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Abstract

A review of the environmental assessment studies shows that most information on tritium emission is related to experimental tokamaks such as INTOR, JET, NET and more recently ITER. Information on commercial reactors is sparsely. Most publications refer to the STARFIRE design or are extrapolations to experimental reactors such as FCTR (First Commercial Tokamak Reactor). More recent studies are ARIES (USA) and EEF (Europe). Only few and very preliminary accident analyses have been performed on conceptual designs of fusion reactors. Therefore predicted values for tritium emissions in normal operation or by accident are preliminary and bear large uncertainties.

Much more research has been conducted on transport of tritium through the atmosphere, biosphere and hydrosphere. Pathways of tritium intake by human bodies are fairly well known and simulated by computer codes. These codes use plausible emission values without considering the internals of the emitting source. This paper gives a survey on results given in various publications and compares how uncertainty and range of alternative is being treated. Suggestions are made to improve their representation.

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1 Tritium emissions from fusion reactors and related consequences

1.1 Containment performance of fusion reactors

In figure 2 a survey is given on the tritium inventories and emission values as predicted by different studies on safety of fusion energy. For comparison and to broaden the view, experimental and calculated results related to other tritium handling facilities are included in the figure.

Inventories of fusion reactors lie between $7.3 \times 10^6$ and $8.7 \times 10^6$ TBq (2.0-23.5 kg). The predicted emission values for normal operational loss cover nearly two orders of magnitude from 17 to 960 TBq/a. These values lie all clearly below the 1 ppm diagonal which is indicated in the figure. In the center of the cluster of predicted values lies the often stated goal of 10 Ci/d (135 TBq/a) which indicates the permissible loss to environment.

The relative loss rate related to this goal for fusion reactors lies in the same order of magnitude as the permitted relative loss from a final deposit for radioactive waste in deep geological formations. All empirically based values for relative emissions from facilities containing more than 50 TBq lie above the 1 ppm diagonal – with one remarkable exception: Emissions from the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory achieved relative emissions as low as $10^{-5}$ with fairly large inventories (110 g).

1.2 Radiation dose to the maximally exposed individual due to normal operational loss of tritium as HTO from fusion reactors

A survey on a number of studies showed a broad range of individual doses as can be seen in figure 3 (tritium as HTO). For comparison the doses calculated for emissions from other types of facility are added. Also given are dotted horizontal lines for maximally permissible doses according to the standard set by the U.S. Nuclear Regulatory Commission (NRC: .05 mSv) and the German radiation protection ordinance (Strahlenschutzverordnung – StrSchV: .3 mSv).

The assumed emission values for normal operational loss in different studies cover two orders of magnitude from 17 to 1350 TBq/a. This covers fully the uncertainty range of predicted values by various publications as shown in figure 2. In some cases the radiation dose from liquid effluents is neglected. This is not quite understandable since at least one study finds that the dose due to liquid tritium discharges is larger as the dose for gaseous emissions. The radiation dose to the maximally exposed individual ranges from .00069 to .216 mSv. Thus all results lie below the German regulatory limit. The lowest estimate is just a factor of two to eight higher than the

1 Please note that all three figures are at a draft stage and bear some deficiencies which are explained in section 2.2.
2 In the appendix a number of publications is reviewed briefly following a general scheme.
3 [BES (1990)] The technical feasibility to ensure the necessary containment for final disposals has been challenged by [Kalinowski (1992)].
4 See [Edlund (1986)] and [Anderson/Bartlit (1989)]
5 [Cannon (1983)] finds .00029 and .00040 mSv respectively; [Rocco et al. (1986)] attributes 30% of the dose to aqueous emissions.
6 Sum of doses due to both gaseous and aqueous emissions as calculated by [Cannon (1983)]; quoted e.g. by [Sowerby/Forrest (1990)], [Holden et al. (1989)] and many others (see figure 1).
7 [Edlund (1986)]
dose everybody in the northern hemisphere gets from tritium which still remains from nuclear testing (indicated as “background” in figures 3 and 4) and factor 30 to 100 higher than from natural background tritium. This variation of consequences is fairly large (three orders of magnitude) but still it can be doubted whether it is large enough to represent the many uncertainties in parameters and the broad range of alternative which has to be kept open (see section 2). To get some insight in different assumptions and methods the appendix contains a schematic review on a number of publications.

In the seventies most research effort concentrated on sources of tritium from nuclear installations and on measurements of distribution of tritium in the environment and the human body. At the same time a lot of data have been gathered on biological effects of tritium intake. The largest deficiencies and uncertainties appeared in the too simple models for tritium transport in the environment.

After understanding the basic parameters and mechanisms the principal effort shifted towards complex modelling of emission scenarios in the eighties. Recently developed computer codes are much more sophisticated than linear and simple models under use in the seventies. The first approximation was that all biota would be in equilibrium with the atmospheric concentration which is assumed to distribute with the gaussian shape.

This progress is reflected in the calculated data. It could be expected that older models made only first approximations. Due to the principle of conservatism the inbuilt safety margin had to be chosen generously to make sure that the “true” value of calculated individual dose would be below the calculated result.

In complex computer codes the margin of error is reduced and the calculated value for individual doses comes closer to the “true” value. It becomes more clearly how the “true” value can vary under different conditions of emission and atmospheric distribution (emission height, wind direction and speed, texture of the landscape etc.).

The influence of choosing different emission heights becomes apparent when looking at calculated radiation dose due to emissions from a projected reprocessing facility in Germany. As a consequence of a very large emission height (200 m) dose values at the lower bound are resulting (see points Sc74, Bo80, Bo80a, and Br84 in figure). The upper point of Bo80 is calculated for a height of 100 m. By the way, it is interesting to note how the assumed emissions were pushed down in the later studies.

Although the safety margin was reduced with the invention of more detailed calculations the resulting individual dose predictions for tritium emissions did not decrease. In the contrary, most values published in the seventies are lower than those published in the eighties. This indicates that former assumptions on radiological consequences appeared as not being conservative enough and had to be corrected upwards.

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8Natural background before nuclear testing was about 6 to .2 to 1 Bq per liter of water causing a dose of about .00001 mSv/a [UNSCEAR (1977)]. This level is a factor of about 15 higher in 1993.
1.3 Radiation dose to the maximally exposed individual due accidental emissions of tritium from fusion reactors

A survey on a number of studies showed a broad range of individual doses as can be seen in figures 3 (tritium as HTO) and figure 4 (HT). For comparison the doses calculated for accidental emissions from other types of facility are added. Also two horizontal lines for the international accepted maximally permissible dose (International Commission on Radiological Protection – ICRP: 250 mSv) as well as the acute fatality threshold at 3200 mSv.

The assumed emission values for accidental release of HTO in different studies range from $1.85 \times 10^4$ to $3.7 \times 10^5$ TBq (50 to 1000 g). This is in general lower than what is defined to be “vulnerable” inventory (200 to 1500 g). The calculated radiation dose to the maximally exposed individual ranges from .85 mSv to 42,000 mSv. In case of accidental release of $3.7 \times 10^4$ TBq (100 g) as HT the radiation dose to the maximally exposed individual is much lower: .14 to 8.3 mSv. Dose reconstructions for three large accidental emissions resulted in even much smaller values (see figure 4).

This variation of consequences is extremely large (more than four orders of magnitude) but still it can be doubted whether it is large enough to represent the many uncertainties in parameters and the broad range of alternative which has to be kept open (see section 2). To get some insight in different assumptions and methods the appendix contains a schematic review on a number of publications.

Much of what has been said for normal operational losses also applies for accidental releases.

The implication which follows from this survey is that accidental releases of tritium remain to be a major critical issue in fusion reactor safety. Especially it is not at all clear whether regulatory limits can be met.

2 Uncertainties and range of alternative in consequence assessment studies for tritium emissions from fusion reactors

2.1 Sources of uncertainty and range of alternative

The uncertainty is defined by the range of different output values which follow from uncertainties in input parameters, intrinsic model features, expressed for example as statistical errors and probability distributions. These uncertainties are not wanted and the aim of their analysis is to find ways to minimize them and eliminate the reasons which introduce them.

Two fundamentally different uncertainties can be distinguished:12

9[Rocco et al. (1986)] assume a release of 150 g for at an emission height of 20 m as a most severe accident. They argue that the resulting dose would be approximately 30 times lower if the release height would be 100 m: .85 mSv. This value is especially low since it is the “acute” dose. A 50-year dose commitment might be one order of magnitude larger.

10[Stasko/Wong (1986)]

11These data relate to just one study, [Raskob (1990)].

12See for example [IAEA (1989)], p.10
Type A uncertainty is related to stochastic variability with respect to the fixed reference unit of the assessment question.

