✓ Use of well trained personnel, proper measures to ensure safety and well-planned and well-managed construction, operation and dismantling
  - ✓ Improve energy efficiency, and use of cleaner technologies and cleaner fuels in the manufacturing of materials
  - ✓ Use of filters, high chimney and proper selection of the location in the recycling plant

Future fusion economy scenario

The impacts of an intense fusion economy scenario have been analysed in two main aspects: the ability to mitigate greenhouse gas emissions and the impacts of radiological emissions. Conclusions obtained are summarised below:

- ♦ Regarding the contribution to greenhouse gases abatement the conclusion of the analysis is that fusion, if commercially available in 2050, can considerably contribute to the reduction of greenhouse gas emissions on the long term replacing intermediate solutions, like the substitution of coal by natural gas.
- ♦ The analysis of the radiological impacts expected in an intense fusion economy installed for a long time period revealed that fusion will definitely not change the global environment significantly. The changes are in the worst case a few percent to the natural background radiation, but in most cases much below this.
- ♦ When global radiation impacts produced by a fusion economy and the avoided global warming impacts are compared is evident that avoided global warming impacts are in the production of fusion power much more important than caused radiation impacts. The very simple studied scenarios include, however, assumptions that have to be studied more carefully.

TABLE OF CONTENTS

1. INTRODUCTION

In the previous phase of the SERF (Socioeconomic Research on Fusion) project an assessment of the external costs of two conceptual models of a fusion power plant was performed, as well as a comparison with other competing energy options (Sáez, et al, 1999). The evaluation was made based on the work performed in the SEAFP project (Raeder et al, 1995). The whole fuel cycle was analysed from the extraction of materials to the disposal or recycling of fusion waste. Results obtained ranged from 1.29 mEURO/kWh to 2.71 mEURO/kWh for the two models analysed respectively. These results were well below those obtained for fossil-fuelled power plants (11.5-54.9 mEURO/kWh) and nuclear fission power plants (4.4-7 mEURO/kWh), confirming the role of fusion as a sustainable energy source in the long term.

Some elements were identified as the predominant cause of external costs. The most important of them was collective doses produced by the global dispersion of C-14 as it enters in the global carbon cycle and become widely dispersed throughout the biosphere.

Additional work has been carried out in the framework of the SEAFP (Safety and Environmental Assessment of Fusion Power) and SEAL projects (Cook et al, 1999) within SEAFP-2 programme of the Fusion Programme, in the aspects identified in the SEAFP project as needed of further study and deeper understanding. The objectives of the SEAFPT–2 programme were: to add a third tritium-generating blanket concept, to update the material specifications, to obtain a more comprehensive description of potential accident scenarios, to analyse and specify the containment concepts which minimise accidental releases to the environment, and to analyse the means for minimising the need for repository disposal of fusion materials. Advances carried out in all of these aspects could have incidence in external costs produced specially the use of low activation stainless steels which results in a decrease in C-14 inventories in the fusion waste.

In the present phase of the SERF project a task devoted to the analysis of externalities of fusion power has been also included. In this task the effects of all of these technological advances in the external costs of fusion power have been evaluated. An analysis of the key variables influencing the external costs figure has been performed aiming to set some recommendations for the design of fusion power plants with minimum external costs. Furthermore, the effects of a scenario of intensive use of fusion power to meet energy requirement in future have been analysed in terms of its incidence in global radiation level and global warming.

In this report, a summary of the main results obtained in Task 1 “Externalities of fusion. Exploitation and improvement of work performed under SERF1” of SERF-2 project is presented.

2. OBJECTIVES

The objectives of this Task 1 Externalities of fusion of the SERF-2 project are:

- Complete specific studies not addressed in the previous phase of SERF: collective doses from the ingestion pathway, assessment of consequences of different combinations of armour materials and shroud gases, review of the methodology for uncertainties, new approach in the relationship among collective and individual doses and assessment of accidents.

- Update the assessment of externalities through the introduction of technological and methodological improvements developed in SEAFP-2 and in the ExternE project.
- Identify key variables influencing external costs
- Carry out a sensitivity and uncertainty analysis
- Identify design criteria aiming to reduce externalities
- Set some recommendations regarding design criteria for fusion power plants
- Define a scenario of a future fusion economy
- Estimate the impact of this fusion economy on global warming and global radiation

3. METHODOLOGY FOR EXTERNALITIES ASSESSMENT

3.1 State of the art of externalities assessment

Over the last decade, several attempts have been made to quantify, and express in monetary terms, the externalities of different energy sources.

The latest approach to externalities assessment is that proposed by the ExternE project of the European Commission (1995a).

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies. Launched in 1991 as a collaborative project with the US-DOE, and continued afterwards by the EC as the ExternE project, it has involved more then 40 different European institutes from 9 countries, as well as scientists from the US. This resulted in the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a wide range of different fuel cycles. The result was identified by both the European and American experts in this field as currently the most advanced project world-wide for the evaluation of external costs of power generation.

Under Joule III, this project has been continued with three distinct tasks. The Core programme was oriented toward refinement of the methodology and to apply the methodology to parts of the energy sector not explored previously (European Commission, 1999a, 1999b). The ExternE transport programme adapted the methodology for the characterisation of the impacts and damages of the transport sector (European Commission, 1999b). And the third one, ExternE National Implementation programme (European Commission 1999c), whose objective was to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 12 fuel cycles. A wide range of technologies have been analysed, including fossil fuels, nuclear and renewables. Fuel cycle analyses have been carried out, determining the environmental burdens and impacts of all stages. Therefore, besides from the externalities estimated, the project offers a large database of environmental aspects of the fuel cycles studied. The metholodogy for assessment of the externalities of transport has been recently updated within the project and also some improvements has been incorporated to the general ExternE methodology within the project "External costs of energy conversion – Improvement of the ExternE methodology and assessment of energy related transport externalities" (Bickel et al,1999).

A more detailed description of the ExternE methodology follows.

3.2 The ExternE methodology

The methodology that will be used for the assessment of the external impacts of the fusion fuel cycle is the one developed within the ExternE project. It is a bottom-up methodology , with a site-specific approach, that is, it considers the effects of an additional fuel cycle located in a specific place.

Quantification of impacts is achieved through the damage function, or impact pathway approach. This is a series of logical steps, which trace the impact from the activity that creates it to the damage it produces, independently for each impact and activity considered. This allows for a marginal, site-specific assessment, and using the same methodology for all fuel cycles allows for a consistent comparison among them.

More details on the methodology in general, and on the specific methods for the valuation of each impact, may be found in the reports issued by the ExternE Project (European Commission, 1995a,b,c, 1999a,b,c and Bickel et al 1999).

The underlying principles on which the methodology for the ExternE Project has been developed are:

Transparency, to show precisely how results are calculated, the uncertainty associated with the results and the extent to which the external costs of any fuel chain have been fully quantified.

Consistency, of methodology, models and assumptions (e.g. system boundaries, exposure-response functions and valuation of risks to life) to allow valid comparisons to be made between different fuel chains and different types of impact within a fuel chain.

That analysis should be comprehensive, we should seek to at least identify all of the effects that may give rise to significant externalities, even if some of these cannot be quantified in either physical or monetary terms.

These characteristics should be present along the stages of the assessment of externalities, which are described below.

3.3 Stages of the methodology

3.3.1 Site and technology characterisation

One of the distinguishing features of the ExternE methodology is the inclusion of site and technology specificity.

The fuel cycle stages will have to be fully characterised, taken into consideration the activities over the lifetime of the plant, from the extraction of the materials needed to construct and operate the plant to the final decommissioning of the plant and disposal of the waste. By-products have to be taken into account up to the point where they are ready to be used elsewhere.

The use of the impact pathway approach requires also a detailed definition of the scenario under analysis in physical terms and the spatial limits of the analysis should be designed to capture impacts as fully as possible. The same applies to the temporal limits. In principle, each impact should be traced for as long as it is considered to be relevant.

3.3.2 Identification of fuel chain burdens

The term ‘burden’ relates to anything that is, or could be, capable of causing an impact of whatever type. The purpose of this identification is to catalogue everything to provide a basis for the analysis of the fuel chain in a consistent and transparent manner, and to provide a firm basis for revision of the analysis as more information on the effects of different burdens becomes available in the future.

3.3.3 Identification of impacts

The next part of the work involves identification of the potential impacts of these burdens. The emphasis here is on demonstrating that certain impacts are of little or no concern, according to current knowledge.

3.3.4 Prioritisation of impacts

It is possible to produce a list of several hundred burdens and impacts for any fuel chain. A comprehensive analysis of all of these for the fusion fuel cycle is clearly beyond the scope of externality analysis. In the context of this study, it is important to be sure that the analysis covers those effects that (according to present knowledge) will provide the greatest externalities. Accordingly, the analysis that will be performed is limited, though only after due consideration of the potential magnitude of all impacts that will be identified for the fuel chain.

3.3.5 Quantification of impacts

Once we have selected the impacts to be analyzed, the impact pathway for each case has to be defined, so that impacts can be quantified. The impact pathway links ‘burdens’ (defined here simply as something that causes an ‘impact’) with monetary costs. In some cases these pathways are very simple, while in others the description of these linkages is far more complex.

A relatively simple model of an impact pathway is shown on the following figure.

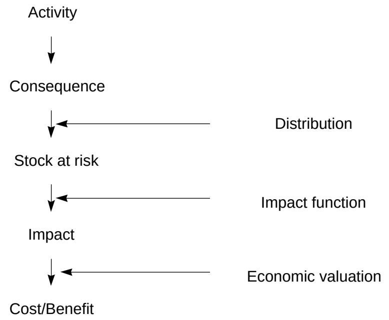

Figure 1. The impact pathway

The first stage to quantify the impacts produced is to determine the consequences or burdens derived from the selected site and technology option. For example the radioactive emissions produced by the fusion power plant in the generation stage. Quantification should be made of both burdens from normal operation and burdens resulting from accidents.

Besides from quantifying them, these consequences have to be distributed along time and space, taking into account the system boundaries that have been previously defined. This can be done more or less easily. For radionuclides distribution, it is required the use of complex models to determine their transport in the atmosphere as well as in the water courses.

The *stock at risk* has to be determined. This is the number of receptors, be it human population, ecosystems, or other, which are likely to be affected by the consequences of the cycle.

The impacts then are quantified linking this stock at risk with the impact functions. Impact functions can be rather straightforward, in some cases. For example, to link occupational accidents with the population at work, accident rates can be used. However, other impacts require the use of more complex dose-response functions. For radionuclides exposure a robust body of knowledge exists for estimating doses and associated impacts.

3.3.6 Economic valuation

The rationale and procedures underlying the economic valuation are those used within the ExternE Project. The approach followed is based on the quantification of individual ‘willingness to pay’ (WTP) for environmental benefit.

A limited number of goods - crops, timber, building materials, etc. - are directly marketed, and for these valuation data are easy to obtain. However, many of the more important goods of concern are not directly marketed, including human health, ecological systems and non-timber benefits of forests. Alternative techniques have been developed for valuation of such goods, the main ones being hedonic pricing, travel cost methods and contingent valuation.

As costs and benefits are distributed along wide time periods, they have to be brought to the present time in order to be compared on the same basis. This is done by discounting. The higher the discount rate, the lower the value attached to the damages or benefits.

The need for discounting arises mainly for two reasons. The first one is time preference, or “impatience”, that is, the preference to spend now rather than in the future. The second reason is the marginal productivity of capital.

These are the two main options for the choice of the social discount rate: the social time preference rate, and the opportunity cost of capital. However, much of the environmental literature argues against discounting, specially against high discount rates. High rates may shift the cost burden to future generations.

Two central discount rates are used in the ExternE methodology: 0 and 3%, with an internediate value of 1% used for sensitivity analysis. The rationale for the selection of this range and best estimate, and a broader description of issues relating to discounting can be found in Bickel et al, (1999).

3.3.7 Assessment of uncertainty

Uncertainty arises in each stage of the assessment. When identifying the consequences of each activity, there may be errors in the estimation, due to the variability of data, or the need to extrapolate them. In the case of fusion technology this source of uncertainty becomes specially important. The quantification of the impacts is also uncertain, mostly due to the complexity of the phenomena involved. There is a lack of detailed information on human and ecosystem responses to pollution or other impacts, and so several assumptions, which may prove unfounded, have to be made.

Economic valuation also presents many caveats. It involves modelling the behaviour of consumers and producers, and projecting future scenarios, as well as making political and ethical decisions, such as the choice of the discount rate.

The present project has made an attempt to quantify the uncertainty involved in the estimation of externalities of fusion power. The approach followed is described in subactivity 1.1.6.

3.4 Update in the methodology from previous SERF

The previous SERF project applied the 1998 ExternE updated methodology (European Commission, 1999a). From then some improvements and changes have been incorporated to the methodology in the EC project “External Costs of Energy Conversion- Improvement of the ExternE Methodology and Assessment of Energy related Transport Externalities” (Bickel et al, 1999). Main modifications are related to:

- Emission modelling. For transport damages estimates, the emissions calculation is homogenised by using the MEET project factors.
- Dispersion modelling. A new model for regional ozone formation and transport is available, the SROM model.
- Health E-R functions have been reviewed and fine tuned. Main changes affect the E-R functions for chronic mortality (Pope at al, 1995) and chronic bronchitis (Abbey et al, 1995) which were scaled down by 30% and 50% to account for the difference between recent and historical estimates of exposure and the higher particle effect in time series studies in the USA compared to Europe.
- New E-R function for materials are available now
- In monetary valuation, the use of the VLYL (Value of Life Year Lost) concept for valuing changes in mortality risk is recommended, and new morbidity estimates and endpoints have been introduced based on new European Contingent Valuation studies. Monetary values have been updated to EURO 2000 values.
- Global warming damages estimates. Now the central estimate for marginal costs due to CO_2 emissions is set in 2.4 EURO/t CO_2, with a 67% confidence interval ranging from 1.4 to 4.1 EURO/t CO_2. These values are considerable lower than the previous estimates of the ExternE methodology.

