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# Safety and Environmental Aspects of Deuterium-Tritium Fusion Power Plants: Work Shop Summary

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and

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## ABSTRACT

In September of 1977 a workshop was held on the safety and environmental aspects of fusion power plants to consider potential safety and environmental problems of fusion power plants and to reveal solutions or methods of solving those problems. The objective was to promote incorporation of safety and environmental protection into reactor design, thereby reducing the expense and delay of backfitting safety systems after reactor designs are complete. A dialogue was established between fusion reactor designers and safety and environmental researchers.

Four topics, each with several subdivisions, were selected for discussion: radiation exposure, accidents, environmental effects, and plant safety. For each topic, discussion focused on the significance of the problem, the adequacy of current technology to solve the problem, design solutions available and research needed to solve the problem.

Each problem discussed appears to have a solution, either through reactor design, choice of reactor materials, or preventive or controlling safety systems. Though the workshop discussed environmental and safety problems of fusion reactors, a positive message was given in conclusion. Fusion provides a means of using an inexhaustible, low cost supply of fuel. Fusion does not intrinsically require fissile materials or produce radioactive by-products. The fusion process allows selection of reactor materials to ensure minimum radiation hazards. No poisonous chemicals are produced.

## FOREWORD

Nuclear fusion has the potential for providing a source of energy which can use abundantly available fuel and have minimal environmental impacts. Realizing this potential poses difficult physics and engineering challenges which are being addressed by major research and development programs in the United States and abroad. Various projections estimate the demonstration of commercially viable fusion energy systems near the turn of the century, but subsequent use of fusion energy will depend on the rate of deployment of the new technology. Recent history shows that the deployment of new technologies can be a lengthy and costly process affected by many factors. Among the most important of these factors are environmental and safety issues associated with the technology and the degree to which widely acceptable solutions for these issues are available. Although fusion has the potential for attractive environmental and safety characteristics, early and sustained effort must be applied to assure that this potential is realized and that the ultimate deployment of the technology is not frustrated by unanswered environmental and safety concerns.

Because of the importance of this deployment issue, the Office of Fusion Energy of the U.S. Department of Energy and the Electric Power Research Institute have cooperated in jointly sponsoring a workshop on the environmental and safety aspects of fusion power. This workshop, described in the attached proceedings, was the first step in bringing environmental and safety analysts together with fusion reactor designers. The early and continued interaction between these groups and the integration of appropriate safety and environmental considerations into conceptual and engineering plant designs at an early stage will assure these issues are resolved as an essential part of fusion technology development. This can be a significant contribution to the ultimate deployment of fusion energy as a commerical power source.

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# INTRODUCTION AND SUMMARY

The Workshop on the Safety and Environmental Aspects of Fusion Power Plants was held in Seattle, Washington, on 14-15 September 1977. The objectives were to establish a dialogue between fusion reactor designers and safety and environmental researchers, to identify the primary environment and safety concerns which might be unique to fusion power plants, to transfer safety and environmental information between the laboratories involved, and to reveal research and development directions which will assure an adequate and timely safety technology base. The participants represented all the major fusion laboratories in the United States. Their expertise includes design of tokamak, mirror, and inertially-confined fusion reactors; fission reactor safety; physics and engineering aspects of safety and environmental protection; and biological sciences. This diversity of disciplines provided an effective forum for discussion of the major safety and environmental issues which might be associated with fusion power plants, and potential design solutions to these problems. The workshop was jointly sponsored by the United States Department of Energy's Office of Fusion Energy and the Electric Power Research Institute. The joint sponsorship represents a landmark in cooperation between these two organizations, which is an indication of the consideration being given to safety and environmental research.