Type B uncertainty is due to the lack of knowledge about parameters which are invariant with respect to the fixed reference unit of the assessment question.

The range of alternative is defined by the variation of results which follows from a deliberate choice of alternative input parameters. Input parameters can be chosen to be an interval rather than a sharp point in order to widen the definition range for which the model calculation should be applicable. A broad variation of input parameters can deliberately be chosen to keep technological options open. For example the consequence assessment calculation should be valid for different sizes of facilities or for sites with different characteristics. Variability between different studies is often a consequence of ill-defined and uncoordinated definition of the assessment question. In fact most studies do not account for ranges of alternatives and pick certain parameter sets with more or less good reasoning for their restricting choice.

Both uncertainty and range of alternative lead to “error” bars $\pm \delta_{\text{unc}}$ and $\pm \delta_{\text{alt}}$ respectively which result in an overall “error” bar $\pm \delta_{\text{overall}}$. This describes the not clear-cut borderlines of lower and upper limits between which the true result can be expected to lie with a certain probability. The overall “error” is larger than the minimum of both and lower than their sum: $\text{Min}(\delta_{\text{unc}}, \delta_{\text{alt}}) < \delta_{\text{overall}} < \delta_{\text{unc}} + \delta_{\text{alt}}$.

There are several different sorts of uncertainty as well as range of alternative.

1. uncertainty and range of alternative due to improper definition and conceptualization of the problem
2. parameter uncertainties and variation
3. modeling inadequacies and variety of model objectives
4. completeness uncertainties
5. uncertainties through incorrect or inadequate information documentation and transfer
6. disagreement among experts about the value of quantities or the adequacy of assessment methods

There are several different sources of uncertainty and range of alternative which can be distinguished by the stage of assessment in which they are introduced. Most of these uncertainties are reflected in the differences in use of input parameters by different authors who made model calculations of emissions and radiation doses as a result of tritium releases. Typical values are indicated in the following list:

A. Source definition and release characteristics:

1. Design and process variations for emitting facility:
   The most relevant parameters are the total and vulnerable inventory. In case of fusion reactors these values lie between $7.3 \times 10^6$ and $8.7 \times 10^6$ TBq ($2.0_{13}^{13} - 23.5_{14}^{14}$ kg) and between $7.4 \times 10^4$ and $56 \times 10^4$ TBq.

13[Draley/Greenberg (1974)]
14[Philipp/Easterley (1980)]
(200-1500 g) respectively.

The main uncertainty in consequence analysis stems from incomplete knowledge of basic physical parameters (e.g., describing plasma performance or the behaviour of tritium in materials) from different technological solutions (regarding tritium management, design alternatives of the breeder blanket and the tritium recovery system etc., especially with regard to the chemical form as HT or HTO) as well as institutional practices (e.g., tritium storage and transportation management, tritium handling regulations). Progress has been made in recent years and the scatter of cited inventory figures decreases.\(^\text{15}\)

2. Prognostic uncertainties for development of science and technology:

Much progress is especially necessary with respect to tritium leakage reduction e.g., by selection of materials as well as minimization of inventory by optimizing the facility design and the processing of tritium containing material streams.

3. Range of possible release modes:

Probabilistic consequence analyses of accidents and normal operational releases are at a very early stage of development for fusion reactors. Therefore this is the largest source of uncertainty. Some studies do not even argue on the release mechanisms. They look upon fusion reactors as a black box and assume plausible parameters.

Each emission scenario has its specific parameters. The most important are:

(a) Release quantity and the release distribution over time: values for fusion reactors range from 17 to 1350 TBq/a for normal operational loss and from \(1.84 \times 10^4\) to \(37 \times 10^4\) TBq (50-1000 g) within minutes, hours or days\(^\text{16}\) in the case of accident. Typical values are 135 TBq/a (10 Ci/d) and 200 g respectively.

(b) Chemical form of tritium, especially the percentage of HTO and HT. Most studies assume releases of 100% of tritium as HTO, because this is the more dangerous form and HT is rapidly converted to HTO anyway. In this paper for those cases where a major fraction (> 30%) is emitted as HTO, the result is shown in the figure for HTO emissions (figure 3).

(c) Composition of released gases or effluents, e.g., dilution with purge gases.

(d) Emission height: Values in studies range from ground level to 100 meter. A special case was the reprocessing plant which was under consideration in Germany. A stack height of 200 m was envisaged in order to disperse as good as technically possible the tritium released. In case of fire the plume rise gives reason to assume larger emission heights (effective stack height).

B. Distribution characteristics and pathways in the environment:

1. Range of possible meteorological and environmental conditions: e.g., characteristics of surrounding conditions.
landscape, variations of wind direction and speed. A range of about one to two orders of magnitude about the geometric mean for most parameters can be expected.\textsuperscript{17}

2. Uncertainties in transfer parameters: wash-out coefficients, dry deposition velocity, resuspension rate, etc.

3. Important pathways not covered or described inadequately by the model: inhalation is always considered, the food chain in general takes into account drinking water but other paths are often neglected (e.g. milk), skin absorption is sometimes accounted for.

C. Assessment of radiological consequences:

1. Uncertainties in basic physical and medical parameters: biological half-life, dose conversion factors, quality factor, cancer rate, healing chances, etc.

2. Variation of human body parameters and deviation of the mean values from the reference man underlying the model calculation

3. Uncertainties in basic societal parameters: population density, demographic parameters, feeding habits, etc.

4. Differences between type of dose calculated by the model and those chosen as guidance on requirements by radiation protection authorities. In case of accident scenarios the prompt, the first year and the 50 years chronic dose can be calculated. In case of routine emissions the 50-year dose commitment can be calculated for exposure due to one year or 50 years emission.

There is still significant variation between national regulations and internationally recommended limits related to tritium (regulatory uncertainty).

5. The plant boundary ranges from 200 to 1000 m. Sometimes it is not given at all. A typical distance from source is 1 km which happens to coincide for typical scenarios with the distance of largest tritium concentration of the plume at ground level.

2.2 Treatment of uncertainty and range of alternative in consequence analysis studies

The most primitive method for treating uncertainty is to add all uncertainties and present the “worst-case”. In this case the confidence levels for different variables are chosen in a way that with high probability the worst possible consequences are selected. \textbf{Uncertainty is covered by conservatism}. Therefore, the worst-case is an over-conservative case which does not at all represent adequately the state of the art of knowledge. Worst case studies for fusion energy have not been published, perhaps because the result would have been unacceptable. It can be taken for sure that with more elaborate uncertainty and error propagation analysis the margin of error goes down and the worst-case comes closer to the “really” worst case.

Especially if worst-case individual doses are above regulatory requirements a more realistic assessment is desired.

\textsuperscript{17}[NCRP (1983)]
This is the case for tritium emissions from fusion reactors. Therefore most studies give “single-value-best-
estimates" but ignore uncertainties. No attempts have been made to estimate uncertainties of input parameters
and propagate these uncertainties through the analysis.

In some cases single values of different assessments are presented in a synopsis\textsuperscript{18} or a “parametric analysis" is performed in which a single-value-result is presented for different values of a certain input parameter (e.g.
emission height)\textsuperscript{19}.

One study makes an “order-of-magnitude based bounding analysis" which estimates bounds on the range
of possible answers.\textsuperscript{20} Besides of [McKone/Kastenberg (1978)] this is the only study which finds an upper value
for individual dose resulting from accident emissions which lies above the acute fatality threshold.

Due to the large variations in basic parameters, it is very difficult to compare the results of different calculations.
Therefore it is desirable that a certain standard is agreed upon. One recent endeavour to reach an agreement on
such a standard has been undertaken by the international BIOMOVS project. It undertakes studies to compare
predictions of models designed to predict the environmental transfer and bioaccumulation of radionuclides and
other trace substances. One Working Group of BIOMOVS concentrates on the special radionuclide tritium. A
reference scenario for HTO release has been set-up and will be modelled by different groups. The predictions by
different models will be compared and differences evaluated.\textsuperscript{21} For sets of calculations had been submitted.\textsuperscript{22}
The best estimate values for the model predictions varied over several orders of magnitude. Several sources
of difference were identified during a group’s discussion. Most of these factors involved interpretation of the
reference scenario.

The synopsis of results from a number of different studies given in this paper can be classified as a “synoptical
bounding analysis". However, it should be noted that figures 2 to 4 are presented in this draft in a preliminary
version. It has not yet been attempted to represent exactly the statements made in the publications the points
are taken from. Some points are lower and upper bounds given, others are upper limits or order of magnitude
estimates. Some discuss qualitatively the uncertainties but no attempt has yet been made to represent this in
the figures 2 to 4. Two points can clearly be made at this stage of the survey: (1) the scatter of published
results can be demonstrated; (2) the need to develop and apply appropriate means for graphical representation
of estimates which are not meant to be defined as sharp as a point becomes apparent.