4. SCOPE

4.1 Spatial limits of the impact analysis

The spatial scope of the assessment of externalities of the fusion fuel cycle is divided into three scales:

- local scale: which covers the effects on a local area of 100 km x 100 km with the power plant in the centre.
- regional scale, which covers the effects on Europe
- global scale, which covers the effects on the whole Earth

Consideration of regional and global impacts has major implications in the size of the total impact, since some pollutants, radioactive and conventional, may become widely dispersed through the regional and global ranges and in many cases regional and global effects are far greater than effects on the local scale.

4.2 Temporal limits of the impact analysis

Impacts should be addressed over their full time course. For the fusion fuel cycle under analysis the time limits are start of construction and the end of site restoration plus 100 years during which radioactive waste is kept in a repository until the radioactivity comes down to a safety limit. However, in some cases for the longest lived radionuclides longer time periods may be considered.

Consideration of long-term impacts introduces a good deal of uncertainty, as it requires a view to be taken on the structure of future society. Future costs will be quantified and then discounted to get their present value. Selection of the discount rate to be applied is an important issue because many of the damages of the fusion fuel cycle will occur many years after the action that causes the damage actually takes place, and the application of any discount rate above zero can reduce the cost of major events in the distant future to a negligible figure. Despite the uncertainties involved it is informative to conduct analysis of impacts that takes effect over periods of many years in order to gain some idea of how important these effects might be in comparison to effects experienced over shorter time scales.

4.3 Stages of the fuel chain.

System boundaries should be drawn so as to account for all potential effects. In practice, a complete analysis of the fuel cycle is not necessary since some impacts or stages can be negligible, but this extreme must be demonstrated and it cannot simply be assumed. As far as the fusion fuel cycle is concerned the stages of the cycle to be considered are:

- Extraction and manufacturing of construction materials
- Construction of the plant
- Plant operation
- Waste management
- Decommissioning
- Site restoration

5. RESULTS

5.1 Analysis of key variables influencing external costs

5.1.1 Completion of specific studies not addressed on previous SERF.

Updating of technical inputs. UKAEA.

Plant models

The assessment of the best options for fusion power is aided particularly by comparison of different models of a fusion power plant using different materials. In the earlier SERF study, 2 plant models were investigated: a third has now been added. The basic plant models are as follows:

Table 1: Summary of the main properties of the 3 plant models.

Plant Model	FW/blanket structure	Tritium-generating material	Neutron multiplier	FW/blanket coolant
1	Vanadium alloy	Li_2O ceramic pebble bed	None	Helium
2	Low activation martensitic steel	Liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	Water
3	Low activation martensitic steel	Li_4SiO_4 ceramic pebble bed	Beryllium	Helium

In the previous SERF study, although the external costs were small, the largest contribution was identified to result from the generation of C-14. The biggest contributor to this was the cooling water in one of the plant models (model 2) however a significant contribution came from the shield materials. In later studies (SEAL/SEAFP-2) an option was studied in which stainless steel (SS-316) was used as the shield material. This has the effect of reducing the C-14 generation but increasing other nuclides, such as Nb-94. In order to maximise the information gained from SERF-2000, this variant on the original designs is chosen for investigation, as a substantial difference from the earlier SERF assumptions.

The changes to the plant concepts, the more realistic materials and the switch to a stainless steel shield are the main changes over the assumptions underlying earlier SERF work. These are described further in Cook et al, which describes the conclusions of the SEAL and SEAFP-2 studies, and in supporting material.

Safety

There has been further work on safety aspects of fusion but the previous conclusions are unchanged: there is no conceivable accident in which evacuation of the public would be considered necessary

Activation of Materials

One of the key aspects of the environmental and safety properties of fusion is the activation of the materials exposed to neutrons. The development of low activation materials has successfully addressed this issue, but the choice between different materials remains. Different materials have advantages and disadvantages, for instance in their short term or longer term behaviour; the short term is of most interest for accident hazards, whilst the long term is of more interest for waste. There are developments in recycling opportunities for materials that can considerably reduce waste volumes and again this varies with materials. The overall optimisation of materials continues and it may well be that a system such as the externalities assessment will facilitate this through its quantitative assessment of benefits to be gained by improvements in each area.

To allow quantification of the changes due to the differences in materials, a spreadsheet has been given as input to the SERF-2000 programme. This lists the activation associated with 104 different nuclides. A summary of the most important is reproduced in Table 2, (after a decay time of 100 years, chosen to be relevant to a waste time scale).

Table 2: Summary of the quantities of the most important nuclides in the three plant models.

Plant Model	C-14 (moles)	Nb-94(moles)	Mo-93(moles)	Ni-59(moles)
1	468	123	410	16,109

2	316	21	69	8,655
3	421	78	312	9,025

Further details are given in Appendix 1 of Ward and Forrest, (2000).

The most important external cost identified in the earlier SERF study was the C-14 generated during the power plant operation. The most important source of C-14 is the nitrogen in steels, and the oxygen content particularly of the water coolant in plant model 2 and the breeder materials in plant models 1 and 3. The nitrogen content of steels could be dramatically reduced, indeed SS-316 contains a factor of 5 less nitrogen than OPSTAB, both materials that were considered for shield materials in the recent SEAFP-2 study. There is still potential for further reduction so that the shield contribution becomes relatively unimportant leaving the coolant and breeder materials as the dominant sources. In this case there would be an overall reduction in C-14 would be by a factor of 5-10.

Material Recycling

Another area of development over recent years has been the consideration of recycling possibilities for materials at the end of the power plant life. In SEAFP-2 it was considered that almost all materials could either be cleared as non-active materials or recycled for use, for instance, in another fusion plant (Cook et al). Although this recycling is considered to be feasible, no judgement was made on how much recycling would be economically practicable. This is an area where further work is necessary, however as a first attempt at quantification, it seems unlikely that materials could be recycled more than ten times, in which case 10% of the activated material should be treated as waste. Although the overall activation level of materials is found not to increase with recycling, the longer-lived nuclides such as C-14 will accumulate with recycling and their full impact must be considered.

Occupational Radiation Exposure

One additional outcome of the more recent studies is the reduced level of occupational exposure envisaged in a fusion power plant. This was of concern in SEAFP but attempts to optimise water chemistry (for plant model 2) indicate that the occupational radiation exposure could be reduced to levels below 1man-Sv per year for all models (Cook et al, and Karditsas, 1999).

Releases during Normal Operation

In the area of routine releases from the power plant, there has been little new work and the results available previously are still relevant.

Assessment of collective doses from the ingestion pathway. CIEMAT

In the previous phase of this SERF project, an assessment of the external costs of two conceptual models of a fusion power plant was performed. However, some impacts were not included in this assessment. This is the case of the external costs originated from the doses produced by the ingestion of contaminated water and foodstuff. A preliminary assessment of the collective dose that could be produced by this pathway yielded considerably high results, for plant model 2. Several reasons could explain these results. Firstly, the assessment was based on several critical assumptions due to the lack of available actual data. Main assumptions regarded hydrological parameters of the river that determine radionuclides fate and dilution, and river water uses mainly water consumption by the population. The assumptions adopted were conservative in the sense that they keep the analysis in the safe side, likely overestimating some of the calculated impacts. As a consequence, radionuclide concentrations in the river water entered as a source term in the food chain were relatively high and so were the calculated doses.

Therefore, in the present phase of the SERF project and within subactivity 1.1.3 an analysis of the relative importance of the ingestion pathway in the total external costs produced was performed. Additional input data regarding the site of the fusion power plant, river characteristics, and river water uses were gathered in order to reduce the uncertainty of the analysis and allow a more realistic assessment. The analysis was limited to the radionuclides identified as causing the most important part of collective doses: Ar-41, N-16, Fe-59, Mn-54, Re-184, Sc-48, Ta-182, W-185, Co-60, Fe-55, H-3 and C-14. Dispersion of routine liquid effluents from the fusion power plant has been performed in a regional scale considering the dispersion of radionuclides on the river Neckar and their eventually incorporation into the flow of the Rhine River until the North Sea. Dispersion of radioactive atmospheric releases was also analysed in order to determine the amount of activity deposited in the ground and the extent to which this activity enters into the food chain though the contamination of the food crops and pastures in the region.

Impacts from the ingestion pathway considered are those originated by both atmospheric emissions of radioactivity as well as the liquid effluents to the river water though the following priority exposure ways:

- ingestion of contaminated agricultural products by deposition of the radionuclides emitted to the atmosphere
- ingestion of irrigated products
- ingestion of river water

Calculation of collective doses from the different pathways is performed following the methodology applied in the ExternE project (European Commission, 1995b). Details can be found in Lechon et al, 2000a. Results of collective doses from the ingestion pathway, shown in table 3 were 7.24e-08 man.Sv/year for plant models 1 and 3 and due to Tritium only and 9.07e-01 man.Sv/year for plant model 2 due mainly to Man-54, Co-60 and Fe-55.

Table 3. Collective doses from the ingestion pathway

	Models 1 and 3		Model 2	
Radionuclide	Dose received	%	Dose received	%
H-3	7.24E-08	100	5.58E-08	0
C-14			4.86E-02	5.36
Fe-55			5.56E-02	6.13
Co-60			2.54E-01	28.06
Zn-65			5.45E-03	0.6
Fe-59			3.31E-06	0
Mn-54			5.17E-01	57.06
Re-184			5.63E-03	0.62
Ta-182			1.05E-02	1.16
W-185			9.19E-03	1.01
TOTAL	7.24E-08	100	9.07E-01	100

Radiological health effects have been assessed, in the same manner as it was done in the previous SERF project, using the risk factors used in the ExternE project methodology (European Commission, 1995) which are those recommended by the ICRP (ICRP, 1991). External costs from the ingestion pathway are obtained using the monetary values proposed by the ExternE project for the different radiological health effects that were estimated. Monetary values for these radiological health effects have been updated by the last ExternE project (Bickel et al, 1999). Details can be found in Lechon et al, 2000a.

The resulting external costs estimated were **2.29e-09** mEURO/kWh for plant models 1 and 3 and **2.87e-02** mEURO/kWh for plant model 2.

Assessment of the consequences of the four different combinations of armour materials and shroud gases. CIEMAT.

All the plasma facing components need armour to optimise plasma-surface interactions. In the SEAFP project (Raeder et al, 1995) different materials were investigated. Both low-Z materials as Beryllium and high-Z materials as Tungsten were considered in the plant models proposed. The former is susceptible to high erosion, the latter require very good retention of sputtered armour material by the divertor to control plasma impurities. The shroud gas used in the cryostat can be Nitrogen or Argon.

These differences in materials composition lead to the identification of four possible cases in each plant model regarding atmospheric emissions. In order to ease the implementation of the analysis, only one possibility in each model was selected in the previous phase of SERF. The combination of materials that produced the higher emissions was selected following a conservative criterion. This combination corresponds to the use of Argon and Tungsten. In subactivity 1.1.4. the consequences of selecting this alternative have been analysed. Details can be found in Lechon et al, 2000b.

Differences in the inventory of atmospheric emissions between these four combinations are more evident in plant models 1 and 3, while in plant model 2 no appreciable differences exist.

In the case of plant models 1 and 3 important differences in gaseous effluents with the base case (case 4) arise for the following nuclides: H-3, C-14, Mn-54, Fe-55 and Co-60. For the rest of the nuclides either the differences are not important or the selected case of analysis (case 4) has higher emissions. In the case of plant model 2 no important differences appear among the different cases with the only exception of N-16 and Sc-48 which are higher if beryllium is used as armour material.

The estimation of the effects in terms of doses and external costs produced by the different cases has been performed based in the simulations and calculations made for the base case. External costs produced by ingestion are not included in this analysis.

In the case of plant models 1 and 3 the analysis of local effects of the dispersion of these four different combinations of atmospheric emissions revealed that the combination selected (Argon-Tungsten) produced the highest external costs.

Important differences were found in C-14 emissions of these four combinations in plant models 1 and 3 as shown in figure 1. The combinations using Nitrogen as a shroud gas produced C-14 emissions nine orders of magnitude higher than those produced using Argon. When estimating the external costs associated we found that in the combination selected (Argon, Tungsten) the external costs estimated were 2.5e-14, while in the combinations using Nitrogen were 2.9e-05. Although these differences are important, they are not going to affect significantly the final value of the external cost of the fusion fuel cycle.

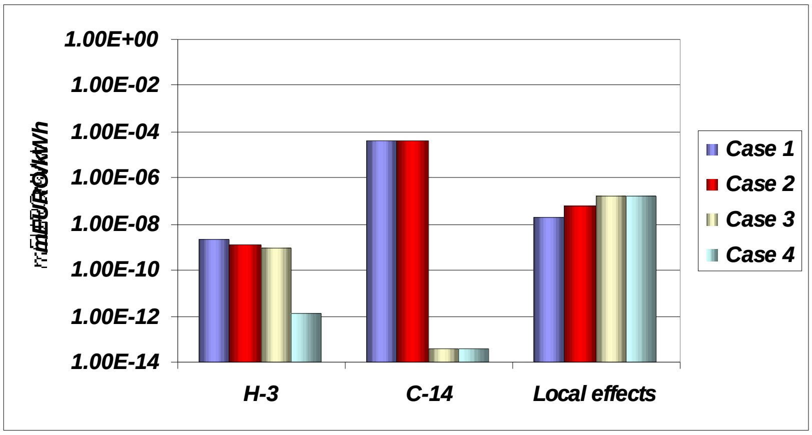

Figure 1. External costs produced in the different cases in plant models 1 and 3.