This workshop is probably the first time that safety and environmental aspects of a new technology have been considered and incorporated into program planning and design so early in the technology development. Such a meeting was felt to be appropriate now for several reasons. First, several reference designs have been developed in the last few years.(1-6) From these designs, an integrated picture of the characteristics of a practical fusion power plant will be developed and some of the engineering problems will be identified which must be solved before such a power plant is built. Based primarily on these reference designs, surveys have been completed recently which attempt to identify the major safety and environmental concerns of fusion power plants if they were to be built as they are currently perceived.(7-11) Using the results of these surveys, interaction between safety and environmental researchers and power plant designers is the appropriate next step before the next iteration of design concepts. This workshop is intended to be a mechanism for establishing contacts for that interaction.

Second, several laboratories have begun to consider integrated designs of experimental fusion reactors that will be built during development of fusion as a commercial power source. In each stage of development, a reactor will be constructed which is succeedingly more prototypic of a commercial reactor. Design decisions being made now for early experimental reactors are likely to influence the characteristics of the later power plants. The long lead time required to develop new technologies causes early design characteristics to continue in succeeding reactors. Two examples of this are the tendency to design with steel blanket materials and water coolants. These materials are considered primarily because their technology is well developed. The time required to develop technological alternatives is apparently greater than the designed lead time of a single facility, so each generation of reactors relies on technology established for preceeding facilities. A base technology program, influenced by safety and environmental considerations, may result in establishment of more attractive design alternatives for later facilities.

Historically, safety and environmental concerns have been considered only after a functional design has been completed. This has often led to long, unnecessary delays while environmental protection and safety systems are fitted into an existing design. Considering safety and environment in the early stages of reactor design may provide systems which are better and more fully integrated into the design and reduce the number and duration of delays and the amount of backfitting later on.

Topics discussed at the workshop are listed in Table 1. A fifteen-minute overview of each topic was presented by one of the participants, followed by an open discussion directed toward identifying the key safety and environmental issues and the kinds of design solutions available to mitigate the hazards that might be associated with these issues. For each topic, the discussion considered four questions:

1. What is the safety and environmental significance of the topic?

2. Is current technology adequate to ensure that the degree of risk is within acceptable levels?
3. What design solutions are available to mitigate the effects?
4. Where should future research and development be concentrated?

The primary purpose of the workshop was to establish communications between the various research groups engaged in fusion reactor design and safety and environmental studies. Based on this objective, it was a useful gathering. The safety and environmental researchers were given an opportunity to express their concerns to a technical audience which included reactor design teams as well as representatives of other safety and environmental groups. The researchers obtained a better perspective of the relationship of each activity to safety and environmental protection and the interaction between this discipline and fusion reactor design. The designers were informed of safety and environmental concerns, and were given the opportunity to describe the bases for design choices and safety control and prevention concepts. The interaction at this stage of development should promote a better understanding of the proper role of safety and environmental research in reactor development and ensure that neither discipline progresses along a path which is incompatible with the other.

The greatest hazard to safe fusion reactor operation is radiation exposure from the utilization of the deuterium-tritium fuel cycle. This includes exposure to the radioactive tritium itself, neutrons and gamma radiation produced in the fusion reaction, and the radioactivity induced by fusion neutrons interacting with reactor materials. The greatest potential source of routine plant exposure is tritium leakage from reactor fuel systems. The rate of release in real systems should be characterized by experiments to be performed in the Tritium Systems Test Assembly, currently being designed for construction at Los Alamos Scientific Laboratory. Tritium decays by soft beta emission, so it represents a significant radiological hazard only if it is ingested. The hazard of tritiated water is therefore much greater than that of tritiated hydrogen gas.

Neutron activation of blanket and structural materials may result in very high radioactivity levels. The activation properties of different materials vary over a very broad range. Careful choice of materials can greatly reduce the radioactive waste storage problems, and possibly permit contact maintenance after about a one week cool-down period. It was suggested that a vigorous materials