A reversed approach has been chosen by some studies to avert the uncertainty problem: Especially by the mid
1980s it was quite common in safety studies related to fusion energy to derive maximally permissible emission
rates as a design goal for normal operation of fusion reactors from dose limits for radiological protection. This
holds especially for accident emissions. Some studies have chosen this approach explicitly,\textsuperscript{23} but it can be ex-
pected that others did it in a heuristic manner. Typical results are around 135 to 675 TBq (10-50 Ci/d). The

\textsuperscript{18}See for example [Stasko/Wong (1986)].
\textsuperscript{19}See for example [Raskob (1990)].
\textsuperscript{20}[Stasko/Wong (1986)]
\textsuperscript{21}[BIOMOVS II (1992)], p.10 and 63.
\textsuperscript{22}[BIOMOVS II (1992)], p.7-9.
\textsuperscript{23}See for example [Stasko/Wong (1986)]
resulting question was whether and how these goals could be achieved technically. In recent publications on routine emissions the argumentation changes. Emission values in the same order of magnitude are presented as extrapolations of the best technically achieved emission rates.\footnote{See e.g. [Sowerby/Forrest (1990)] and [Pease et al. (1989)] which quotes the first one.}

The experience with the Tritium Systems Test Assembly at Los Alamos National Laboratory is most significant to the evaluation of tritium emission rates from fusion power reactors. Not only does it contain one of the world’s largest civilian tritium inventories (110 g), it also simulates major parts of future fusion plants, e.g. the exhaust clean up system. The operational experience of TSTA is outstanding as far as tritium containment is concerned. According to \cite{Anderson/Bartlit (1989)} in four years of operation only less than 1.48 TBq was emitted to the environment. Consequently it is cited as a promising grant for the containment performance of fusion reactors: “Increased experience in the last several years with the handling and control of tritium at Los Alamos suggests that fusion can meet the same high standards for routine emissions with which fission reactors now comply.”\footnote{[Stever (1990)], page 14}

Other authors\footnote{[Rocco et al. (1986)]} refer to experiences in containing tritium in heavy water reactors which seems not to be well backed by all publications.\footnote{See for example [Brown (1990)] who makes the statement that the total emission amounts to about 1.5\% of the plant inventory at Chalk River per year.}

Although basic assumptions as well as results of different studies differ severely it seems that the fusion research community has adopted a strategy of \textit{“harmonizing assumptions”} to reduce uncertainty and range of alternative. It would be an interesting question for interdisciplinary research in research and technology to find out how an international scientific community reaches consensus on certain points and how dissidents are being treated. For example the consensus finding process is supported by proposing source terms of tritium as \textit{“Chairman’s Perspective”} in the proceedings to a conference.\footnote{[Rocco/Kirchmann (1986)]}

As a result of a consensus finding process specific values for tritium inventories, emissions and consequent doses are widely accepted. The social-generated value for tritium inventory is $3-5 \text{ kg/GW}_e$ of which $200-1500 \text{ g}$ are assumed to be “vulnerable” or mobile. Accepted emission values are $10 \text{ Ci/day}$ for normal operation and $200 \text{ g}$ due to accidents. Derived doses are said to be comparable to those from fission power stations and remain below $0.05 \text{ mSv/year}$. This is lower than the accepted radiation dose to the maximally exposed individual of the public according radiation protection standards in different countries, $(0.5-3) \times 10^{-4} \text{Sv/a}$. In case of accidents, it is generally assumed that the most exposed individual will receive a dose which does not exceed $250 \text{ mSv}$. This would be low enough not to require evacuation of the public in the region around the facility.
2.3 Transfer from original work to policy papers and representation of uncertainties in "risk communication"

Having control over all sources of uncertainty and range of alternative does not account for the fact that errors in communication and information transfer can influence the uncertainty at any stage of the analysis and representation of the results.

Much progress has been made in quantitative methods of uncertainty analysis especially with respect to radiation protection and nuclear safety which will in future be increasingly applied to fusion reactor safety research. However, much has to be done in communicating scientific insight to a wider scientific community for interdisciplinary collaboration and to the public for decision making. For this purpose the high complexity of uncertainty aspects has to be reduced and the meaning and significance of uncertainty estimates has to be illustrated.

The practice of uncertainty reduction by harmonizing assumptions can be misleading if in policy papers the agreed values are presented without error bars and as results of careful scientific analysis rather than of a social process of assumptions harmonizing.

Individuals respond differently to perceived risks. The perception of risks by radioactive emissions leads to stimulus uncertainty and the resultant impulse to react leads to response uncertainty. In a similar way uncertainty is generated on the public level by media, discussions and other ways of collective shaping of opinions. "Risk communication" attempts to take these uncertainties on the individual and public level into consideration.

[Funtowicz/Ravetz (1987)] suggested a notational scheme which can be used to make more transparent uncertainty in policy-related research. Part of this scheme is the "research pedigree matrix" which is intended to indicate the state of the art in the field in which the quantity (e.g. radiation dose) is produced. According to this matrix the predicted emission values for fusion reactors as well as related radiation dose could be classified "educated guesses" or at best "calculated data" which score one point and two respectively on a scale from 0 ("uneducated guesses") to 4 ("experimental data"). Colleague consensus on these values appears to be in an "embryonic field" (1 score) but their peer acceptance seems to be "high" (3 scores).

Technology assessment studies have questions which are in general much broader defined as they are in the original research work they dwell on. One relevant policy related question is: How large is the radiation dose to the maximally exposed individual (MEI) resulting from tritium emissions from fusion reactors (e.g. assuming a range of alternative in emission height from ground level to 100 m). Original research papers give answers to more restrictly defined questions in which most input parameters are sharply defined (e.g. emission height: 60 m). The results of different original calculations vary from paper to paper more widely than the range of uncertainty of each single paper. Their error bars sometimes would not even overlap, but in general they are not even given. Technology assessments should not only pick the "best estimate" but should also demonstrate the broad scatter of results and provide careful reasoning to explain why the other data can be discarded. However, adequate representation of the uncertainty and the range of alternative in technology assessment studies and policy related research papers seems to be almost never attempted. It could be indicated by the above mentioned "research pedigree" classification but a transparent representation is still lacking.

It is quite remarkable that most relevant policy-related technology assessment studies for fusion energy of the
past ten years\textsuperscript{29} quote – using rounded figures – the consequence assessment published by [Cannon (1983)] (see table 2.3 and figure 1) which arrived at the lowest of all individual dose levels which are compared in this synopsis (see figure 2). Another important policy study aimed at research evaluation and strategy recommendation for the European Community\textsuperscript{30} even dismisses the results of [Cannon (1983)] as being outdated and giving too large dose values because assuming too high inventory values (11.6 kg for STARFIRE).

[Cannon (1983)] is based on two different designs: STARFIRE\textsuperscript{31} and SS-Li-He\textsuperscript{32}. The latter has the larger emission values and is never quoted in secondary technology assessment studies. Thus, most relevant technology assessment studies on fusion energy refer to STARFIRE which is a more than 12 years old fusion reactor design. No alternative reference design was available and its development is recommended.\textsuperscript{33} The only elaborated new design has been made for ITER, but this is meant to be an experimental reactor and therefore not well suited to model a commercial power reactor. Extrapolations on test facilities like JET, NET, and INTOR have been conducted, e.g. the FCTR (First Commercial Tokamak Reactor).\textsuperscript{34} A citation hierarchy similar to that building on [Cannon (1983)] could be depicted for [Casini et al. (1985)].\textsuperscript{35}

\begin{center}
\begin{tabular}{l}
\textbf{Colombo et al. (1990)} \\
\textbf{Holdren et al. (1989)} \\
\textbf{OTA (1987)} \\
\textbf{Cannon (1983)}
\end{tabular}
\end{center}

\textsuperscript{29}Namely [Holdren et al. (1989)], [OTA (1987)], [Pease et al. (1989)]
\textsuperscript{30}[Colombo et al. (1990)]
\textsuperscript{31}[Baker et al. (1980)]
\textsuperscript{32}[Karborski et al. (1980)]
\textsuperscript{33}e.g. [Colombo et al. (1990)]
\textsuperscript{34}Defined by [Spears (1985)]
\textsuperscript{35}For example [Rocco et al. (1986)], [Edlund (1986)] as well as some policy related studies dwell on that work.
Tabelle 1: Tritium emissions through normal operation of fusion reactors calculated for STARFIRE and the SS-Li-He reactor as quoted in technology assessment studies.