Recalculation of externalities in all the fusion fuel cycle stages considering new activated materials.

Upstream stages and power generation. CIEMAT.

The objective of subactivity 1.1.5 of this task was to update the assessment of externalities of fusion power performed under SERF1 through the introduction of technological and methodological improvements developed in SEAFP-2 (Cook et al, 1999) and in the ExternE project (Bickel et al, 1999). Within this subactivity, CIEMAT is in charge of estimating the externalities associated with the upstream and power generation stages.

The site selected for the implementation of the fusion power plant has been Lauffen the same location selected in the first SERF project, from where some additional data have been gathered and provided to CIEMAT by IPP (Hamacher, 2000).

The reference technology is a hypothetical fusion power plant of 1000 MW that would be installed in Lauffen (Germany) around 2050. For the reactor core three different models have been considered, differing in the used cooling medium and blanket concept (Ward and Forrest, 2000).

The methodology for impacts and external costs estimation is the same as the one used in the former SERF project, incorporating the methodological improvements developed within the ExternE project. Details can be found in Saez et al (1999) and Lechon et al (2000c).

Upstream stages of the fusion fuel cycle analyzed in this study are the manufacturing of materials and the construction of the power plant. Impacts from fuel supply and fuel transport stages have been considered negligible due to the reduced amount of fuel required for the operation of the fusion power plant. Impacts from radiological accidents have been taken out of the analysis since they are the object of another subactivity.

The assessment of impacts is primarily focused on radiological impacts on both workers and the general public, including fatal and non-fatal cancers and hereditary effects. In addition occupational and traffic accidents leading to deaths and injuries are analysed. For the non-radioactive pollutants emitted from the fusion cycle, mainly in transport activities and manufacturing of construction materials, the set of impacts assessed for fossil fuel cycles and transport in the ExternE methodology are considered based on previous work performed on these cycles (European Commission, 1999a; European

Commission, 1999b). These impacts include effects on public health, crops, materials, ecosystems and global warming.

Results obtained revealed that for plant model 2, the prevalent cause of external costs were the collective doses produced by the global dispersion of C-14 emissions as they enter in the global carbon cycle and become widely dispersed throughout the world. Occupational impacts of the plant, and the impacts indirectly caused by the energy use on the manufacturing of materials were identified as other important causes of external impacts for the three plant models. Radiological effects of the routine releases of the power plant on the general public are very reduced. Only in plant model 2 there is a significant figure of external costs caused by the effect of radioactive emissions in the local area. These costs are caused by the ingestion of foodstuff and water contaminated with Mn-54, Co-60 and Fe-55. Total external costs estimated amount for ***0.52*** mEURO/kWh for plant models 1 and 3 and ***2.99*** mEURO/kWh for plant model 2.

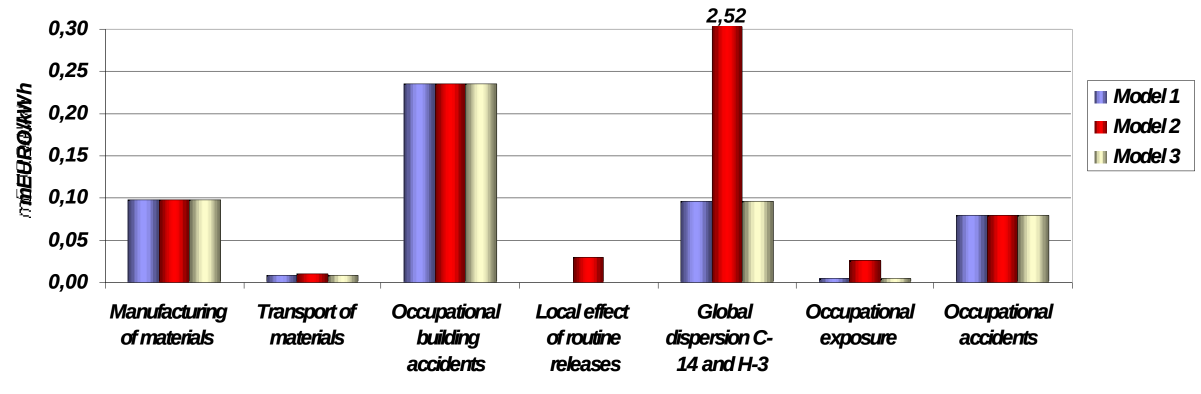

Figure 2. External cost components of upstream and power generation stages of the fusion fuel cycle.

Uncertainty estimation

There is a special task in this SERF2 related to the estimation of the uncertainty in the external costs calculation performed: Subactivity 1.1.6. "Review of the methodology for uncertainties". Results from this subactivity could not allow a complete estimation of the uncertainty involved in all the stages of the fusion fuel cycle. A preliminary estimation of uncertainty ranges for upstream and power generation phases of the fuel cycle was performed though, following the approach proposed within the ExternE methodology (European Commission, 1999a, Rabl, A; J.V. Spadaro, 1999).

The ExternE updated methodology (European Commission, 1999a) recommended the use of uncertainty labels for each impact with a more or less quantitative definition based on geometric standard deviations σ_G and confidence intervals of the lognormal distribution.

The labels are:

A = high confidence, roughly corresponding to σ_G = 2.5 to 4;

B = medium confidence, roughly corresponding to σ_G = 4 to 6;

C = low confidence, roughly corresponding to σ_G = 6 to 12.

These labels can be interpreted in terms of multiplicative confidence intervals: if the cost has been estimated to be μ_g, the probability is approximately 68% that the true value is in the interval $[\mu_g/\sigma_G, \mu_g.\sigma_G]$ and 95% that is in $[\mu_g/\sigma_G^2, \mu_g.\sigma_G^2]$.

Following the recommendations set in subactivity 1.1.6. 95% confidence intervals will be used to show the expected range of the results.

Labels have been assigned to the different categories of impacts following the results obtained in the ExternE National Implementation Project (European Commission, 1999c) and the more precise indications made in Rabl and Spadaro (1999) regarding the incidence of cancers from exposure to radionuclides. These labels are the following:

Table 4. Uncertainty labels considered for different impacts

Stage	**Burden**			**Uncertainty label**
Materials manufacturing	Damages from atmospheric emissions			B
Transport of construction materials	Damages from atmospheric emissions			B
	Road accidents			A
Building activities	Occupational accidents			A
Power plant operation	Radioactive emissions	Local	Inhalation	C
			External exposure from the cloud	C
			External exposure from the ground	C
			Ingestion	C
		Global		C
	Occupational exposure			A
	Other occupational accidents			B

Decommissioning and site restoration. STUDSVIK.

This subtask deals specifically with updated and new calculations of the externalities of decommissioning and site restoration, considering new activated materials in the three alternative fusion plant models.

The decommissioning phase includes radiological decontamination of the plant and demolition of the buildings, interim storage during 50-100 years and transport of waste to final repositories. Also included is the transport of waste to recycling plant and recycling. The last phase when the site will then be restored to conditions as similar as possible to those before the construction of the plant is not further developed in this report. This is due to that the estimates regarding site restoration from SERF 1 have not been affected by the use of new activated materials for the plant models.

Methods of an earlier EU project (ExternE) were employed (European Commission, 1995a). Data for calculation of external costs could in many cases be found from earlier work in ExternE.

The generated radioactive waste is assumed to be interimely stored during a period of 50-100 years at the fusion power plant site. Recycling of waste material are assumed to take place thereafter, at a site somewhere in the EU together with a facility for manufacturing of new fusion plant components.

An overview of the proposed handling of high-level tritiated and neutron-activated radioactive waste is given in Figure 3.

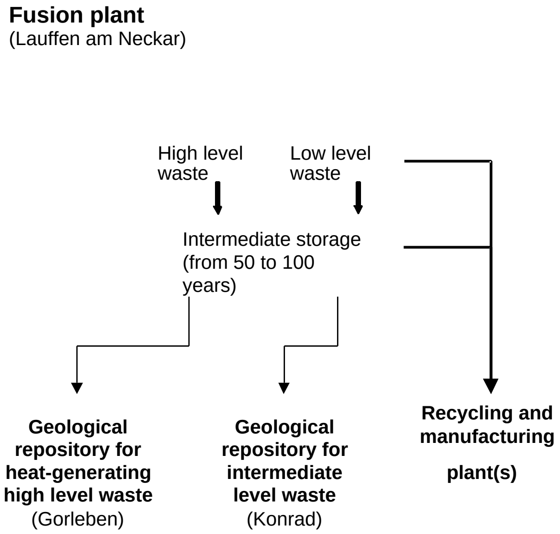

Figure 3 A schematic picture of radioactive waste management of a commercial fusion plant.

Radioactive components will be kept in an intermediate storage at the site from 50 to 100 years, although material might be recycled continuously, as the radioactivity of different parts become lower than the safety limit set by authorities. Non-contaminated and decontaminated materials may be taken to ordinary depositories, or recycled immediately after decommissioning. Radioactive material must be stored, and radioactive decay will with time reduce the activity of the components. The activity will thus become lower than the safety limit set by authorities. That material might then be recycled and used for other purposes. This includes segmentation, packaging and transportation to one or more recycling plants.

Two scenarios have been considered in this report. In the first, waste is treated according to present practice, and only the not heat-generating part of the radioactive waste (intermediate level waste, ILW) is assumed to be recycled. Clearance of material has been considered if the total activity concentration is lower than 1 Bq/g at the end of the interim storage period [Brodén *et al*, 1998].

In the second future prospective scenario, the calculations were based on criteria reported in (Rocco and Zucchetti, 1998). According to these criteria, the recycling of waste material will be much more extensive than according to present practise, although mainly into new fusion power plant components. In this scenario, only 10 % of the activated material, in addition to the beryllium material, is considered to be treated as waste for final disposal.

Separate final repositories were considered, one for heat-generating waste (HLW), and another for waste with negligible thermal influence on the host rock (ILW). The former waste type was assumed to be kept in a salt formation in Gorleben. The other repository is an abandoned iron mine, Konrad, near Braunschweig.

The plant's total electrical energy production (kWhe) was used for normalisation. External costs are dominated by decommissioning in both scenarios, see Figure 3. The decommissioning phase in turn is dominated by the external costs for occupational accidents and diseases, i.e. the same situation as in SERF 1. The external cost for the future prospective scenario is somewhat larger, due to more extensive releases from recycling. This scenario was designed to avoid long-term storing of radioactive waste, however. Disregarding the occupational accidents and diseases, the external costs of the latter was larger than those found here, which means that this might compensate the higher external costs for recycling.

The uncertainty analysis gave a rather small range of variation in the results. There were not much data available regarding parameter uncertainty, except for a few of the parameters.

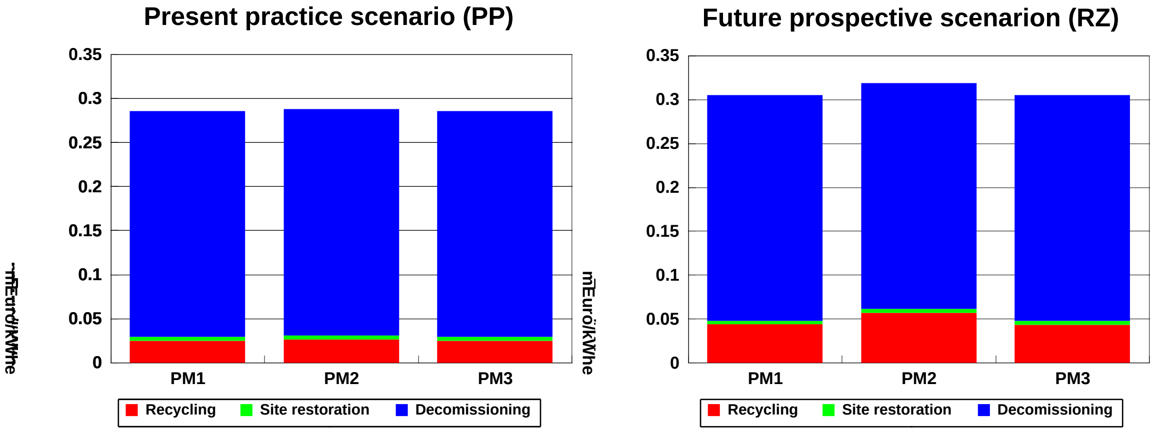

Figure 4 Estimated external costs for decommissioning, recycling and site restoration for three fusion power plant models in two scenarios; one according to present practice as regards waste handling and another future prospective scenario.

Waste disposal. VTT.

The scope of the study is 1) to evaluate external costs of waste disposal in fusion power production and 2) to consider more generally disposal of fusion waste and questions regarding long term integration of doses.

The use of fusion produces activated materials that have to be disposed of when the fusion plant is decommissioned. In this study some possible disposal cases are estimated. Radioactive waste is assumed to be disposed in geologic repositories and different disposal options are given.

If waste packages are used in disposal it takes time before releases to the ground water occur, as packages have first to be broken. Activation products in stainless steel are assumed to be released relatively easily in some thousand years also in deep repositories if in contact with groundwater flow. Concrete, sand and bentonite are assumed to be used to cause retention. The important barriers in the case of C-14 are concrete and such conditions that the water flow rate is small.

After that the release begins groundwater flow takes time and causes that biospheric releases are still delayed. Steady-state situation for biospheric transfer is assumed.

In the local scenario a small local well is considered. Drinking water from the well is the dominant dose pathway, but also irrigation has been considered (Vieno et. al. 1993). A small lake could also be studied.