TABLE 1. Discussion Program

| | | |
|---|---|---|
| September 14 | | |
| | 9:00 a.m. | Welcome |
| | 9:15 a.m. - 12:00 | Radiation Exposure |
| | | A. Tritium |
| | | B. Activation Products |
| | | 1. Blanket and Structures |
| | | 2. Corrosion Products |
| | | 3. Air |
| | 1:15 - 5:30 p.m. | Accidents |
| | | A. Liquid Metal Spills |
| | | B. Magnet Safety |
| | | C. Power-Flow Mismatch |
| | | D. Hydrogen and Tritium Accidents |
| | | E. Plasma Disturbances |
| | | F. External Hazards |
| September 15 | | |
| | 9:00 a.m. - 12:00 | Environment |
| | | A. Tritium |
| | | B. Magnetic Fields |
| | | C. Natural Resources |
| | | D. Radioactive Waste |
| | 1:30 - 4:30 p.m. | Plant Safety |
| | | A. Safety Criteria |
| | | B. Safety Instrumentation |
| | | C. Maintenance and Operation Requirements |
| | 4:30 p.m. | Summary, Conclusions and Recommendations |

technology program can permit the use of low activation materials rather than stainless steel by the time commercial reactors are built. Besides activation of stationary blanket materials, activated mobile fluids, including corrosion products and reactor building air, may complicate reactor maintenance.

It is desirable to examine the potential for accidents that may result in release of either large amounts of energy or potentially hazardous materials so that such accidents can be either eliminated through various design options or systems can be provided to mitigate them and to determine the associated safety risk. Examination of events leading to major hypothetical accidents and their possible consequences is necessary to guarantee that they cannot occur, or that the consequences can be controlled. Even though the likelihood of such accidents may appear remote, the consequences may be so severe as to warrant an exacting mechanistic analysis. There is no existing data base on which to develop reliability information for reactor systems in a fusion environment, so all the accident analysis is presently done in a mechanistic manner. To evaluate the consequences of a given event, accident initiation is assumed independently of its actual probability of occurence. Possible pathways for progression of the accident are investigated to determine the maximum credible release of energy or hazardous materials. Even if such a release were to occur, it is likely that the primary hazard would be to plant personnel and not to the general public, since the building itself would offer partial or complete resistance to dispersal in the environment outside.

The accidents with the greatest potential for release of energy or hazardous materials appear to be liquid metal spills, superconducting magnet failures, loss-of-flow/loss-of-coolant type accidents, and hydrogen explosions. An analogy was drawn between liquid sodium-concrete fires analyzed for fast breeder reactors and liquid lithium-concrete fires which might occur with fusion reactors. Much of the liquid sodium technology should apply to liquid lithium, so that many engineering safety features which are effective for liquid metal fast breeder reactors should be effective for liquid metal-cooled fusion reactors.

Superconducting magnet safety experience is very limited. Superconducting magnets built to date have been much smaller and simpler than those required for tokamaks, have very little operating time, and so far have experienced high failure rates. An active research program is in progress to identify magnet faults and design safety systems. Electrical breakdown and magnet quench probably have the greatest potential for severe consequences.

Accidents resulting from a lack of adequate cooling ability, such as loss-of-flow and loss-of-coolant scenarios, may lead to release of hazardous materials. Blanket loss-of-flow may be important only during power operation in a pure fusion reactor, but in a fusion-fission hybrid reactor, it may be a problem even with the power off. This appears to be a more serious hazard for the divertor in a lithium-cooled pure fusion tokamak than for the blanket. Under worst-case conditions the first wall or divertor might melt, leading to serious consequences. In either case, however, melting would result in plasma quench, terminating the rapid heating of the coolant.

Fires and explosions are fairly common in industries which handle large amounts of hydrogen. Release of hydrogen to air, either as an accident initiator or as a consequence of another accident, may result in explosions under certain conditions. Safety systems must be designed to prevent, detect, and suppress explosions resulting from the release of deuterium and tritium in the fuel system.

The four environmental interactions which are peculiar to fusion power plants and represent potentially significant environmental effects are tritium releases, magnetic fields, natural resource use, and radioactive wastes.

A considerable body of information exists in the literature on atmospheric and ecological transport of tritium. The integrated dose to the public as a result of even large accidental tritium releases seems small. A number of unknowns still exist, however, in the characterization of routine long-term tritium releases.