<table>
<thead>
<tr>
<th></th>
<th>STARFIRE [Baker et al. (1980)]</th>
<th>SS-Li-He reactor [Karborski et al. (1980)]</th>
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<tbody>
<tr>
<td>calculated emission rate (Ci/a):</td>
<td>6445 to 7145 (gas.) + 910 (aqu.)</td>
<td>6440 to 9790 (gas.) [Cannon (1983)]</td>
</tr>
<tr>
<td>quoted emission rate (Ci/a):</td>
<td>7100 (gas.) + 910 (aqu.)</td>
<td>- [Holdren et al. (1989)]</td>
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<tr>
<td></td>
<td>5000 to 10000 (gas.)</td>
<td>- [OTA (1987)]</td>
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<tr>
<td></td>
<td>8000 (gas.) + 800 (aqu.)</td>
<td>- [Pease et al. (1989)]</td>
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3 Conclusions

There are different reason for inadequate reduction in representing uncertainties and range of alternative. Suggestions can be made to improve their representation.

1. The first recommendation is a general one:
   (a) Uncertainties should be analyzed, reduced as far as possible, made explicit and documented clearly and completely.
   (b) The range of alternative should be clearly defined, made transparent and a careful rationale should be provided.

2. In fact most studies do not choose an appropriate interval of input parameters but decide to rely on certain values without thorough arguing why extreme values are discarded. Instead, appropriate ranges of input parameters should be chosen as input parameters and illustrated graphically e.g. by “error“ bars.

3. What is more, no attempts have been made to completely study the propagation of uncertainties through successive calculational steps and present their influence on the final output. Any attempt towards this are hampered by the fact that no original study covers the whole range from reactor design to dose calculation. Each stage of analysis (reactor design and emission scenario, distribution in the environment, dose calculation) is handled by different research teams where one uses the results of others as guidance to define its own input parameters.
   It should be studied how uncertainty propagates through the consequence analysis and especially how it gets lost at interfaces.

4. In many cases the calculated consequences are stated without indicating the margin of error and confidence. If uncertainties are large (e.g. > ± 10%) it should be made a first principle never to quote results without giving the margin of error. At least rough guesses should be made.

5. Particular attention should be given to the transformation of uncertainty estimates for particular results into probability statements that will be more clear and descriptive to representatives of other disciplines.
and the public. For example besides stating the best estimate and its probability it should at least be tried to state the probability of much lower and higher doses (factor 10 or 100) as well as the probability that regulatory doses limits are exceeded.

6. In policy related studies it should be made clear whether quantitative results represent a worst case, a realistic best estimate, an extrapolation of the best technically achieved performances, or design goal that has to be reached to meet radiation protection standards. Especially it should be made clear, that at the present stage of research nothing else but recommendations for the design goal can be made with regard to accidental emissions.

7. Always not only results but also implication of uncertainties should be interpreted so as to make them understandable to representatives of other disciplines and the public.

8. Both for relative emission rates in normal operation as well as for dose values resulting from routine emissions most technology assessment studies quote the values which lie at the lower bound of a broad spectrum over several orders of magnitude covered by different original works on consequence assessment. It should at least be made visible that there are studies which arrive at values a factor of 1000 or more higher and careful argumentations should be presented why all larger estimates could be discarded.

9. Even the most successful undertakings to reduce uncertainty and eliminate incorrect representation of consequence analysis results will – for sure – leave a certain range of unresolvable uncertainty. It should be discussed whether this remaining uncertainty is tolerable or not.
Figure 2: Containment performance of different tritium systems under normal operational conditions.

- + - loss from inventory, experiment
- - uncertainty in accountancy, experiment
- X - expected loss to environment, model
- - permissible loss to environment, goal

Figure 2 shows a log-log plot of emission or loss rate (TBq/y) versus inventory (TBq) for different tritium systems. Points marked with symbols indicate experimental data, while lines represent model predictions. The graph includes a 5 kg safety margin for permissible loss to the environment.
Figure 3: Radiation dose to the maximally exposed individual (MEI) due to tritium (HTO) emissions.

- Max. dose from aqueous emission, routine
- Max. dose from gaseous emission, routine
- Max. dose from gas. + aqu. emission, routine
- Max. permissible dose, goal

Routine emission rate/(TBq/y); accident emission/TBq

- Max. permissible dose, goal
- 0.3 mSv - StSch
- 0.5 mSv - NRC
- 0.25 mSv - ICRP
- Max. dose from routine and accident

10 kg background
Figure 4: Radiation dose to the maximally exposed individual (MEI) due to tritium (HT) emissions

- max. dose from gaseous emission, routine
- max. dose from gaseous emission, accident
- max. permissible dose, goal

<table>
<thead>
<tr>
<th>Radiation dose/mSv</th>
<th>Routine emission rate/(TBq/y); accident emission/TBq</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}</td>
</tr>
<tr>
<td>10^{-6}</td>
<td></td>
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<td>10^{-5}</td>
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<td>10^{-1}</td>
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<tr>
<td>10^{0}</td>
<td></td>
</tr>
<tr>
<td>10^{1}</td>
<td></td>
</tr>
<tr>
<td>10^{2}</td>
<td></td>
</tr>
</tbody>
</table>

- 3.2Sv - AFT
- 0.250mSv - ICRP
- 0.3mSv - StSch
- 0.05mSv - NRC

- Ra90
- Sc74
- Bo80a
- My73
- Bo80
- Br84
- Mu77

10 Ci/d | Mu77 | 1 kg background
Abbreviations for references used in the figures:

An89  [Anderson/Bartlit (1989)]
BfS90 [Bundesamt fuer Strahlenschutz (1990)]
Bo80  [Bonka (1980)]
Bo80a [Bödege/Fenzl (1980)]
Br84  [Brücher (1984)]
Br85  [Brown (1985)]
Ca83  [Cannon (1983)]
Ca85  [Casini et al. (1985)]
Co87  [Cochran et al. (1987)]
Dr74  [Draley/Greenberg (1977)]
Ed86  [Edlund (1986)]
Fa79  [Farges/Jacobs (1979)]
Fe85  [Fetter (1985)]
Fi92  [Fiege (1992)]
Go79  [Gorman/Wong (1979)]
Ho89  [Holdren et al. (1989)]
Hu73  [Hugony et al. (1973)]
Ka86  cited in [Sowerby/Forrest (1990)]
Ko89  [Kobisk et al. (1989)]
La89  [Lässer (1989)]
Li87  [Lindsay (1987)]
Mc78  [McKone/Kastenberg (1978)]
Mo69  cited in [Sowerby/Forrest (1990)]
Mu77  [Murphy/Watts/Corey (1977)]
My73  [Myers/Tinney/Gudiksen (1973)]
Pe89  [Pease et al. (1989)]
Ph80  [Philipp/Easterley (1980)]
OTA87 [OTA (1987)]
Ra90  [Raskob (1990)]
Ro86  [Rocco/Casini/Ponti (1986)]
Sc74  [Schnez et al. (1974)]
Si88  [Sienkiewicz (1988)]
St86  [Stasko/Wong (1986)]
Su89  [Sumita (1989)]
Ta88  [Tanase et al. (1989)]
UN88  [UNSCEAR (1988)]
Other abbreviations in the figures:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFT</td>
<td>Acute Fatality Threshold (3.2 Sv)</td>
</tr>
<tr>
<td>background</td>
<td>individual dose by tritium background from nuclear testing</td>
</tr>
<tr>
<td>ICRP</td>
<td>International Commission for Radiation Protection (250 mSv)</td>
</tr>
<tr>
<td>LWR</td>
<td>Light water reactor</td>
</tr>
<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission (.05 Sv)</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>StSch</td>
<td>Strahlenschutzverordnung (German radiation protection regulation, .3 mSv concept)</td>
</tr>
<tr>
<td>TSTA</td>
<td>Tritium Systems Test Assembly, Los Alamos</td>
</tr>
<tr>
<td>waste</td>
<td>final disposal for radioactive waste, [BfS (1990)]</td>
</tr>
</tbody>
</table>
**Publication:** [BfS (1990)]


**Type of study:** license application

**Type of facility:** Planned repository for low heat generating radioactive waste: “Schacht Konrad”.

**Tritium inventory:** In a backward calculation as described by [Illi (1989)] the maximum activity was determined leading to the (desired) emission values as given below: $6 \times 10^{17}$ Bq (about 1.62 kg of elementary tritium) at the end of the operational phase.

**Emission scenario:** Routine losses from conditioned and stored waste containers.

**Absolute emission (rate):** Proposed values in the license application:

- Emissions to water: 7.4 TBq/a, to air: 15.0 TBq/a.

**Relative emission (rate):** 37 ppm/a (0.0037% per year) of total inventory given above.

**Assumptions/Method for deriving radiological consequences:** The models used to derive transport and consequences of emissions are described in the “Allgemeine Verwaltungsvorschrift” to the radiation protection ordinance (“Strahlenschutzverordnung”, paragraph 45), dated February 1990.