From the sites where the repositories are located radionuclides could also via the rivers be transferred to the North Sea. Radionuclides having high solubility (low Kd-value) are easily transferred to the North Sea, when less soluble nuclides are also transferred to the sediment. Consumption of fish or also other seafoods causes then dose impacts which can be estimated on the basis of the catchment. In this study regional scale (North Sea) is not considered. Finally radionuclides reach ocean, where it takes relatively long for soluble radionuclides to be transferred to the sediment. Consumption of fish or other seafood may cause remarkable collective doses, also when individual doses are very small. A simple model for accumulation into ocean and caused collective doses (global scale) is used for Nb-94. Doses due to C-14 are estimated using a global carbon cycle model.

Only two important nuclides are studied: C-14 and Nb-94. The inventories considered are shown in table 5.

Table 5. Inventory of C-14 and Nb-94 in waste for an electricity production of 230 TWh.

Nuclide	Half-life (a)	Inventory of Model plants 1…3 (Bq) Model 1	Model 2	Model 3
C-14	5700	$1.1 \cdot 10^{15}$	$0.73 \cdot 10^{15}$	$0.97 \cdot 10^{15}$
Nb-94	20000	$8.2 \cdot 10^{13}$	$1.4 \cdot 10^{13}$	$5.2 \cdot 10^{13}$

Three release cases are constructed and also assumptions from SEAFP study are used (Raeder et al, 1995). In the first case releases are assumed to begin 20000 years after disposal and to continue 10000 years. In the second case releases begin after 50000 years and continue 10000 years. In the third case a somewhat longer duration time of the release 25000 years is assumed.

In the SEAFP-study it has been assumed that duration time of C-14 releases from the repository to the rock is $40 \cdot 10^6$ years (Broden and Olsson 1994). The retention time in geosphere is assumed to be only some hundred years.

The most important activation product seems to be C-14 when using generally applied long term global dose factors. Then doses due to transfer of Nb-94 are studied. If not separated very effectively from biosphere rather high collective doses and external costs can be caused due to C-14. Also local considerations give that disposal causing retention of nuclides is necessary. The caused external cost component depends very much on how the disposal of activated structures will be performed. Methodological questions are also very important, especially the question how the long time spans are taken into account.

Preliminary estimation gives that if C-14 retention at least for about 20000 years can be achieved, the estimated external cost ranges for model plants are 0.09…6.5 mEuro/kWh (0.8 mEuro/kWh) for Model plant 1, 0.06...4.3 mEuro/kWh (0.5 mEuro/kWh) for Model plant 2 and 0.08...5.8 mEuro/kWh (0.7 mEuro/kWh) for Model plant 3 if integrated over 100000 years. If retention about 50000 years could be assumed (due to waste disposal solution) external costs from waste disposal would be very small for all three model plants. On the other hand methodological questions are very important in the estimation and if especially shorter integration times are chosen external costs can be estimated to be some orders of magnitude smaller. Then also cases giving by using the present methodology rather high costs were appropriate.

Summary of the recalculation of externalities

In table 6 and figure 5, all the external costs estimation of the different stages of the fusion fuel cycle are summarised considering the present practice (PP) scenario for decommissioning and site restoration externalities.

Total values amount for 1.61, 3.76 and 1.51 mEuro/kWh for plant models 1, 2 and 3 respectively. For plant models 1 and 3 external cost are dominated by the effect of waste disposal and followed by occupational impacts in the construction and decommissioning of the power plant. Effects of routine radioactive emissions are very reduced even considering global dispersion of C-14 and H-3 nuclides. For plant model 2, external costs are dominated by the effect of the global dispersion of C-14.

The new plant model 3 shows a better performance in terms of external costs than the other two previous models. It is worthy to stress the much more feasible characteristics, especially in terms of materials, of plant model 3 compared to plant model 1 and its still lower external costs.

Table 6. Summary of external costs of the fusion fuel cycle (mEuro / kWh)

Stages	Burdens			*Model 1*	*Model 2*	*Model 3*
Material manufacturing				*9.75E-02*	*9.75E-02*	*9.75E-02*
Construction	Emissions of the transport			4.63E-03	4.81E-03	4.63E-03
	Road accidents			4.48E-03	4.68E-03	4.48E-03
	Occupational accidents			2.35E-01	2.35E-01	2.35E-01
Power plant operation	Routine releases	Local	Inhalation	4.04E-04	3.50E-04	4.04E-04
			External irradiation	1,03E-07	1,04E-04	1,03E-07
			Ingestion	2,29E-09	2,87E-02	2,29E-09
		Global		9,65E-02	2,52E+00	9,65E-02
	Occupational exposure			4.68E-03	2.60E-02	4.68E-03
	Other occupational accidents			7.97E-02	7.97E-02	7.97E-02
Subtotal upstream and power generation				*0,52 (0.0 4-6.17)*	*2,99 (0.27-33.40)*	*0,52 (0.04-6.17)*
Decommissioning	Emissions of the transport			2.56E-03	5.02E-03	3.17E-03
	Road accidents			4.84E-04	9.49E-04	6.01E-04
	Occupational accidents			2.57E-01	2.57E-01	2.57E-01
Recycling	Emissions of the transport			2.22E-03	3.08E-03	2.22E-03
	Road accidents			4.10E-04	5.84E-04	4.10E-04
	Non radioactive dust emissions			1.70E-02	1.60E-02	1.70E-02
	Radioactive emissions			4.65E-03	6.37E-03	4.65E-03
	C-14			3.14E-04	2.06E-04	2.90E-04
Site restoration	Emissions			3.79E-03	3.79E-03	3.79E-03
	Traffic accidents			6.24E-04	6.24E-04	6.24E-04
Subtotal decommisioning, recycling and site restoration				*0.29 (0.10-0.88)*	*0.29 (0.10-0.88)*	*0.29 (0.10-0.88)*
Waste disposal				*0.8 (0.09-6.5)*	*0.5 (0.06-4.3)*	*0.7 (0.08-5.8)*
Accidents					*1,90E-05*	
Subtotal				***1.61 (0.22-14.24)***	***3.79 (0.42-38.79)***	***1.51 (0.21-13.32)***

95% confidence intervals are shown in brackets

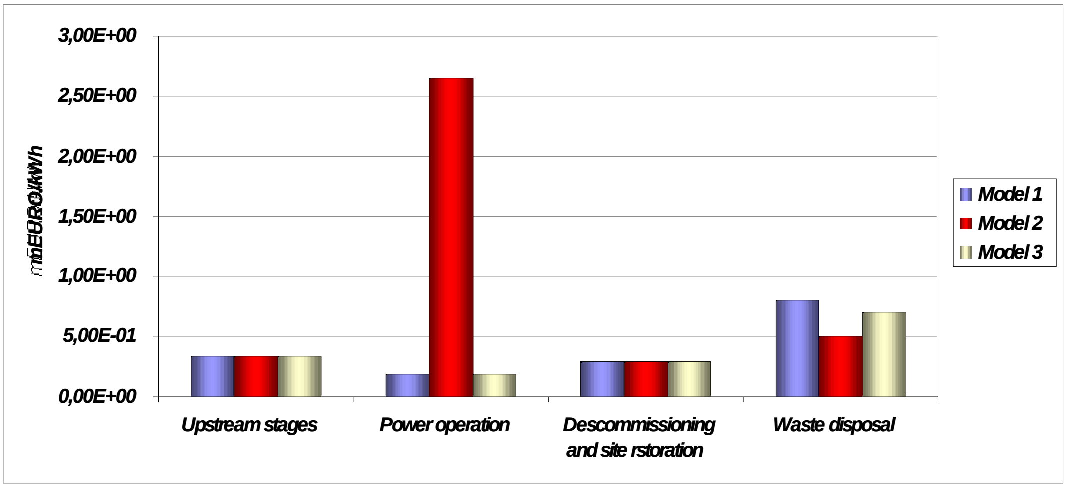

Figure 5. External costs of the fusion fuel cycle

Effect of increased efficiency of plant model 3

An impact of choosing helium as coolant in the case of plant model 3 relates to the thermodynamic efficiency of the plant. Although this has been neglected in the work so far, it is an important factor since the external costs are normalised to the electrical output of the plant. A more efficient plant would have higher electrical output, without increasing the external impact so the cost per kWh is reduced. There is little doubt that a helium-cooled plant would have a higher thermodynamic efficiency than a water-cooled plant and the efficiency would be higher than assumed in the externalities assessment performed so far. To give an estimate of this, the overall conversion efficiency of helium-cooled plant (from fusion power to electrical power) could be up to 50% higher than a water-cooled plant (Ward, 2000a). Following Ward (2000b), the change in net electrical power due to increased efficiency would primarily affect plant model 3 which would have a net electrical power of approximately 1300 MW. Considering a 75% of availability and 35 years of operation, the electrical output of the plant model 3 would be 8,54 TWh per year and 299 TWh in the whole life of the plant. Results considering this new efficiency of power plant model 3 are shown in table 7.

Table 7. Summary of external costs of the fusion fuel cycle (mEuro/kWh) considering the increased efficiency of plant model 3.

Stages	Burdens			*Model 1*	*Model 2*	*Model 3*
Material manufacturing				*9.75E-02*	*9.75E-02*	*7.50E-02*
Construction	Emissions of the transport			4.63E-03	4.81E-03	3.56E-03
	Road accidents			4.48E-03	4.68E-03	3.45E-03
	Occupational accidents			2.35E-01	2.35E-01	1.81E-01
Power plant operation	Routine releases	Local	Inhalation	4.04E-04	3.50E-04	3.11E-04
			Exter.irrad.	1,03E-07	1,04E-04	7.89E-08
			Ingestion	2,29E-09	2,87E-02	1.76E-09
		Global		9,61E-02	2,52E+00	7.39E-02
	Occupational exposure			4.68E-03	2.60E-02	3.60E-03
	Other occupational accidents			7.97E-02	7.97E-02	6.13E-02
Subtotal upstream and power generation				*0,52* *(0.04-6.17)*	*2,99* *(0.27-33.40)*	*0,40* *(0.03-4.74)*
Decommissioning	Emissions of the transport			2.56E-03	5.02E-03	2.44E-03

	Road accidents	4.84E-04	9.49E-04	4.62E-04
	Occupational accidents	2.57E-01	2.57E-01	1.98E-01
Recycling	Emissions of the transport	2.22E-03	3.08E-03	1.71E-03
	Road accidents	4.10E-04	5.84E-04	3.22E-04
	Non radioactive dust emissions	1.70E-02	1.60E-02	1.31E-02
	Radioactive emissions	4.65E-03	6.37E-03	3.58E-03
	C-14	3.14E-04	2.06E-04	2.23E-04
Site restoration	Emissions	3.79E-03	3.79E-03	2.92E-03
	Traffic accidents	6.24E-04	6.24E-04	4.80E-04
Subtotal decommisioning, recycling and site restoration		*0.29 (0.10-0.88)*	*0.29 (0.10-0.88)*	*0.22 (0.07-0.67)*
Waste disposal		*0.8 (0.09-7.20)*	*0.5 (0.06-4.5)*	*0.54 (0.06-4.85)*
Accidents			*1,90E-05*	
Subtotal		***1.61 (0.22-14.24)***	***3.79 (0.42-38.79)***	***1.16 (0.16-10.26)***

95% confidence intervals are shown in brackets

External costs of plant model 3 have been reduced significantly considering its higher efficiency, confirming the better characteristics of this plant model in terms of external costs.

Comparison with previous SERF1 results

Results obtained in this phase of the SERF project are fairly similar to those obtained in the previous SERF although slightly increased. This is due mainly to the following reasons:

- ✓ External costs due to occupational accidents updated to EURO 2000 values are somehow higher. Since these costs have an important share in the total external costs of fusion increasing monetary values has a noticeable effect.
- ✓ C-14 collective global dosis have been integrated over 100,000 years instead of 10,000 years as it was done in the previous SERF. This effect is also noticeable.
- ✓ Waste disposal external costs are higher due to the retention time considered
- ✓ Some other components of the external cost has been reduced such as the externalities due to material manufacturing, those due to the effect transports emissions and the local effect of radionuclides effluents.

All these aspects are depicted in figure 6.

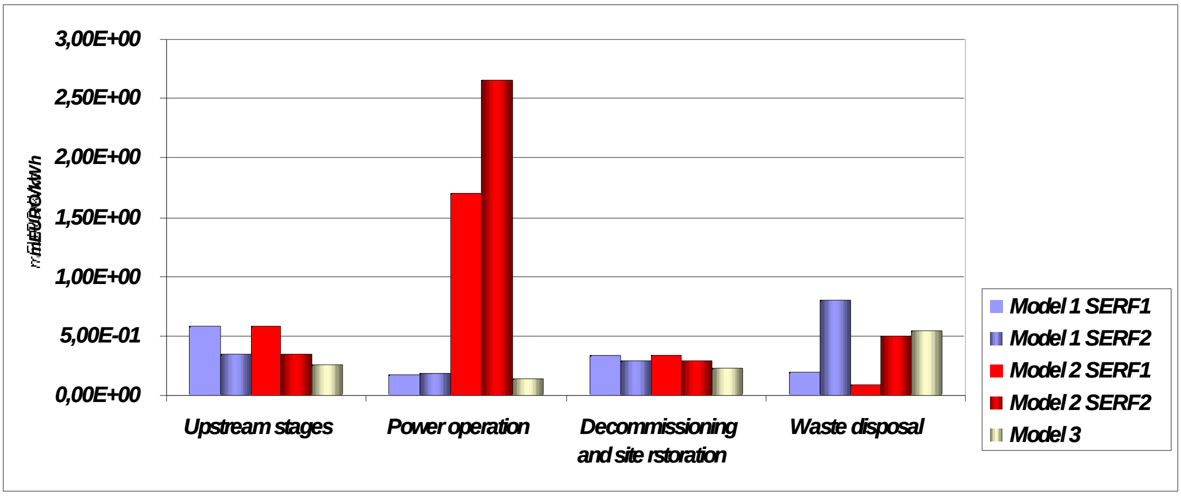

Figure 6. Comparison with previous SERF1 results

Review and improvement of the methodology to calculate uncertainties: STUDSVIK

This subtask is a part of the SERF 2 programme, one goal of which is to improve previous work, performed under the SERF 1 programme, on quantitative assessments of external costs of fusion power plants. This section deals specifically with model uncertainty due to varying input parameters, and how to improve the methods to assess this.