The biological effects of magnetic fields are very poorly understood at the present time. No chronic effects have been positively identified, and only minor acute effects have been reported. An integrated research program is underway to determine the biological significance of magnetic fields.

Early conceptual designs of commercial fusion power plants utilize substantial fractions of the world's known resources of certain materials. Designs now being developed, however, significantly reduce the materials requirements. No materials considered as alternatives for those identified as scarce in the early designs would be a problem compared to world reserves when proper design considerations are made.

A similar condition exists for blanket materials with respect to environmental considerations of radioactive waste disposal. Blanket material choices result in decay time ranging from weeks to millenia. Use of low-activation materials could reduce by several orders of magnitude the radiation doses due to handling of blanket wastes, and even permit recycling of the blanket materials after decay.

Assuming that safety licensing will be required for commercial fusion reactors, it will be necessary to develop a framework of design codes and standards. Emphasis during the design stage should be placed on accessibility when developing fusion reactor safety criteria, to ensure minimum radiation exposure to plant personnel. Lower inventories of radioactive materials and less severe design basis accidents should permit relaxation of some criteria when compared to those for fission reactors. Recognizing the inherent conservatism of safety licensing organizations, it is likely that, without a concerted effort from within the technical fusion community to establish a uniform framework for fusion standards, safety criteria would evolve from the existing fission safety review structure, with the burden of proof resting on the fusion community to justify less restrictive criteria. Applying fission standards to fusion seems somewhat arbitrary, so the preferable approach would be to begin soon to develop a consistent code of design standards that address the unique characteristics of fusion power plants.

Although many safety and environmental concerns were discussed at the workshop, no insurmountable problems were revealed. Each of the problems discussed appears to have an acceptable solution either in reactor design, choice of material, or preventive and controlling safety systems. Tritium release will be minimized on the basis of better understanding of its permeation and leakage properties. Radiation exposure will be reduced either by judicious choice of reactor materials or by utilization of remote maintenance techniques. Liquid metal spills can be mitigated either by vacuum containment, steel lining of concrete structures, or rapid fire extinguishment. Safe magnet systems will be provided through engineered safety features during the development of large superconducting magnets. Depletion of natural resources and radioactive waste management will be alleviated by careful choice of materials and engineered safeguards.

The environment and safety assessment work done to date has focused on the potential impact of commercial fusion reactors as they are currently perceived. This perception is based on a small number of conceptual designs. The scope of these designs was limited to providing a plausible integration of the necessary power plant subsystems for technological reference. Safety concerns did not represent a primary focus. Although these designs represent the best current projection of the characteristics of a commercial fusion reactor, it is doubtful that a reactor will actually be built according to any of the existing designs. The reference designs only represent a current best guess; they are projections based on existing technology and anticipated progress. Fusion technology will evolve between now and its commercialization period. Since the first reference design studies done in 1974-76, there have already been a number of substantial advances in technology which should affect reactor design. Among them are indications of favorable plasma stability scaling with high plasma beta and better first wall radiation resistance, both suggesting more compact reactors; better tritium control technology; vacuum outer containment; reactor blanket modularization; and remote maintenance concepts. This workshop itself should have some impact on the course of future reactor design, thereby effecting change in the safety and environmental impact.

Even in areas where significant safety and environmental hazards might be possible, a range of alternative concepts are available to mitigate them. There are alternative confinement concepts available for fusion reactors: tokamaks, mirrors, inertial confinement, and a number of other alternatives. There are alternative materials which may be chosen for reactor structures, coolants, and breeding materials. Finally, there are other fuel cycles available to fusion, such as deuterium-deuterium and protium-boron. Some of these "advanced" fuel cycles require no tritium or other radioactive material at all, and would induce no other radioactivity, since they produce no neutrons. These advanced fuels would, if feasible, eliminate the need for tritium or lithium or even the need for thermal energy conversion. At this stage of fusion technology development, it would be desirable to continue to explore a variety of these options.