**Radiation dose to the maximally exposed individual (MEI):** 0.045 mSv/a due to aqueous, 0.047 mSv/a due to gaseous releases.

**Conclusions:** The emission values were chosen in a way that calculations predict doses being an order of magnitude lower than german dose limits (0.3 mSv/a for each path (aqueous, gaseous): “Strahlenschutzverordnung”, paragraph 45).

**Main references:** [Illi (1989)].
Publication: [Cannon (1983)]


**Type of study:** Computer calculation.

**Type of facility:** STARFIRE reference design given by [Baker et al. (1980)], alternatively the SS-Li-He reactor defined by [Karborski et al. (1980)].

**Tritium inventory:** 11.6 kg for the STARFIRE design, 4.6 kg for the SS-Li-He reactor design, values taken from the corresponding literature.

**Tritium throughput:** 140-200 kg burned per year.

**Emission scenario:** Operational and (qualitatively discussed) accidental releases.

**Absolute emission (rate):** STARFIRE design: 238.5-264.4 TBq/a (6445-7145 Ci/a) as HTO to atmosphere from a stack height of 100 m, 33.7 TBq/a (910 Ci/a) to water. SS-Li-He reactor: 238.3-362.2 TBq (6440-9790 Ci/a). The individual contributions to the total release rates are either calculated from first principles, or assumed by comparing with established operating histories.

**Relative emission (rate):** STARFIRE design: 63.4-69.4 ppm/a (of total inventory). SS-Li-He design: 140-213 ppm/a.

**Assumptions for deriving radiological consequences:** Ingestion and inhalation rates taken from [NRC (1977)], various ICRP publications.

**Method for deriving radiological consequences:** Dose commitments due to atmospheric releases are calculated by the AIRDOS-EPA computer code, provided by [Moore et al. (1979)].

**Radiation dose to the maximally exposed individual (MEI):** Due to routine emissions: 50-yr dose for individual at the boundary (320 m) of reference fusion power plant, exposed to effluents from one year's operation:
- $2.9 \times 10^{-4}$ mSv (0.029 mrem) due to gaseous emissions;
- $4.0 \times 10^{-4}$ mSv (0.040 mrem) due to aqueous emissions.

**Collective dose commitment:** 50-yr dose to population within 80 km of the reference fusion power plant: 34 man-mSv. (United States: 59 man-mSv, World: 255 man-mSv).

**Cited in:** [OTA (1987)], [Holdren et al. (1989)]

**Main references:** [Baker et al. (1980)], [Kabele et al. (1976)], [Karborski et al. (1980)], [Moore et al. (1979)], [Watson et al. (1980)].
Publication: [Colombo et al. (1990)]


Type of study: Research evaluation and strategy recommendation.

Type of facility: Ficticious fusion reactor.

...: Tritium inventory and emission scenarios (with corresponding doses to population) are not discussed or estimated.

Conclusions: The authors establish that the Starfire concept is outdated and therefore inadequate to cope with safety and environmental issues. It is recommended to launch a new European reference design for a commercial fusion reactor.

Main references: [OTA (1987)].
Publication: [Edlund (1986)]


Type of study: Literature based paper.

Type of facility: Test facilities JET, NET and INTOR. Results are extrapolated to future fusion reactors, called FCTR (First Commercial Tokamak Reactor), defined by [Spears (1985)].

Tritium inventory: Total inventory not given. The inventory of tritium in the first wall of NET (Next European Torus) is estimated to be 54-97 g, values taken from [Gervasini/Reiter (1985)].

Emission scenario: Normal operation and maintenance loss.

Absolute emission (rate): Contributions to atmospheric releases are summarized in the table below. The total quantity of about 777 TBq/a can be subdivided into 444 TBq/a as HTO and 333 TBq/a as HT. Additional aquatic releases of tritium are estimated to be 56 TBq/a. All values are taken from [Casini et al. (1985)].

<table>
<thead>
<tr>
<th></th>
<th>Operation</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant systems:</td>
<td>185.00 TBq/a</td>
<td>56.00 TBq/a</td>
</tr>
<tr>
<td>Torus:</td>
<td>0.37 TBq/a</td>
<td>185.00 TBq/a</td>
</tr>
<tr>
<td>Diagnostics:</td>
<td>—</td>
<td>37.00 TBq/a</td>
</tr>
<tr>
<td>Process systems:</td>
<td>3.70 TBq/a</td>
<td>111.00 TBq/a</td>
</tr>
<tr>
<td>Tritium storage:</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Reactor hall:</td>
<td>—</td>
<td>185.00 TBq/a</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>189.07 TBq/a</strong></td>
<td><strong>574.00 TBq/a</strong></td>
</tr>
</tbody>
</table>

Relative emission (rate): Not given.

Another example is quoted from [Casini et al. (1985)]: At the TSTA (Tritium System Test Assembly), Los Alamos, an amount of 0.037 TBq/a was lost from an inventory of 11 g (3910 TBq). This corresponds to a relative emission rate of less than $10^{-5}$ per year (9.5 ppm/a).

Assumptions/Method for deriving radiological consequences: Normalised results from [Kempe et al. (1985)]: Comparison of (ten different) computer codes modelling the dispersion of tritium released to the atmosphere. Additional calculations were made for dry deposition with fixed and variable velocity.
Radiation dose to the maximally exposed individual (MEI): Chronic dose for individual at 1 km from emitting source (20 m release height):

Due to HTO: 7.2-163.0 μSv/a (Span arising from whether or not the evaporation process is considered). If about 65% of the deposited HTO is assumed to evaporate the dose becomes: 121 μSv/a (fixed dry deposition velocity), 216 μSv/a (variable velocity).

Due to HT: 1.8×10^{-4}-3.4 μSv/a (Span arising from whether or not the oxidation process of HT to HTO is included).

Conclusions: The additional calculations demonstrate the importance of the method used to calculate the dry deposition velocity. It is concluded that future tritium dispersion models have to consider these processes.

Cited in: [Rocco/Kirchmann (1986)].

Main references: [Casini et al. (1985)], [Gervasini/Reiter (1985)], [Kempe et al. (1985)].
**Publication:** [Fetter (1985)]


**Type of study:** Computer simulation, developing the FUSEDOSE code.

**Type of facility:** Fictitious fusion reactors. Reference design: MARS (*Mirror Advanced Reactor Study*), defined by [LLNL (1984)].

**Tritium inventory:** Total: 3087 g. About 50 g of this amount are considered to be vulnerable.

**Emission scenario:** Accidental release of tritiated water vapour (HTO).

**Scenario A:** Release of "vulnerable" inventory.

- **Absolute emission (rate):** 50 g.
- **Relative emission (rate):** About 1.7% (of total inventory).
- **Assumptions for deriving radiological consequences:** Based on several ICRP and NRC publications (NRC guideline for emergency releases).
- **Method for deriving radiological consequences:** Computer simulation. Dose calculations based on following parameters: Ground level release with no plume rise, initial plume dimension: 33×12 m, deposition velocity: 0.01 m/s, wind speed: 1.0 m/s, inversion layer height: 250 m.

  **Radiation dose to the maximally exposed individual (MEI):**
  - Maximum off-site (whole-body) dose: 38 mSv, 50-year dose: 60 mSv, 5 % chance of one late cancer death. No early illnesses or fatalities.

**Scenario B:** Release of entire tritium inventory in the (modified) lithium breeder/coolant.

- **Absolute emission (rate):** 1000 g.
- **Relative emission (rate):** About 30%.
- **Assumptions/Method for deriving radiological consequences:** Equal to scenario A.

- **Radiation dose to the maximally exposed individual (MEI):**
  - Maximum off-site dose: 0.75 Sv, 50-year dose: 1.2 Sv, one late cancer death. No early illnesses or fatalities.

**Cited in:** [Holdren et al. (1989)]


Type of study: Computer calculation.

Type of facility: “Conceptual design” for a 1000 MW(t) tokamak reactor, defined by [Fraas (1973)].

Tritium inventory: Active inventory: 400 g (tritium circulating in the lithium blanket, potassium vapour cycle and tritium recovery systems).

Emission scenario: Accidental loss of entire active inventory, assuming a release height of 100 m and normal weather conditions.

Absolute emission (rate): 400 g at once.

Assumptions/Method for deriving radiological consequences: “... analyses indicate that ...” (p. 13).

Radiation dose to the maximally exposed individual (MEI): “... the maximum dose that anyone would get on the ground downwind of the reactor would be limited to a few rem, about 10% of the maximum dose generally considered acceptable for such a severe accident” (p. 13).

Conclusions: The biological hazard potential due to tritium is considered to be more than a factor of a million lower than that represented by the radioactive iodine in a fission reactor of similar output. Thanks to many degrees of freedom in reactor (esp. blanket) design, the author concludes that the possibility of any accidental release of activity can be reduced to “virtually zero”.