In ExternE (European Commission, 1995), a subjective judgement method was employed. This means the range of variation of the calculated results has been given according to subjective estimation for all sources of uncertainties by given three classes of uncertainty defined as geometric standard deviations, due the degree of confidence in various assumptions and data.

For the SERF studies, it is proposed to use the PRISM code [Gardner *et al*, 1983] for these analyses, which is specifically developed in order to perform effective error propagation studies. By using effective error propagation methods it is easy to perform a thorough investigation of the models, such as sensitivity and uncertainty analyses.

An uncertainty analysis gives the confidence in results due to the uncertainties coupled to the parameter values.

A sensitivity analysis implies that all parameter values are changed in the same manner, e.g. assuming normal distribution with a percentage of the average value as standard deviation. The results of such analysis give information about the parameters for which the model is most sensitive.

The basis for the analyses is the parameters of a model. By specifying them, and their distribution, it is possible to generate an ensemble of input data files, cf. Figure 7. Running a model with these produces a set of output data files, which can be analysed subsequently, yielding distributions of result variables (named responses).

Regression analysis provides information about which parameters contribute most to the uncertainty of the results.

The PRISM system consists of three main subprograms:

- In PRISM 1, random parameter values are generated by using a systematic sampling method, Latin Hypercube. As input to PRISM 1, the mean values or best estimate, type of distributions, standard deviations and the upper and lower limits are given for each parameter. These data are then used to define probability density functions. The Latin Hypercube method, used to generate the sets of values from the given distributions, is an efficient Monte Carlo sampling technique which produces random values within the whole desired range. In addition, correlation between model parameters can be taken into account, irrespective of the type of distribution the parameter values are drawn from.
- In PRISM 2 the model is run for each set of input parameter values generated with PRISM 1.
- PRISM 3 statistically evaluates and summarises the joint set of model parameters and responses. The general statistics for the distribution of each parameter and the response of the model to this distribution presently include: arithmetic mean, standard deviation, coefficient of variation, geometric mean, percentiles (5, 25, 50, 75, and 95 %), and the five highest and five lowest values, respectively. Each parameter's relative contribution to the variation of the results is also given.

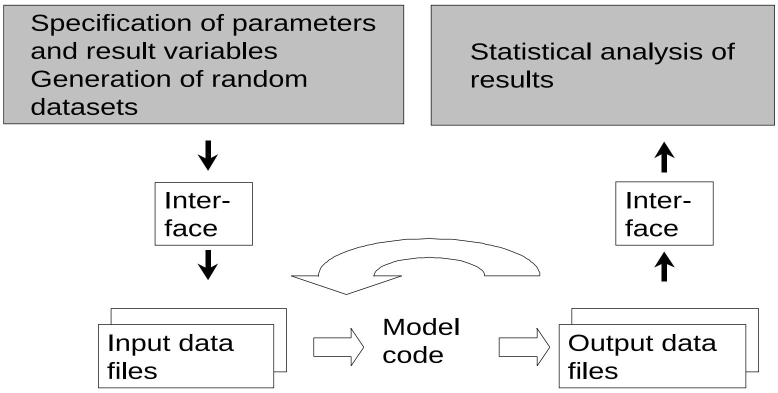

Figure 7 Stepwise overview of how PRISM is used to analyse a model. The greyed parts belong to the general PRISM tool, while the model code, data files and interfaces are model specific.

Two correlation coefficients are calculated: the simple Pearson correlation coefficient, and Spearman rank, which is the correlation of the ranked values of the parameters and model responses. Associated with each correlation coefficient is their percent covariation (COVAR). This represents the percent variance that one parameter accounts for in another parameter or response. In the cases of correlated model parameters and responses, percent COVAR indicates the amount of variability in the model response that is explained by the variability of that particular model parameter. The regression procedures are used to obtain the relationship between model parameters and model responses. The parameters to be entered into the regression analysis are selected from those, which give the greatest improvement on the sum of squares of regression. From these analyses the relative contribution to the total uncertainty from each parameter is obtained. Furthermore, parameters and processes contributing significantly to the uncertainty in results can be identified.

When analysing the results from the various models in the SERF studies it is proposed to use the median and the 5-% and 95-% percentiles as best estimate and range of results, respectively.

Evaluation of radiological and economic consequences associated with an accident of a fusion power plant. CEPN.

As far as the health and environmental impacts are concerned, one of the interests of the fusion fuel cycle is the limitation of consequences associated with the occurrence of a potential accident with releases to the environment. The evaluation of the external costs associated with an accident allows pointing out the main expected impacts and shows that their contribution to the global external costs of the fusion fuel cycle is small. The aim of this report is to further develop the evaluation on accident, performed in the framework of the Studies on Socio-Economic Research on Fusion SERF, mainly by including regional consequences and taking account of risk aversion. Details can be found in Shneider and Lepicard (2000).

According to the current safety analyses, the accidental situation considered refers to a release of a few tens of g of ^{3}H, with a probability of occurrence lower than 10^{-7} per year. Such an accidental environmental release leads to a cumulated collective dose integrated on 50 years of about 60 man-Sv for the local population (i.e. 100 km around the power plant, for the selected site of Lauffen in the south-western part of Germany), while the collective dose of the population located between 100 and 1000 km around the power plant in case of an accident is in the range of 130 man-Sv. In this larger area, the individual dose is reduced by a factor 10 compared with the individual dose of the local population.

Generally, one of the major sensitive aspects in the case of an accident concerns the restrictions that should be imposed on food trade and consumption due to the activity concentration of the products. For a fusion power plant, it appears that due to the limited amount of radioactive materials potentially released in case of occurrence of an accident, the restrictions, if any, should be rather limited to a small area (less than 10 km), for a short duration (less than a week) and only for a few products (mainly milk and cow meat).

The recent developments concerning severe accidents have pointed out the need to take into account the economic consequences associated with the disturbances of the local economy. Once again, in the case of a fusion power plant accident, such disturbances are rather limited as far as there is no need to relocate people according to the estimated level of individual doses. The indirect costs represent less than 5% of the direct external costs of the accident.

As far as the risk aversion of public is concerned, based on recent methodological developments, calculations have been performed for the fusion power plant accident and show that the initial external costs of the accident have to be multiplied by a factor ranging from 8 to 27, according to the selected discount rate, instead of higher values suggested in the past in the literature.

According to these different components, the external costs of the fusion accident is in the range of 10^{-6} to 10^{-4} mEURO / kWh while the total external costs for fusion are estimated in the range of a few mEURO / kWh.

Table A summarises the main results for the external costs associated with accident with and without taking account of risk aversion. It should be noted that even with the integration of risk aversion, these external costs still remain quite limited due to the low radiological impacts that the populations surrounding the power plant would have to support if an accident occurred.

Table 8. Total external costs and normalised external costs for an accident of fusion power plant *(Model 2 - BDBA(1) scenario - DR: annual discount rate)*

	DR = 0%	DR = 3%	DR = 10%
Total cost of the accident	EUROS	EUROS	EUROS
Without risk aversion	4.52 E7	3.38 E7	2.57 E7
With risk aversion	1.22 E9	5.07 E8	2.07 E8
Cost of the accident per kWh	mEURO / kWh	mEURO / kWh	mEURO / kWh
Without risk aversion	6.9 E-7	5.1 E-7	3.9 E-7
With risk aversion	1.9 E-5	7.7 E-6	3.1 E-6

5.1.2 Identification of key variables and range of variation

The external costs of fusion has been evaluated in the Task Externalities of fusion of the SERF2 program (Socio-Economic Research on Fusion). Exploitation and improvement of work in previous phase (CIEMAT 2000) includes Identification of key variables, which is summarized in this section. The work includes subactivities:

1.2.1 Upstream stages and power generation CIEMAT

1.2.2 Decommissioning and site restoration STUDSVIK

1.2.3 Waste disposal VTT

1.2.4 Uncertanty ranges UKAEA

Subactivities have been reported separately. Upstream stages have been reported in (Lechón et al. 2000d), decommissioning and site restoration in (Aquilonius and Hallberg 2001b). The disposal of radioactive waste of fusion power production has been be analyzed in the report (Korhonen 2000b).

This section contains identification of key variables on the basis of best estimate assessment results of SERF2 External costs of fusion. The scope is to study the importance of various components in external costs and estimate key variables on the basis of the weight of component. Methodological questions are also important in the comparison of different cost components, but these are only shortly considered.

Identification of key variables in different stages of the fusion fuel cycle.

Key aspects identified by partners of the 1.2 subactivity are summarized in the following section.

Manufacturing of materials, power plant construction and power plant operation

Key aspects influencing the external costs of the fusion fuel cycle in the upstream stages (manufacturing of materials, power plant construction and power plant operation) identified in reference (Lechón et al, 2000d) are:

- ✓ **C-14 and H-3 emissions in the normal operation of the power plan**t. These radionuclides produce collective doses to the global population that represent the prevalent cause of external impacts in case of Model plant 2 and an important part in Model plant 1. Measures intended to control or reduce these emissions would be very effective in the minimization of externalities of the fusion fuel cycle. H-3 emissions originate in the cooling loops and in elements of the fuel cycle in similar amounts in the three plant models. C-14 emissions of Model plants 1 and 3, with a helium-cooled reactor, are very reduced. In the case of Model plant 2, with a water-cooled reactor these emissions, originated by direct activation of the water of the cooling system are very important. The paramount importance of the effects of these emissions makes a Helium-cooled reactor preferable in terms of external costs.
- ✓ **Occupational accidents in the construction and operation of the plant**. The analysis of external costs has revealed the importance of occupational accidents in the final figure of externalities of the fusion fuel cycle. A further reduction in external costs would be achieved increasing the safety of the working conditions in building activities and in the operation of the plant.
- ✓ **Energy use and emissions in the manufacturing of the materials.** The most important materials contributing to the external costs figures are in order of importance rebars, steels and concrete. The Tokamak building having the 78% of the rebars, the 47% of the concrete and the 24% of the steel contributes with a 50% to the total external cost produced, followed by the reactor core, composed mainly by steel, and the other buildings. The costs associated to these emissions can be reduced significantly if recycling of materials is considered, especially in the Future Practice Scenario (RZ) (see Aquilonius and Hallberg, 2000) in which only a 10% of the activated material together with the beryllium material is considered to be treated as waste. However concrete, and the rebars embedded in it, which account for more than 55% of the total costs, are not considered to be recycled but used

to refill the excavation in the site restoration. Energy efficiency and reduction of emissions by introduction of cleaner technologies and fuels in a national scale in the production and transport processes of these materials will be the possible ways to reduce the external costs.

- ✓ **Occupational exposure and local population exposure to routine radioactive emission**s. Tritium for plant models 1 and 3, and for plant model 2 Mn-54, and in lesser degree Co-60 and Fe-55 originated in the steels of the coolant loops become the key variables in the external costs due to local doses from radionuclide emissions of this fusion power plant. However efforts in achieving reductions in these emissions would minimise the total external costs only little since these effects are not important if we consider whole fusion fuel cycle.

Decommissioning and site restoration

Two waste handling scenarios were considered (Aquilonius and Hallberg 2000c), one according to present practice, and another according to a future prospective scenario in which a large part of the activated waste is assumed to be recycled into new fusion power plant components.

The overall dominating contribution to external cost for decommissioning and site restoration is due to **occupational accidents and diseases during decommissioning.** This has not changed since SERF 1. The external costs, for occupational accidents and diseases are so much larger than the other contributions, so the recalculations considering new activated materials only decreases the total external cost for decommissioning and site restoration slightly.

C-14 emissions in recycling are assumed to be very small. These could potentially cause relatively high contribution to external costs, if part of C-14 in recycling waste is assumed to escape during recycling.

Waste disposal

A somewhat general perspective to consider disposal has been chosen. As costs depend very much on technical choices in disposal the final assessment needs detailed data about technical choices. Also site specific features in repositories (e.g. groundwater flow) have not been considered. Of course the detailed safety analysis of the disposal of fusion waste requires much more work in future, especially for phases before the biospheric release of radionuclides. These continue in other projects. Technical solutions have here been combined to some simple parameters, which describe the release from repository.

Key variables are given to be:

- ✓ **Amount of C-14 in waste.** This is highly dependent on the nitrogen content of materials. In SERF2-study about 1PBq C-14 was estimated to be produced by neutron activation during the operation of one 1000MW fusion power plant. Other nuclides than C-14 are mostly important only in maximal individual doses, but have minor impact on (best estimate) collective doses and external costs.
- ✓ **Retention of releases, especially C-14, in geosphere.** Estimation gives that if by using enough concrete in decommissioning waste packages, C-14 retention at least for about 20000 years can be achieved: External costs in the ranges of 0.09…6.5 mEuro/kWh for Model 1, 0.06...4.3 mEuro/kWh for Model 2 and 0.08...5.8 mEuro/kWh for Model 3 are estimated if integrated over 100000years.

- ✓ **Global transfer of C-14 in the environment and especially the integration time.** Estimation of the transfer of C-14 is based on carbon cycle studies. Changes in the future are possible e.g. due to increased carbon dioxide emissions and global change. However, integration time is probably more important than changes in carbon cycle. Discounting would – if assumed - due to long time spans have drastic impacts on the costs.