Main references: [Fraas (1973)].
Publication: [Holdren et al. (1989)]


Type of study: Technology assessment.

Type of facility: Several fictitious fusion reactors (ESECOM reference cases).

Tritium inventory: 300-700 g + inactive kilogram quantities in vault storage. Values mainly taken from [Smith et al. (1985)] and [Holland et al. (1989)].

Emission scenario: Operational and accidental release.

Scenario A: Operational release.

Absolute emission (rate): Target release: 129.5-1295.0 TBq/a (3500-35000 Ci/a). “In the absence of operating experience with actual fusion reactors, it would be futile to try to estimate quantitatively the routine emissions to be expected from the various designs”.

Refering to [Cannon (1983)] the emission values for the STARFIRE design are indicated: 7100 Ci/a as HTO to air, 910 Ci/a to water (p. 232).

Relative emission (rate): Typically between 1 part in \(10^5\) and 1 part in \(10^6\) of a kilogram-quantity inventory per day.

Assumptions/Method for deriving radiological consequences: —

Radiation dose to the maximally exposed individual (MEI): \(6.6 \times 10^{-4}\) mSv (0.066 mrem/a) for the STARFIRE reactor (individual at the plant boundary (320 m), 50-year dose commitment resulting from exposure to one yr’s gaseous and aqueous effluents), reference: [Cannon (1983)].

Collective dose commitment: STARFIRE design: The estimated whole-body dose to population within 80 km of the plant is taken from [Cannon(1983)]: 34 man-mSv/a (50-yr dose commitment resulting from exposure to one yr’s effluents).

Scenario B: Accidental release.

Absolute emission (rate): Backward calculation, reversed argumentation.

Assumptions for deriving radiological consequences: Generally accepted threshold doses (based on several NRC and EPA regulations). Definition of the “critical dose threshold” (200 rem delivered by the passage of the plume to an individual at a distance of 1 km from release) and the “chronic dose threshold” (50-year whole-body dose of 25 rem from ground contamination at a distance of 10 km from release).

Method for deriving radiological consequences: Computer simulation, using the FUSEDOSE code given by [Fetter (1985)]. Parameters: 1 m/s wind speed, inversion layer at 250 m, release at ground level with no thermal plume rise, and a deposition velocity of 0.01 m/s.
Radiation dose to the maximally exposed individual (MEI): The 200-rem "critical dose threshold" is reached by a (tritium) release of 2.52 MCi (about 252 g), the 25-rem "chronic dose threshold" by a release of 0.77 MCi (about 77 g).

Cited in: [OTA (1987)].

Publication: [IAEA (1986)]

Type of study: Literature based study.

Type of facility: Experimental fusion reactor INTOR (International Tokamak Reactor) defined by [IAEA (1983)].

Tritium inventory: 4.7-7.5 kg, up to 1.5 kg vulnerable.

Emission scenario: Operational and accidental release.

Absolute emission (rate): Into reactor hall: <1.11 TBq/d (30 Ci/d) under normal system conditions, <37 TBq/d (10³ Ci/d) while maintenance, <3700 TBq (10⁵ Ci) in case of accident. Values taken from: [EG&G]. Releases to the environment are estimated to be small.

Relative emission (rate): Annual loss into reactor hall (under normal system conditions): <0.015-0.023% of total inventory. In case of accident: <0.13-0.21% of total (or: <0.67% of vulnerable) inventory.

Assumptions for deriving radiological consequences: Based on ICRP recommendations.

Radiation dose to the maximally exposed individual (MEI): Only concentrations given: 5 μCi/m³ for unprotected, 500 μCi/m³ for protected worker in reactor hall.

Cited in: [Holdren et al. (1989)]

Main references: [EG&G], [IAEA (1983)].
Publication: [Kobisk et al. (1989)]


**Type of study:** Empirical study.

**Type of facility:** The (in particular: tritium target fabricating) Isotope Research Material Laboratory (IRML) at the Oak Ridge National Laboratory (ORNL).

**Tritium inventory:** Annual processed quantity: 74000 TBq (200 g).

**Emission scenario:** Routine releases due to gaseous waste discharged into the cell ventilation system.

**Absolute emission (rate):** Approximately 13 TBq per month.

**Relative emission (rate):** 0.21% per year of total inventory.

**Assumptions/Method for deriving radiological consequences:** Not given.

**Radiation dose to the maximally exposed individual (MEI):** Not estimated, but it is stated that “since the elemental tritium ($^3$H$_2$) has such an affinity for nearly everything, there is significant potential for contamination” (p. 336).

**Conclusions:** “The uncertain long-term effects resulting from the exposure of processing personnel (or the general population) to radiation from tritium contamination would seem to dictate that tritium production and/or atmospheric processing procedures be improved to minimize tritium releases” (p. 340).
Publication: [Léger (1986)]


Type of study: Literature based paper.

Type of facility: Fictitious fusion reactors, especially the INTOR-Design defined by [IAEA (1983)].

Tritium inventory: Values for the INTOR-Reactor: Total inventory: 4.33-5.73 kg, about 370 g of this amount in the plasma exhaust system, taken from the corresponding literature.

Tritium throughput: Quantity burned per day: about 450 g (which is a generally accepted value for a commercial fusion reactor).

Emission scenario: Losses due to operational release.

Absolute emission (rate): 15 g/day lost (but not emitted) from the plasma exhaust reprocessing system:
The author considers the estimated INTOR process flow (about 1.5 kg/day) and a loss of 1% of this quantity which is "beyond the current practice in chemical engineering" (p. 191).

Supposing an absolute emission rate into the reactor hall atmosphere of some Curies per day, a tritium concentration in the reactor hall of $5 \times 10^{-6}$ Ci/m$^3$ is considered to be an upper limit. This would require flow rates in the detritiation systems in the order of $10^5$ m$^3$/h which is "far beyond the present technology and is certainly too expensive. This implies that a possible entrance in the reactor hall without bubble suit is impossible." (p. 194)

Relative emission (rate): Loss rate for INTOR: 15 g/d, i.e. 20% of tritium burned, "considering losses of one percent, that is beyond the current practice in chemical engineering, and implies efficiencies equal to 99%". (p.191)

Refering to [Carré/Rocaboy (1983)] it is pointed out that tritium losses have to be kept below 0.1% to be without impact on the breeding capability.

Assumptions/Method for deriving radiological consequences: Not given.

Radiation dose to the maximally exposed individual (MEI): Not estimated.

Conclusions: Tritium permeation takes place everywhere in a fusion reactor and becomes the principal source of tritium losses. The main problem resulting from this phenomenon does not seem to be the hypothetic dose to the public, but to maintain a tritium breeding ratio equal to (or greater than) one. The author concludes: "If ways to improve the tritium recovery inside the fusion plant and to limit the tritium permeation phenomena are not developed, it will become very difficult if not impossible to rely on this future energy source" (p. 194).

Main references: [Carré/Rocaboy (1983)], [IAEA (1983)].
Publication: [Pease et al. (1989)]

Type of study: Technology assessment.

Type of facility: Several fictitious fusion reactors, especially the EEF Reference Reactor defined by [Cooke et al. (1989)] and the STARFIRE design defined by [Baker et al. (1980)].

Tritium inventory: about 5 kg in fuel cycle + 0.03-0.25 kg in structural materials (ten years after final shutdown of reactor). Values taken from [Watson et al. (1987)].

Tritium throughput: about 100 kg burned per year assuming a 75 % load factor.

Emission scenario: Operational and accidental release.

Scenario A: Operational release.

Absolute emission (rate): about 300 TBq/a (atmosphere) + 30 TBq/a (liquid waste), taken from the STARFIRE assessment.

Relative emission (rate): 10 ppm/a of tritium burned.

Radiation dose to the maximally exposed individual (MEI): around 0.1 mSv/a received by a member of the Critical Group, [Sowerby/Forrest (1990)]. (possibly 0.1 mrem/a is meant instead of 0.1 mSv/a, because [Sowerby/Forrest (1990)] refer to [Cannon et al. (1983)] who give .00069 mSv = 0.069 mrem.)

Scenario B: (Worst plausible) accidental release.

Absolute emission (rate): 1 kg.

Relative emission (rate): 20% of inventory at once.

Radiation dose to the maximally exposed individual (MEI):
under worst conditions 100-200 mSv. In general many kilograms could be lost without exceeding 50 mSv.

Assumptions for deriving radiological consequences: Generally accepted threshold doses.

Method for deriving radiological consequences: Calculations, assuming tritium released as tritiated water vapour, a release height of 20 m and unfavourable weather conditions.

Conclusions: “Many kilograms of tritium can be released without exceeding a dose to the most exposed individual of 50 mSv which is generally accepted as the dose limit for abnormal events of low probability in most countries”.

Publication: [OTA (1987)]

**Type of study:** Technology assessment.

**Type of facility:** Fictitious fusion reactors, for example the STARFIRE design given by [Baker et al. (1980)].

**Tritium inventory:** —

**Emission scenario:** Operational and accidental release.

**Scenario A:** Operational release.

Absolute emission (rate): 185-370 TBq/a (5000-10000 Ci/a) as HTO, taken from [Cannon (1983)].

Radiation dose to the maximally exposed individual (MEI): 0.01 % of the dose from natural background sources for population within 80 km of the fusion reactor.

**Scenario B:** Accidental release.

Absolute emission (rate): No values given.

Radiation dose to the maximally exposed individual (MEI): Qualitative discussion, it is referred to [Holdren et al. (1989)].

**Cited in:** [Colombo et al. (1990)], [Pease et al. (1989)].

**Main references:** [Baker et al. (1980)], [Cannon (1983)], [Holdren et al. (1989)]
Publication: [Phillips/Easterly (1980)]


**Type of study**: Literature based study.

**Type of facility**: Twelve fusion reactor reference designs (or parts of them). Here only these ones are quoted for which both, tritium inventory and release rate, are given.

**Tritium inventory**: Between 1 and 16 kg/1GWₑ, see table.

**Emission scenario**: Operational and (briefly) accidental release.

**Scenario A**: Operational release. When information given by the original literature was not sufficient, assumptions (for example: extrapolated values based on fission power experience or reasonable arbitrary numbers) were made to obtain these data needed for the tritium release calculations.

<table>
<thead>
<tr>
<th>Reference design:</th>
<th>UWMAK I</th>
<th>BNL</th>
<th>UWMAK II</th>
<th>PPPL</th>
<th>LASL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net electrical output: (MWₑ)</td>
<td>1473</td>
<td>1605</td>
<td>1710</td>
<td>2030</td>
<td>4132</td>
</tr>
<tr>
<td>Total inventory (kg)</td>
<td>23.50</td>
<td>10.10</td>
<td>17.50</td>
<td>2.58</td>
<td>3.80</td>
</tr>
<tr>
<td>Vulnerable inventory (kg)</td>
<td>13.50</td>
<td>0.13</td>
<td>4.60</td>
<td>0.56</td>
<td>3.80</td>
</tr>
<tr>
<td>Absolute emission: Gaseous: (TBq/day)</td>
<td>0.127</td>
<td>0.263</td>
<td>0.091</td>
<td>0.036</td>
<td>0.004</td>
</tr>
<tr>
<td>Liquid:</td>
<td>0.128</td>
<td>0.000</td>
<td>0.009</td>
<td>0.000</td>
<td>0.096</td>
</tr>
<tr>
<td>Total:</td>
<td>0.255</td>
<td>0.263</td>
<td>0.100</td>
<td>0.036</td>
<td>0.100</td>
</tr>
<tr>
<td>Relative emission: (ppm/a)</td>
<td>10.70</td>
<td>25.69</td>
<td>5.64</td>
<td>13.77</td>
<td>25.96</td>
</tr>
</tbody>
</table>

**Assumptions/Method for deriving radiological consequences**: Not given.

**Radiation dose to the maximally exposed individual (MEI)**: Not estimated.

**Scenario B**: Maximum credible accident suggested by [Draley et al. (1975)]: Liquid metal fire which releases the entire blanket tritium inventory.

**Absolute emission (rate)**: $1.7 \times 10^5$ TBq of tritium as HTO or HT.

**Radiation dose to the maximally exposed individual (MEI)**: Not estimated.

**Conclusions**: “At the present time it is impossible to quantify precisely the emissions of tritium from fusion power plants because fusion reactor development is yet in the experimental stage” (p. 36).

And: “Accidental releases should be rare, if at all, and should make only minor contributions to releases from CTRs [Controlled Thermonuclear Reactors]” (p. 39), reference: [Draley et al. (1975)].

**Main references**: [Draley et al. (1975)].
Publication: [Raskob (1990)]


Type of study: Computer simulation, using the especially developed UFOTRI (Unfallfolgenmodell für Tritiumfreisetzungen) computer code.

Type of facility: Fictitious fusion reactor.

Tritium inventory: Computer calculation.

Emission scenario: Accidental release of gaseous tritium (HT) and tritiated water vapour (HTO) in a height of 10, 20, and 60 m.

Absolute emission (rate): 100 g in 2 minutes.

Assumptions for deriving radiological consequences: —

Method for deriving radiological consequences: Calculations subdivided into two successive parts: (1) Atmospheric transport and dispersion of tritium, based on the Gaussian trajectory model MUSEMET, provided by [Straka et al. (1981)]. Two dispersion categories, defined by [Bultynck/Malet (1972)], differing in wind speed and height of mixing lid. (2) Pathway of tritium in food chains, numerical solutions supported by the COMA (Compartment Model Analysis) computer model, [Shaw/Haywood (1986)]. Sum of doses results from inhalation, skin absorption and ingestion. Organically bound tritium is considered as HTO.

Tabelle 4: Radiation dose to the maximally exposed individual (MEI) at 1 and 60 km distance from source emitting 100 g. Plume centerline doses [Raskob (1990)]

<table>
<thead>
<tr>
<th>distance</th>
<th>1 km</th>
<th>80 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 m</td>
<td>60 m</td>
</tr>
<tr>
<td>release height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt dose: HT 0.093-0.54 mSv 0.02-0.038 mSv</td>
<td>0.0004-0.0018 mSv 0.0002-0.0009 mSv</td>
<td></td>
</tr>
<tr>
<td>HTO 8.8-27 mSv 3.1-4.7 mSv</td>
<td>0.002-0.018 mSv 0.015-0.15 mSv</td>
<td></td>
</tr>
<tr>
<td>Chronic dose: HT 0.62-8.3 mSv 0.14-0.92 mSv</td>
<td>0.003-0.035 mSv 0.0015-0.02 mSv</td>
<td></td>
</tr>
<tr>
<td>HTO 47-310 mSv 16-51 mSv</td>
<td>0.02-0.1 mSv 0.08-0.16 mSv</td>
<td></td>
</tr>
</tbody>
</table>

Main references: [Bultynck/Malet (1972)], [Shaw/Haywood (1986)], [Straka et al. (1981)].
Type of study: Literature based paper.

Type of facility: FCTR (First Commercial Tokamak Reactor) defined by [Spears (1985)].

Tritium inventory: About 5 kg/GWe, extrapolation from experimental reactors. 1.5 kg/GWe of this amount are considered to be vulnerable.

Emission scenario: Normal operation, maintenance and accidental release.

Scenario A: Normal operation and maintenance release.

Absolute emission (rate): Data quoted from [Casini et al. (1985)] (see table on [Edlund (1986)] in this paper). Total atmospheric release: 770 TBq/a (440 TBq/a as HTO, 330 TBq/a as HT), aqueous release of tritium: 55 TBq/a.

Relative emission (rate): 4.46 x 10^-4 per year of total inventory.

Radiation dose to the maximally exposed individual (MEI): 0.01-0.02 mSv/a, 30% of which is due to the aqueous emissions, [Casini et al. (1985)].

It is also established that in a fusion powered world (2000 plants of 3 GW_e each) the effective dose to the population would be 0.2% of the dose due to natural background radiation, [Hancox/Redpath (1985)].

Scenario B: Accidental release. Studies for INTOR and NET found that the release of 100-150 g of tritium as HTO at a release height of 20 m represents the most severe accident (of very low probability of occurrence).

Absolute emission (rate): 150 g of tritium as HTO.

Relative emission (rate): 3% of total, 10% of vulnerable tritium inventory.

Radiation dose to the maximally exposed individual (MEI): Acute dose at 1 km: 25.5 mSv, at 5 km: 3.4 mSv. Doses approximately 30 times lower if the release height is 100 m, all values derived from [Edlund (1986a)].

Conclusions: Routine radioactive emissions of a D-T fusion reactor can be maintained within values producing very small environmental effects. Release due to a most severe accident produces small effects on the environment.

Publication: [Sowerby/Forrest (1990)]

Type of study: Literature based paper.

Type of facility: Two versions of the EEF Reference Reactor, called the standard and the low activation variant. The standard design is given by [Cooke et al. (1989)]. In the low activation variant the main structural materials have been replaced by ones which are less radioactive.

Tritium inventory: Total inventory varies with design but is of the order of 2-10 kg. EEF Reference Design: about 5 kg.

Emission scenario: Operational release. Data for the reference reactor are not available. It is referred to the STARFIRE design, [Baker et al. (1980)] and [Cannon (1983)]. (Qualitative) extrapolation to the EEF reactor.