If radionuclides are assumed to reach regional and global scales the estimated very small dose levels due to long living radionuclides can sum up to considerable doses if long time spans are used (e.g. 1000 manSv due to dose level $1.0 \cdot 10^{-11}$ Sv/a, $1.0 \cdot 10^{10}$ people, 10000 years). Also when diluted to large volumes on the global scale long term accumulation and high population give that major part of collective doses can be caused from the global scale.

Overall identification of key variables causing externalities for fusion power production

The contribution of various stages to the external costs has been presented in Table 9. Key variables of the most important components are in the simple analysis considered to be key variables of the overall externalities. It is possible that more precise evaluations including all uncertainty considerations would give different results. The percentage of various stages has been given in Table 10.

Table 9. External costs of various stages (key components)

MEURO/kWh	***Model 1***	***Model 2***	***Model 3***
Materials manufacturing	*0,098*	*0,098*	*0,098*
Construction stage			
Occupational accidents	0.235	0.235	0.235
Total construction stage	*0,24*	*0,24*	*0,24*
Total upstream stages	***0,34***	***0,34***	***0,34***
Normal operation	***0,18***	***2,65***	***0,18***
Global radiation impacts	0,10	2.52	0,10
Occupational accidents	0,08	0,08	0,08
Decommissioning and site restoration	***0,29***	***0,29***	***0,29***
Decommissioning (occupational impacts)	0,26	0,26	0,26
Waste disposal	***0,80***	***0,50***	***0,70***
Subtotal externality	***1,61***	***3,74***	***1,51***

The most prominent stage that contributes to the external costs is normal operation in the case of Model plant 2 (70%). For Model 1 and Model plant 3 waste disposal is estimated to contribute by about 50%. These components are mainly caused by C-14 emissions and are global impacts. Together about 80% from external costs are caused by global impacts in the case of Model 2 and more than 50% is caused by the global component in the cases of Models 1 and 3. (Part of the impacts of relatively small component manufacturing of materials is also caused due to global impacts.) Key variables are therefore factors contributing to C-14 emissions or to the impacts due to transfer of C-14 emissions.

Emissions of C-14 due to recycling (decommissioning stage) are also possible and could increase the global contribution. About 2% release from the total C-14 inventory would give the same external cost contribution as C-14 emissions in Model 2 normal operation.

Occupational accidents are other important causes of costs. External costs in the construction stage and due to decommissioning and site restoration are caused mainly by occupational accidents. Also building of repositories has a smaller contribution, which has not been considered. The component of occupational accidents is estimated to have the value 0,5 mEuro/kWh in all Model cases and contributes, when component of accidents due to normal operation is added, about 35% (Model 1 and Model 3), and 15% (Model 2) to the external costs. Timing of accidental impacts differs from the global C-14 impacts. Discounting would make a difference between the two about equal components of construction and decommissioning as about 50 years is between them.

Key variable is occurrence of accidents. This could be lower in future due to technical development. Also statistical evaluation of accidents gives a somewhat rough estimate for the fusion case.

Table 10. Contribution of the component to the external costs (%)

% from the total	***Model 1***	***Model 2***	***Model 3***
Materials manufacturing	*6*	*3*	*7*
Construction stage			
Occupational accidents	15	6	16
Total construction stage	*15*	*6*	*16*
Total upstream stages	***21***	***9***	***23***
Normal operation	***11***	***70***	***12***
Global radiation impacts	6	67	7
Occupational accidents	5	3	5
Decommissioning and site restoration	***18***	***8***	***19***
Decommissioning (occupational impacts)	16	7	17
Waste disposal	***50***	***13***	***46***
Subtotal externality	***100***	***100***	***100***

These two cost component groups, global C-14 impacts and occupational accidents, contribute more than 90% in all model cases. It is evident that local radiation or other impacts have a minor role in external costs.

Key variables are shown in Table 11.

Table 11. Key variables in the evaluation of external costs of nuclear fusion

% from the total	***Model 1***	***Model 2***	***Model 3***
Global exposure (mainly C-14)	*56*	*80*	*53*
Activation;			
Water as a coolant (normal operation)			
N-14 in materials (waste disposal)			
Retention in geosphere due to barriers (waste disposal)			
Integration of impacts (time)			
Carbon cycle in future			
Price of statistical life			
Occupational accidents	*36*	*16*	*38*
Construction stage, normal operation and			

Decommissioning accidents			
Together	***92***	***96***	***91***

An important result is also that many of the studied cost components are very small. Impacts of power plant accidents are very small even when risk aversion is taken into account in estimation. Also local scale and regional scale collective doses contribute very little to the environmental impacts.

Estimation of key variables is here based on best estimate values. Sensivity and uncertainty considerations are not considered.

Uncertainty ranges of key inputs

As input to the assessment of the external costs which may be expected of fusion power when used as a source of electricity, three designs of conceptual power plant have been included, (Ward and Forrest, 2000; Raeder et al, 1995; Cook et al). The three plants are considered for two different reasons:

- ✓ firstly, to cover the range of possible plants that are presently foreseen thus giving the range of external costs to be expected,
- ✓ and secondly, so that the results of the analysis provide additional information on the advantages and disadvantages of the different designs, hence guiding the future fusion research programme.

Because the use of the three different conceptual designs is intended to give an idea of the range of possibilities, it is considered here that this represents the range of uncertainties in the analysis. That is, at this stage, the uncertainty in the actual design of fusion power plant is larger than the uncertainty in calculating the performance for a given design. For that reason, this section concentrates on the variation in key parameters between the plant models, as the main source of uncertainty in the inputs. Where variation outside this range is foreseen, this is briefly described.

Key variations between plant models

The principle differences in the plant models are the choice of coolant, the materials used for the first wall and blanket structure, and the multiplier/tritium generating material. In what follows these are discussed under the headings of the area on which they have the largest impact.

Effluents

The biggest single factor in determining the effluents from a fusion power station is the choice of coolant. Water coolant can respond to the fusion neutron flux by generating C-14 (from the O-17 in the water), which is assumed to be released to the environment. The global impact of this C-14 when incorporated into the carbon cycle is one of the more important potential externalities of fusion, although still small compared to other energy sources such as fossil fuels. Use of helium as the coolant eliminates the production of C-14 effluent so the range of uncertainty over the three plant models is substantial, (Raeder et al, 1995; Cook et al; Sáez et al, 1999). Overall the variation in effluents is approximately a factor of 2, however the variation in C-14 release is much larger, varying by orders of magnitude.

Occupational Radiation Exposure

A related issue is the amount of exposure that might be expected by the workforce. This is higher in the water cooled plant, by a substantial margin. Again, the fact that there is a choice of coolant leads to large uncertainty in the actual exposure to be expected, , (Raeder et al, 1995; Cook et al; Sáez et al, 1999) although here the water cooled plant produces a worse result primarily as a result of corrosion products carried by the coolant, rather than direct activation of the coolant. The variation is up to a factor of approximately 5.

Activated Materials

In optimising materials for a fusion power plant, careful consideration is given to the potential harm of the nuclides that make up the activated structure at the end of the life of the power plant.

In the externalities analysis it is found (Sáez et al, 1999) that the dominant cost arises from C-14 production because of its incorporation into the global carbon cycle. Here we use the C-14 generation as a proxy for the external costs of activation, and determine the range of uncertainty across the plant models. The variation in the plant models as specified is approximately 20% (Ward and Forrester, 2000), however there are clear possibilities for reducing this further, by the use of low nitrogen steels for instance. That remains the subject for further investigation.

A similar consideration applies to the activation of the tritium generating material. Those which contain oxygen, plant models 1 and 3, will produce C-14 as a result of neutron bombardment of the O-17 which occurs at a low concentration in natural oxygen. Again, the use of a tritium generating material that does not include oxygen effectively removes this externality. Including this in the total inventory means that the 20% range is still applicable for the activation of materials.

Accidents

Although the external costs of accidents is extremely low (Sáez et al, 1999, analysis of the safety of fusion has been extended to the different plant models so that a comparison can be made (Raeder et al, 1995; Cook et al). In terms of release of activated materials, the plant models vary by up to an order of magnitude. Even in the worst case, however, the external impact due to the accidents remains very low.

Recycling

One of the areas presently under re-appraisal in the fusion programme is the potential for recycling, since it is envisaged that the activated materials will have sufficiently low activation levels that extensive recycling into new power plants, or re-use for other purposes, can be envisaged. This is expected to reduce the potential for externalities in some areas, such as disposal, but increase in others – the recycling process. This is an area where future work will be needed to define more reliably the levels of recycling that are feasible. At present this must be considered to be an area with relatively high uncertainties.

Conclusions

The uncertainties in the inputs to the assessment of fusion externalities are described. Because the uncertainty in what a fusion power plant would actually be like is greater than the uncertainty in calculating the consequences, the technical uncertainties are given here as the range across several conceptual designs.

The largest uncertainties arise in the area of effluents, due in turn to the different choices of coolant. A water cooled plant has much higher potential for effluents than a helium cooled plant, due to the generation of C-14 in the water.

The occupational exposure is also much larger for a water cooled plant, although this is a result of the corrosion products in the water rather than direct activation.

There is substantial variation in the accident impacts between the different plant models, although even in the worst case the impact remains small.

The activated materials are rather similar across the three plant models although there is the possibility of significant improvement, primarily by using materials with a low nitrogen content. There are now considered to be strong benefits associated with recycling the materials although the details of this, and the associated costs, are still being investigated.

5.1.3 Sensitivity analysis

This section is based on two studies performed in the framework of the Socio-Economic Research on Fusion 2 (SERF 2) by Studsvik Eco & Safety AB (1.3.1) and CEPN-NTE (Lepicard and Schneider, 2000). The first study considering model sensitivity to input parameters and the latter sensitivity for site location.

Sensitivity analysis with key variables. STUDSVIK.

Sensitivity analysis has been performed in order to identify which parameters that have the largest influence on the calculated external costs. The sensitivity analysis have been performed on models calculating external costs for waste transport to repositories and/or recycling, decommissioning and site restoration (Aquilonius and Hallberg, 2000) and for routine release of radioactivity into a river (CIEMAT, 2000).

A sensitivity analysis implies that all parameter values are changed in the same manner. The results of such an analysis give information about the parameters for which the model is most sensitive. The method of sensitivity analysis using a statistical error propagation method is more extensively described in (Bergström and Hallberg, 2000).

Parameter values, their distribution and range used for the calculations of external costs and the sensitivity analysis are given in Appendix A of Aquilonius and Hallberg 2001.

The models used for the sensitivity analysis calculates:

- ✓ External costs for waste transport, considering transport of waste to repositories and recycling
- ✓ External cost for recycling of non-radioactive material, generating release of dust
- ✓ External costs for recycling of radioactive materials, generating release of dust and radioactivity
- ✓ External costs for decommissioning of plant
- ✓ External costs for restoration of site
- ✓ Radionuclide concentrations in river water and sediments, due to release of radionuclides from a fusion power plant during normal operation

Considering sensitivity analysis for waste transports, the distance to recycling or repository gives, except for power production, the largest influence to the variability of the calculated costs for waste transports. This indicates not unexpectedly that the distance is an important parameter and altering of this parameter (which might be easier than altering the power production) would influence the result a lot.

In recycling models, plant parameters, like melting rate, particle release, production time is of great importance for the calculated results, as well as the amount of waste. Since the techniques for recycling hopefully will be better and more effective in the year of 2050, these plant parameters probably gives a conservative result.

The parameters concerning construction costs, upon which costs for decommissioning have been calculated, influences the variation in the calculated external costs the most as well as parameters concerning occupational accidents. The decommissioning phase is the dominating contributor to the calculated external costs for decommissioning and site restoration. In order to minimise the uncertainty in the results of this phase and the calculated external costs, attention should be put on these parameters.

For the model calculating external costs of site restoration, distance to recycling (conventional) gives the largest influence on the variability of the calculated results. This parameter has been set by own judgement, to be 50 km, which seemed reasonable.

The sensitivity analysis for the model calculating routine release of activation products into a river, the length of one compartment and velocity, which determines the dilution of a contaminant is of importance as well as the source term.

Sensitivity of the impacts associated specifically with the power plant localisation. CEA

The objective was to evaluate the sensitivity, with the site location, of the collective doses associated with the routine radioactive releases from a fusion power plant. External exposures, inhalation and ingestion pathways were taken into account for collective dose calculations.

Collective doses were calculated for each selected site for different space and time scales – respectively 100 km, 500 km and 3,000 km, and 1 year, 50 years and 100,000 years. In order to estimate the sensitivity analysis with the site location (meteorological conditions, grid of population around the site, dietary habits and agricultural production, etc.), the calculations were performed for two site locations. One site is inland (Marcoule, France) and the other one is coastal (Flamanville, France). Results were also compared with those obtained for the Lauffen site (inland site).

The results show that the site location does not strongly affect the impacts at the global scale, nor the fact that liquid releases may occur into a river rather than into the marine environment. Gaseous releases are largely pre-eminent in collective dose estimates. Furthermore, in the long term, the impacts are largely dominated by the global impacts of C-14. For local and short-term impacts, results obtained for the 3 sites remain in the same order of magnitude – a maximum difference of a factor 5 is observed between Flamanville and Marcoule for 1-year integration time.

Table 12. Synthesis of site location sensitivity analysis

	Collective dose[a)]	
Site location	in man.Sv.y^{-1}	in man.Sv.TWh^{-1}
Flamanville 'coastal'		
Local	1.84x10^{-2}	2.80x10^{-3}
Regional	9.74x10^{-1}	1.48x10^{-1}
Remote	4,15	6.32x10^{-1}
Total	5.14	7.82x10^{-1}
Marcoule 'inland-river'		
Local	7.83x10^{-2}	1.19x10^{-2}
Regional	8.52x10^{-1}	1.30x10^{-1}
Remote	4.53	6.89x10^{-1}
Total	5.46	8.31x10^{-1}
Lauffen 'inland-river'		
Local range	9,21x10^{-1}	1,40x10^{-1}
Global range	7,97x10^{1}	1.17x10^{1}

[a)] *An annual production of electricity of 6,57 TWh is assumed for the plant model considered*

5.2 Identification of design criteria pursuing externalities minimization.

5.2.1 Identification of design criteria.

Introduction

An important part of the process of determining the external costs of fusion power is to identify the areas where improvement is both possible and beneficial. This section is aimed at highlighting these areas and comparing with the direction taken by the European fusion R+D programme.

There is now an extensive body of work on the external costs associated with fusion power, based on the studies of conceptual power plants, produced during the SEAFP programme (Raeder et al, 1995) and updated in the more recent SEAFP-2 and SEAL studies (Cook et al). In the first SERF programme (Sáez et al, 1999) analysis was made of the SEAFP conceptual designs of fusion power plants, and in SERF-2 (Ward and Forrester, 2000) this has been updated and extended to include developments in fusion and also in the methodology of the externalities assessment. Because the studies have looked at different power plant designs, there is now a lot of information on the strengths and weaknesses of different aspects of a fusion power plant with regard to external costs. Combined with the knowledge of the other properties of the power plant designs, we can progress towards more optimised designs.

In this report we look at the possibilities of reducing the external impact of fusion power. The SERF analysis already shows that the external costs of fusion are more than an order of magnitude lower than for fossil fuels, so it is not necessary to reduce the external costs to make fusion acceptable. However we must do what we can to internalise the external costs by altering the plant design. There will come a point where further minimisation is not economically justifiable, and we will attempt to determine where that point is reached.

There are two main types of external costs: one related to conventional activities such as materials manufacturing, plant construction and dismantling; the other to more fusion specific issues such as activation of the power plant. It is the second of these groups that is most dependent on the power plant design and so has most implications for the optimisation of a fusion power plant. These will be the focus of attention here.

Areas of uncertainty in optimisation of fusion power

Although apparently a controversial way to start the discussion, in order to follow some of the reasoning in later sections it is necessary to understand how optimisation of the safety and environmental properties of a fusion power plant can differ from minimisation of the external costs. This section is included to highlight the areas where the approach taken by the fusion R+D programme, to obtain the fullest expression of the safety and environmental advantages of fusion, diverges from the attempt to minimise the external costs. It is not suggested here that either approach is wrong, but that we should consider the merits of the different approaches.

An obvious example is the case of safety. It is concluded in the externalities assessment that the external cost of accidents in a fusion power station is extremely small, sufficient to make no contribution to the overall external costs (CIEMAT, 2000) This would imply that, in order to optimise a fusion power plant, other areas should be the focus of attention. However, the optimisation of fusion carried out in the fusion R+D programme assumes that ultra-safety is paramount, and is one of the key targets for further improvement. This discrepancy arises because the role of safety in the arguments for the development and introduction of fusion power is not based on economic arguments, but relates to the public acceptability of this new technology. This emphasis on ultra-safety is unlikely to be changed by the externalities work. On the other hand, the assessment of safety properties and consequences by independent experts is very valuable and will certainly influence the future work in this area.

Another area where different optimisation is used in the externalities assessment from the fusion R+D programme, relates to the choice of materials in the power plant. As an example, the introduction of OPTSTAB (an optimised low activation steel) as a shield material is motivated by the goal of reducing the level of activation and hazard potential in the longer term, based mainly on considerations of maximum individual doses, in order to reduce the need for repository disposal of activated materials. In the SERF programme, however, the collective doses are emphasised, where nuclides such as C-14, which becomes part of the carbon cycle, can have an impact disproportionate to their level of activation. This leads to different conclusions, for instance that OPSTAB is **worse** than SS-316 in terms of external costs associated with activated materials, because its higher nitrogen content leads to a higher C-14 content (higher by a factor of 6). In this case there is no conflict with the underlying principles of the fusion programme concerning safety so the externalities assessment should be an input to the process of optimising the design of a fusion power station.

In the following section, the implications of the externalities assessment for the optimisation of the environmental properties of fusion power is described.

Key issues

Coolant

The three plant models considered in the present SERF activity are as shown in Table 13. Plant model 2 uses water as coolant whilst 1 and 3 use helium.

Table 13. Summary of the main properties of the 3 plant models.

Plant Model	FW/blanket structure	Tritium-generating material	Neutron multiplier	FW/blanket coolant
1	Vanadium alloy	Li_2O ceramic pebble bed	none	Helium
2	low activation martensitic steel	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	Water
3	low activation martensitic steel	Li_4SiO_4 ceramic pebble bed	beryllium	Helium

The most obvious conclusion of the externalities work is that power plants using water coolant are much less favourable than those that use helium. This is essentially because of the generation of C-14 in the oxygen of the cooling water, which is assumed to be released to the environment, becoming part of the carbon cycle and impacting on the global population. Although only a tiny effect compared to background radiation, the ExternE methodology assumes a linear dose-response function and ascribes costs accordingly. With a large population involved, this is considered non-negligible, although still small compared to fossil fuel sources. Such conclusions are the subject of debate in areas of radiological protection, but here we will take the result at face value. The implication is that rejecting water as a coolant immediately halves the external costs of fusion.

Another impact of choosing helium as coolant relates to the thermodynamic efficiency of the plant. Although this has been neglected in the work so far, it is an important factor since the external costs are normalised to the electrical output of the plant. A more efficient plant would have higher electrical output, without increasing the external impact so the cost per kWh is reduced. There is little doubt that a helium cooled plant would have a higher thermodynamic efficiency than a water cooled plant and the efficiency would be higher than assumed in the externalities assessment. Although the existing calculations provide a conservative estimate, an approach that is often used in safety analysis, we should take this into account when comparing the benefits of different coolants. To give an estimate of this, the overall conversion efficiency of a helium cooled plant (from fusion power to electrical power) could be up to 50% higher than a water cooled plant. The helium cooled plants already have a factor of more than 2 lower external costs; taking account of the improved efficiency would lower the costs further to less than 1/3 of the water cooled plant. At the same time the external costs are reduced to approximately 1mEuro/kWh. With direct costs of future electricity generation projected to lie in the range of 30-100 mEuro/kWh, the external costs at this level are becoming negligible.

Materials Selection

In optimising materials for a fusion power plant, careful consideration is given to the potential harm of the nuclides that make up the activated structure at the end of the life of the power plant. In the externalities assessment, collective dose pathways analysis plays an important, additional, role which gives strong weight to nuclides that enter the global carbon cycle (C-14) or the water cycle (tritium). This could be incorporated in the optimisation by applying an additional weighting factor to such elements.

Because tritium is short lived, it is of less importance than C-14 in determining global impacts from fusion activated materials, so here we concentrate on C-14. Before describing the sources of C-14 in the different plant models a short description is given to introduce the potential difficulty.

C-14 is naturally present in the atmosphere, generated by cosmic ray bombardment of nitrogen, with an annual source of 1PBq. A fusion power plant mimics this process by its neutron bombardment (primarily of nitrogen in the structural materials) and approximately 30 1GW fusion plants would produce a source equivalent to the natural source. Although C-14 represents only approximately 0.5% of background radiation dose, a strong fusion economy could produce sufficient C-14 that, if not contained, would make a noticeable impact on the background radiation level. In the externalities work, this is relatively easily solved by use of a repository for the activated material, however we should consider the possibility that the levels could be reduced sufficiently that repository use is unnecessary, even if it may nonetheless be used in practise.

The following table shows a breakdown of the source of C-14 from the 3 plant models. Each column shows the fraction of the total C-14 that is generated in that material. Note that in this modelling, the shield was assumed to be made of SS-316 in each case.

Table 14. Source of C-14 from the 3 plant models.

Plant Model	Blanket Structure	Shield	Other
1	Vanadium – 20%	SS-316 – 53%	Li_2O – 26%
2	LAM – 60%	SS-316 – 35%	LiPb – 1.2%
3	LAM – 43%	SS-316 – 34%	Li_4SiO_4 – 8.5% Be – 12%

The main sources of C-14 are the nitrogen in the steels and Vanadium alloy, and the oxygen content of the model 1 and 3 tritium generating material. It is believed that the nitrogen in steel could be reduced, for instance to 0.01%, which would reduce the steel contents by approximately a factor of 5. In the case of plant model 2, this allows a reduction of the C-14 to 20% of its present level, however plant models 1 and 3 would remain at 40% or higher of their existing levels. Given that plant model 2 structures produce lower C-14 anyway, at about 70% of the others, this is a substantial benefit for plant model 2, arising primarily because of the lack of oxygen in the tritium generating material.

What are the implication for material selection? SS-316 has been chosen instead of OPTSTAB as shield material here specifically because the C-14 generation of OPTSTAB is particularly high. However if we wished to reduce the C-14 content further, it would be necessary to reduce the nitrogen content even further. If one wished to avoid the need for a repository storage of materials whilst affecting background radiation by less than a few percent, lithium oxide and lithium orthosilicate should not be used. Plant model 2 could be optimised to reduce the radiation exposure level from C-14 (when 1000 fusion plants were in operation, with no use of repository) to global levels comparable to those due to air travel, however even in this case, it might still be deemed appropriate to make use of a repository.

Conclusions

The externalities assessment allows comparison of the different impacts that an energy source has on human health and the environment and so gives a technique for making optimum choices in power plant design.

In the assessment of fusion, the external costs are small compared to fossil fuels, for instance, but we can and should reduce further the external impacts as much as is feasible.

In the case of fusion, the paramount importance given to improving ultra-safety is not based on an economic argument so the fact that externality assessment shows the associated costs to be negligible already will not influence the fusion programme.

In the choice of coolant the externalities assessment strongly supports the use of helium rather than water, due to the C-14 production by neutron impact on O-17 in the water. There is an additional strong benefit that the overall plant efficiency is higher in the plant models using helium. This further reduces the external cost per kilowatt hour.

In the choice of plant materials, there are differences between the approach in the fusion programme and that of the externalities assessment. For instance in the fusion programme OPTSTAB is considered to have advantages in terms of long term activation whereas the external cost assessment suggests that SS-316 is better.

Additional factors that have not been addressed here are the impact of recycling of activated materials from a fusion power plant and the use of silicon carbide as a structural material for the blanket. These have potential to further reduce the amount of activated materials produced by a fusion power plant.

If we were to attempt to optimise a fusion power plant on the basis of the present understanding of the external costs, and combining different aspects of the plant models studied so far, we would choose a helium cooled model, with no oxygen in the tritium breeding material (for instance using lithium-lead) and a shield made of a reduced nitrogen steel (not OPTSTAB). The Dual Coolant concept comes closest to meeting these requirements. The results obtained suggest that reducing external costs below 1 mEURO / kWh is feasible.

5.2.2 Analysis of interdependences and consequences of changes

This subtask is a part of the SERF 2 programme, one goal of which is to identify how to design the future fusion power plant, as well as the procedures used during its whole life cycle, in order to minimise external costs. This must be considered in an integrated manner, because the design influences the procedures that are possible. The procedure for waste handling, for example, is largely dependent on the choice of materials, because of their difference in neutron activation.

This subtask considers only the minimisation of external costs, i.e. the cost of society due to the impact of the fusion plant, and not the internal costs of building and running the plant.

The analysis considers interdependencies and consequences of e.g. changes in design. The method to do this is to identify the variables that contribute the most to the external costs, and discuss how changes in them will affect the total external costs.

The assessment of external costs in the SERF programme is based on three power plant designs: the SEAFP (Cook *et al.)* plant models 1, 2 and 3. These differ mainly in use of materials and type of coolant, cf. also (Ward, 2000a).

The external costs are rather low, especially when compared with the external costs of other energy production options (Sáez et al, 1999). Even so, it should be worthwhile to minimise the impacts on the environment in order to get public acceptance of a new form of energy production.

Construction and Operational Phases

External impacts during these phases were due to activities: fuel supply, fuel transport, materials manufacturing, construction and power plant operation.

The external costs were reported in (Lechón et al, 2000c). The relative contributions to the total cost are given in Figure 8. The external costs of fuel supply and transports were negligible.

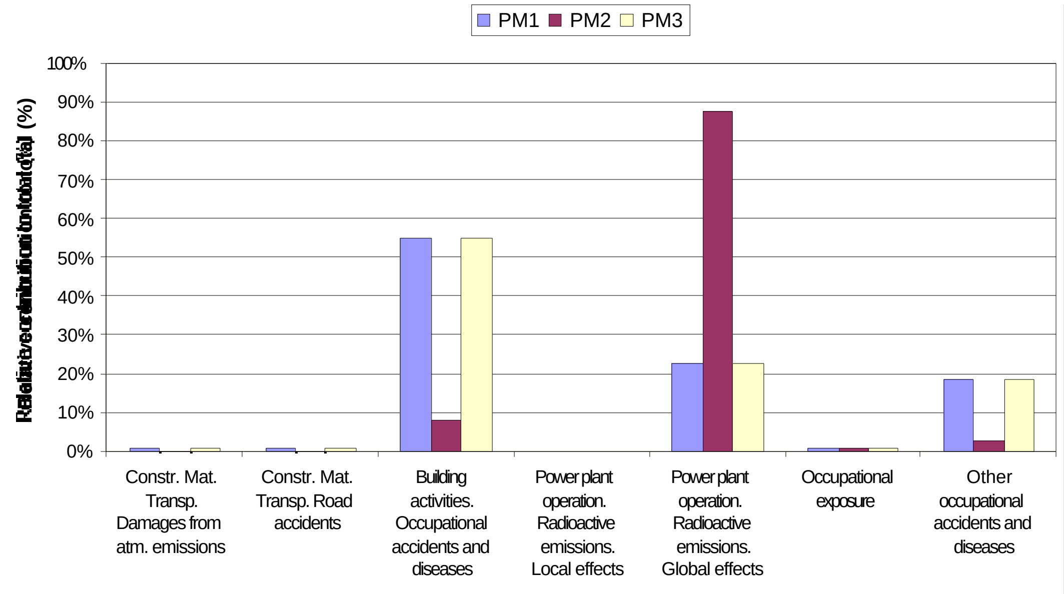

Figure 8. Relative contribution to external costs for the Construction Phase and the Power Generation Phase (Lechón et al, 2000c). SEAFP plant models 1-3.