....... : Absolute emission values and resulting doses are entirely quoted from [Cannon (1983)].

Relative emission (rate): Another example is given: Losses of tritium from the integrated exhaust gas processing loop at TSTA (Tritium System Test Assembly), Los Alamos. Over a four year period of operation of the facility less than 1.48 TBq (or: 40 Ci) of the total Tritium inventory of 110 g were released to the environment. A relative emission rate of $9 \times 10^{-6}$ per year is resulting. References are [Anderson/Bartlit (1989)] and [Coffin (1988)].

Conclusions: Tritium doses (calculated by Cannon) are well below the limit of 5 mSv/a set by the ICRP. The environmental impact of fusion is significantly lower than that of a PWR. Coal-fired stations give much less impact at short times, but in the long run (about 100 years) fusion tends to be similar or more favourable than coal.

"In view of the uncertainties in the models and data used in the study, differences of the order of a factor 10 are significant, but those of a factor 2 should not be given weight".

Publication: [Stasko/Wong (1986)]


Type of study: Computer simulation.

Type of facility: Fictitious fusion reactor.

Tritium inventory: —

Emission scenario: Operational and accidental (or: acute) release.

Scenario A: Operational release.

Absolute emission (rate): Backward calculation, reversed argumentation.

Assumptions for deriving radiological consequences: ICRP recommendations, [ICRP (1978)].

NRC limit for off-site dose: 0.05 mSv/a.

Method for deriving radiological consequences: (1) Simulation, employing ten different computer codes, assuming a release height of 20 m and annual average meteorological data. (2) Experimental data from the Pickering Nuclear Generating Station near Toronto, Canada. Its effective release height is less than 40 m.

Radiation dose to the maximally exposed individual (MEI): (1) For a release of 1.85 TBq/day (50 Ci/day) the computer codes calculate chronic doses between 0.011 and 0.104 mSv/a (at 1 km) with a mean value of 0.042 mSv/a. (2) For a daily release of 1.48-1.85 TBq (40 to 50 Ci) the dose was less than 0.01 mSv/a (0.0045-0.0088 mSv/a, measured during three years, infants and adults treated separately). Under very unfavourable assumptions this dose could be 2 to 3 times higher.
Scenario B: Accidental release.

Absolute emission (rate): 10 g (not indicated here), 100 g and 1000 g of tritium as HTO.

Assumptions/Method for deriving radiological consequences: Computer simulation using the tritium dispersion code PATHWAY, developed at Ontario Hydro (Canada), with following parameters: Puff release of oxidized tritium, open grassland, 5000 m$^2$ building area and unfavourable weather conditions. Three different dispersion categories for the 1 kg-emission scenario.

Table 5: Doses to most exposed individual due to accidental release of tritium as HTO

<table>
<thead>
<tr>
<th>quantity</th>
<th>100 g</th>
<th>1000 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>release height</td>
<td>0 m</td>
<td>60 m</td>
</tr>
<tr>
<td>Distance: 0.1 km</td>
<td>1500 mSv</td>
<td>9.0 mSv</td>
</tr>
<tr>
<td>1.0 km</td>
<td>40 mSv</td>
<td>7.0 mSv</td>
</tr>
<tr>
<td>10.0 km</td>
<td>3 mSv</td>
<td>2.5 mSv</td>
</tr>
</tbody>
</table>

Conclusions: A design target of 1.85 TBq/day (50 Ci/day) for chronic emissions of HTO will provide reasonable assurance that the design target of 0.05 mSv/a (5 mrem/a) for individual members of the public will not be exceeded.

Any facility design that could limit the tritium inventory to approximately 500 g, or could demonstrate the effectiveness of passive barriers which would limit the releaseable tritium to this level, could be considered to be "inherently" safe.

Main references: [Cannon (1983)], [ICRP (1978)], [Piet (1986)].
Publication: [Sumita (1989)]

Type of study: Empirical study.

Type of facility: OKTAVIAN, a rotating tritium target for neutron production.

Tritium inventory: 7.4 or 14.8 TBq.

Emission scenario: Normal operation and maintenance loss.

Scenario A: Normal operation loss, primarily release from the accelerator during normal high-power operation through the evacuation system in the form of tritium gas, THO and/or fine powder of tritium compound. More than 95% of tritium in the evacuated gas through two cascade tritium collection systems. Remaining tritium is released through the stack.

Absolute emission (rate): <5920 MBq/week (loss from target), <296 MBq/week (stack release).
Relative emission (rate): <4.2% per year (loss from target), <0.2% per year (stack release).

Scenario B: Inevitable tritium release during target replacement. The whole target assembly is replaced within a glove box as one block to minimize tritium gas release.

Absolute emission (rate): 2.22 TBq as T₂ gas (loss from target), [Tabuchi et al. (1983)].
Relative emission (rate): 15% (of 14.8 TBq inventory).

Assumptions/Method for deriving radiological consequences: —

Radiation dose to the maximally exposed individual (MEI): “In the past, the levels of tritium inhaled by operators working on target replacement was higher than optimal, though it was well within the permitted level for the health physics control."

Main references: [Tabuchi et al. (1983)].

Type of study: Empirical study.

Type of facility: Sandia National Laboratories Livermore, Tritium Research Laboratory (TRL, Building 968).

Tritium inventory: Maximal inventory (excluding vault): 120 g. The SSNL site inventory could increase to 300 g if programmatic activities demand.

Emission scenario: Accidental losses into glove box, routine and accidental releases to atmosphere.

Scenario A: Accidental discharge of 6 g of elementary tritium (corresponding to $6 \times 10^4$Ci) into a 7.25 m$^3$ glove box. The tritium is assumed to react with water forming HTO.

Absolute emission (rate): Amount diffused in the room: $10^{-5}$ g of tritium ($6.8 \times 10^{-5}$ g HTO), calculated value.

Relative emission (rate): 1.67 ppm.

Assumptions/Method for deriving radiological consequences: Not given.

Radiation dose to the maximally exposed individual (MEI): Not estimated.

Scenario B: Sub-publication [Devlin (1976)] discusses routine releases of airborne tritiated water to the Livermore-Amador Valley (before the full-operational phase of TRL at Sandia). The main contributors are building 331 at the Lawrence Livermore National Laboratory (LLNL) and the TRL, which is immediately adjacent to LLNL.

Since it is mentioned that all tritium activities will be moved to the (new) TRL at Sandia, it is supposed that the total inventory of 120 g (or: 300 g) was distributed among all LLNL sites before.

Absolute emission (rate): Total release from all LLNL sites: 92.5 TBq (1973), 70.3 TBq (1974), and 125.1 TBq (1975, increase due to improved sensitivity of stack monitoring).

Relative emission (rate): 0.28% per year of 120 g inventory (for the latter value), 0.11% per year of 300 g inventory.

Assumptions/Method for deriving radiological consequences: Not given.

Radiation dose to the maximally exposed individual (MEI): Concerning tritium concentrations it is stated that average annual background concentrations are comparable to natural background levels (which leads to the conclusion that the effect of LLNL releases is not measureable).

Scenario C: Accidental release of the maximum quantity of tritium from all of the apparatus in the facility.

Calculations were based on a release height of 30 m and different (especially: worst) weather conditions.

Absolute emission (rate): 120 g at once.
**Assumptions/Method for deriving radiological consequences:** Plume dispersion and ground level concentrations were principally calculated by [Briggs (1969)], [Peterson et al. (1976)], and [Slade (1968)]. For determining several biological parameters some additional literature was used, especially [NUREG (1977)] for the calculation of the dose conversion factors.

**Tabelle 6:** Individual and collective doses due to an accidental release of 44400 TBq (1.2 MCi) of tritium. Width arising from different weather conditions the (median and 95%-percentile, wet and dry season)

<table>
<thead>
<tr>
<th>Release as:</th>
<th>Site boundary</th>
<th>Nearest neighbour</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTO</td>
<td>8.00-53.00 mSv</td>
<td>5.00-38.00 mSv</td>
<td>0.10-1.26 man-Sv</td>
</tr>
<tr>
<td>$T_2$</td>
<td>0.023-0.130 mSv</td>
<td>0.013-0.095 mSv</td>
<td>0.25-3.15 man-Sv</td>
</tr>
</tbody>
</table>

**Conclusions:** “Based upon the analysis in this report, we conclude that the Tritium Research Laboratory can be operated without undue risk to employees, the general public, or the environment” (p. 7 of the afterwards added answers to the review comments made by the Director of the Operational Safety Division).

**Main references:** [Briggs (1969)], [Devlin (1976)], [NUREG (1977)], [Peterson et al. (1976)], [Slade (1968)].

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gnificance for Transnational Cooperation in Western Europe“

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