The most significant feature is the domination of global radiation effects, because of global collective doses due to release of H-3 from all plant models, and C-14 from PM 2. The latter is designed to use water as coolant, while the others employ helium. The obvious conclusion would be not to use water, which would reduce the (already low) external costs with a factor 5 for PM 2. Steels with a low content of Nitrogen would also be favourable.

The contribution from external costs due to occupational accidents and diseases are also significant. The model used to assess those is according to ExternE [European Commission, 1995b], which uses French accident and disease statistics for construction work as function of the investment cost. An effort to reduce these costs could consist of:

- ✓ use of well-trained personnel,
- ✓ proper measures to ensure safety,
- ✓ well-planned and well-managed construction,
- ✓ design of components that facilitates the above,

Decommissioning and Site Restoration Phases

This consists of decontamination, dismantling and waste handling (including recycling) of the plant, and restoration of the site afterwards. The latter is not treated in this report, because it is not dependent on the plant design. The choice of site will influence how large the external costs will be, but anyway site restoration costs constitute a small part of the total external costs. The external costs were reported in [Aquilonius and Hallberg, 2000]. The relative contributions to the total cost are given in Figure 9.

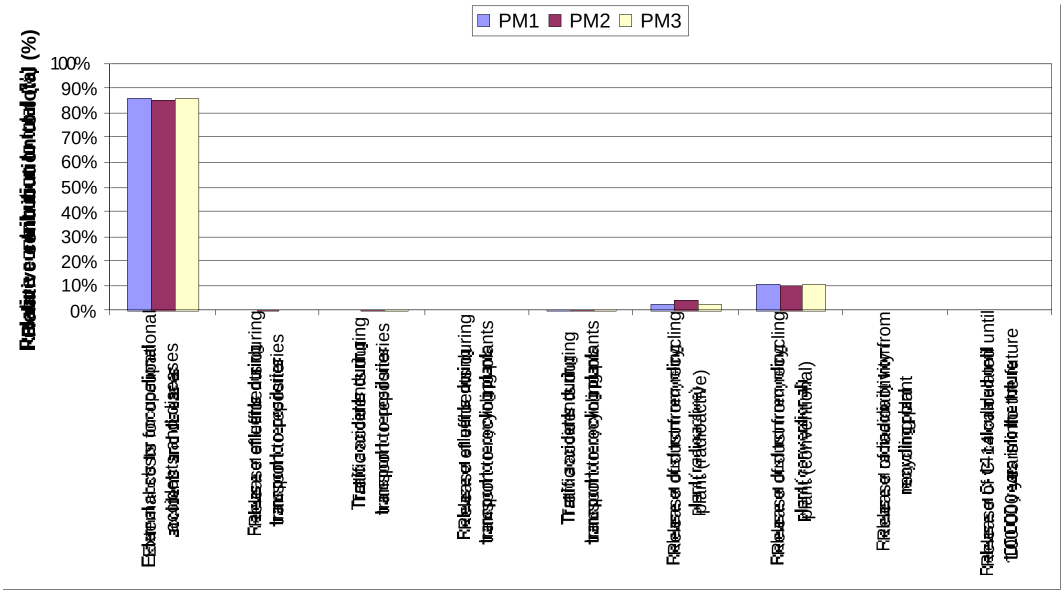

Figure 9. Relative contribution to external costs for the Decommissioning Phase [Aquilonius and Hallberg, 2000]. Present Practice scenario. SEAFP plant models 1-3.

The external costs due to occupational accidents and diseases dominates. The same model as in the above section was employed. The costs comprised those for decommissioning and for replacement of materials during the operational phase. An effort to reduce these costs could consist of those given in, and in addition a design that facilitates replacement during the Operational Phase (e.g. modular design).

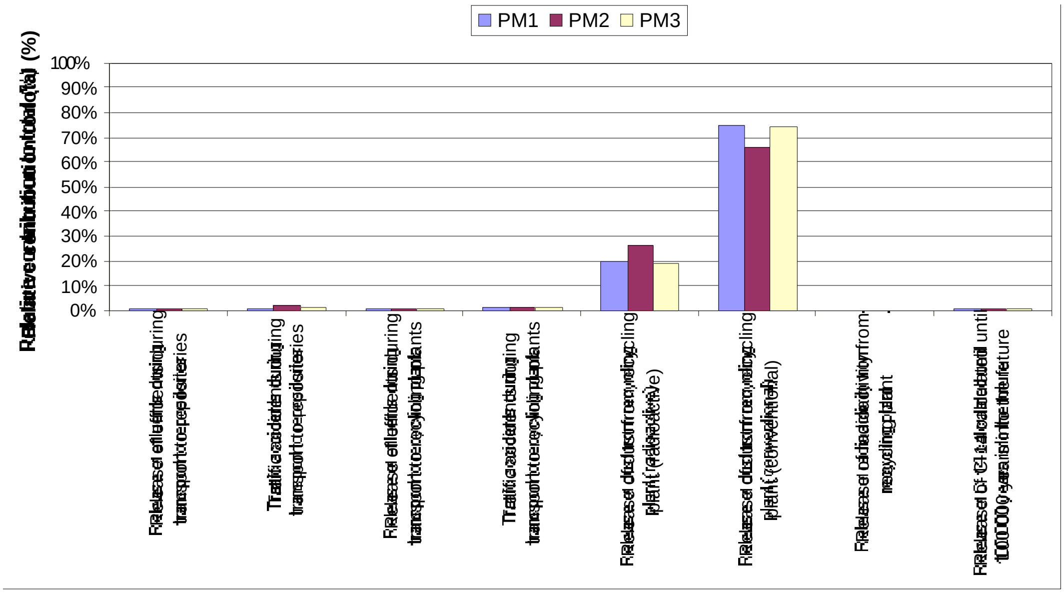

Figure 10. Relative contribution to external costs for the Decommissioning Phase, disregarding occupational accidents and diseases. Present Practice scenario (Aquilonius and Hallberg, 2000). SEAFP plant models 1-3.

Disregarding external costs due to occupational accidents and diseases, the most important other impacts are shown in Figure 10. Release of dust during recycling exhibits the highest external costs. This is due to (rather small) impact on human health. The most sensitive parameters for this are several of approximately equal size (Aquilonius and Hallberg, 2001a).

Use of separate plants for recycling of radioactive waste and conventional materials, respectively, was assumed (Aquilonius and Hallberg, 2001a). Possible actions to minimise the external costs are mostly not in the hands of the designers and builders of fusion power plants, unless a special fusion waste recycling plant is constructed for all of e.g. Europe, as suggested by Rocco and Zucchetti (1998). Examples of actions are:

- ✓ reduce particle concentration around the recycling plant(s):
- ✓ minimise the amount of waste material
- ✓ use highly efficient filters
- ✓ use a high chimney stack
- ✓ locate the recycling plant(s) in a not densely populated area

One could also discuss if it would be possible to skip the recycling of fusion plant components. This, however, goes against current environmental considerations. Recycling of e.g. metal causes a significant volume reduction, which means that omitting recycling would lead to a larger amount of materials in repositories, both for non-radioactive and radioactive waste. Furthermore, as far as we know, it is more energy-efficient to melt e.g. old steel than to produce new steel from iron ore. An analysis of external costs due to steel works would probably show a net gain for the environment when employing recycling. Moreover, recycling of radioactive waste causes most of the radioactivity to be contained in the slag, which will be put in an underground repository. In a dry repository, as the proposed German repositories Konrad and Gorleben, there are no difference as regards the possibility to mobilise the nuclides. On the other hand, in a wet repository, one must always consider the possibility that groundwater eventually will breach the integrity of the waste containers. In such a case, it will be a longer process to dissolve the nuclides from slag, than from metal, because the process of corrosion (Lindberg, 2001).

Waste Disposal

Only disposal of radioactive waste was considered in this study. The waste consists of contaminated (mostly steel) components from the fusion reactor, and if recycling is employed, the slag from the melting process. There are two proposed disposal sites in Germany: Konrad, a former iron mine, and Gorleben, a salt dome. The former is for intermediate level waste, and the latter has been suggested as a possible deep disposal of heat-generating high level waste.

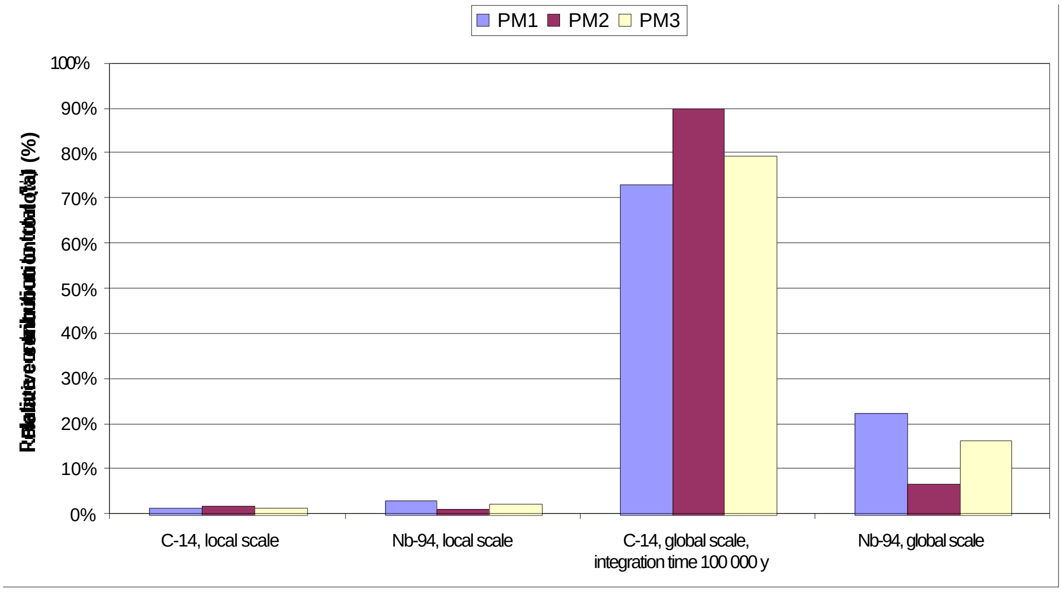

Figure 10. Relative contribution to external costs for waste disposal (Korhonen, 2000a). SEAFP plant models 1-3.

A short description of the waste handling was given in (Aquilonius and Hallberg, 2000). Two scenarios were considered. The first is called “present practice scenario” and the second was that proposed by Rocco and Zucchetti [1998], which was devised to minimise the amount of waste for long-term disposal. The main difference between the scenarios is therefore the amount of waste in the two types of repositories.

The SERF 2 waste disposal study (Korhonen, 2000^{a}) considered both types of disposal. The deeper storage causes much lower doses than those for the shallower repository (e.g. Konrad), and therefore only the latter is discussed in this report.

Collective doses due to releases of the nuclides C-14 and Nb-94 were assessed for the local scale and global scale. Different assumptions regarding the time until the integrity of the concrete containers will be breached, and nuclides transported to the biosphere by groundwater, were made. The shortest time, 20 000 years, which result in the highest external costs, was considered below. Relative contributions to external costs (Korhonen, 2000a) are given in Figure 10.

As can be seen, the global effects tend to dominate, and also here C-14 causes the highest collective doses. This is due to small doses exposing a lot of people, which because of the linear dose-response relationship are assumed to cause an extra risk for cancer. To lower the dose, it is important that a long time passes until nuclides may expose the population. Using geological repositories is a common way of achieving this. A reduction in external costs with one order of magnitude was found in (Korhonen, 2000a), when the assumed time until exposure was increased from 20 000 years to 50 000 years. One way of achieving this is recycling, the residues of which will be more difficult to dissolve that the pure metal, as discussed in Chapter 3. Recycling also reduces the volumes that need to be kept in the repository. Of course, the repository design and the ambient conditions at the site are important. One would e.g. look for a site for which the groundwater flow to the surface is minimal.

5.2.3 Design criteria and recommendations

As a summary of the aspects analysed in the previous two sections, 5.2.1. and 5.2.2., we include here a table (Table 15) with the key variables determining the external costs of fusion fuel cycle obtained in the externalities assessment, the technical issues to which these aspects are related, the design aspects involved and finally the design criteria and other type of recommendations in order to minimise the external costs of the fusion fuel cycle.

Summarising, the following recommendations should be followed in order to optimise a fusion power plant on the basis of the present understanding of the external costs, and combining different aspects of the plant models studied so far:

Related to the design of the fusion power plant

- ✓ helium cooled reactor
- ✓ tritium breeding material with no oxygen (for instance using lithium-lead)
- ✓ shield made of a reduced nitrogen steel (not OPTSTAB).
- ✓ Recycle fusion plant components
- ✓ Dispose the waste in geological repositories

Related to conventional activities:

- ✓ Use of well trained personnel, proper measures to ensure safety and well-planned and well-managed construction, operation and dismantling
- ✓ Improve energy efficiency, and use of cleaner technologies and cleaner fuels in the manufacturing of materials
- ✓ Use of filters, high chimney and proper selection of the location in the recycling plant