Although the fusion and fission processes have little in common, they both utilize nuclear energy for electrical power production. Deuterium-tritium fusion requires a radioactive material for its fuel, and produces considerable radiation in the plasma, the blanket, and the surrounding building. There is a large body of existing experience with radiation, its effects on materials and biological entities, and its safety assurance in the fission industry. This experience should represent a substantial technical data base for the fusion industry to draw upon.

The role of safety and environmental research in the development of a new technology is a peculiar one. It is often perceived as hindering progress toward a technically promising system; occasionally an otherwise ingenious design concept is rejected because of the safety and environmental consequences of a very unlikely event. At best, it often appears to dwell on the negative aspects of design, concentrating on the possibility that a system will not operate as designed--that things will not happen as planned. It seems to be a pessimistic pursuit when performed in isolation.

Safety and environmental research does not have to be such a gloomy mission. The objective of the national fusion program is to develop and demonstrate the production of commercial electrical power based on the nuclear fusion process in a manner which will meet environmental, health and safety requirements. As such, safety and environmental research is an integral part of technology development. Performed in coordination with system design, its purpose is to identify potential problems with design concepts, and to cooperate with other design disciplines in exploring acceptable solutions, so that safe, reliable systems can be developed and demonstrated. This coordination will lead to an optimistic approach to safety and environment - to the idea that, through judicious engineering, safety and environmental aspects can be fundamental elements in the design process.

In reviewing the potential safety and environmental concerns for fusion power plants, negative aspects have been revealed. A balanced perspective can be better obtained by enumerating some of its more positive aspects. Exploitation of the fusion process will provide a means to utilize an effectively inexhaustible supply of fuel for energy production which can be available at very low cost to all countries in the world. Major release of radioactive materials to the environment due to nuclear excursion and loss-of-coolant flow accident is not possible in a well-designed fusion reactor. The biological hazard due to radionuclides present in a fusion reactor is much less than that of fission products and plutonium. A fusion power plant would not require fissile materials--a fact that should ease nuclear proliferation concerns. Finally, release of chemicals from the fusion fuel cycle should be very low. The fusion reaction produces no chemical combustion products at all.

## SESSION 1: RADIATION EXPOSURE

Participants: J. M. Mintz - Chairman
J. L. Anderson
J. R. Powell
T. J. Kabele
H. J. Willenberg

Various sources of radiation exposure, both for operating personnel and for the general public, are possible in an operating fusion facility. The goal of the first session was to identify these sources, to explore their effects on plant operation, and to discuss appropriate methods for dealing on a routine basis with any hazards to personnel. Where appropriate, research and development needs and areas requiring further design efforts were noted. The discussion covered tritium, blankets and structures, corrosion products, and air activation.

### TRITIUM

Tritium (T) is a radioactive isotope of hydrogen which decays by emitting a soft beta particle ($\bar{E}$ = 5.7 keV, $E_{max}$ = 18 keV) and no gamma ray, and is therefore a significant radiological hazard only if ingested. Since $T_2$ is virtually insoluble in human tissue (about 98% of $T_2$ inhaled is immediately exhaled), it is relatively innocuous. Tritiated water ($T_2O$, HTO or DTO), however, is a much greater hazard. The maximum permissible concentration (MPC) value for tritiated water is 0.2 $\mu Ci/m^3$ (uncontrolled area), 1/200 of the comparable value for $T_2$.

Research and development is therefore required for tritium monitors capable of discriminating between molecular tritium and tritiated water and of accurate real-time measurement of tritium concentrations on the order of 0.1 $\mu Ci/m^3$. Without this development, all tritium detected in the facility atmosphere must be assumed to be tritiated water. Such an assumption will decrease design and operational flexibility and increase costs.

Tritium released as $T_2$ is converted to tritiated water (mostly HTO) at a rate that is a strong function of many environmental parameters (e.g. surface conditions, air temperature and humidity, etc.). Because emergency detritiation component sizing, both normal and off-normal detritiation scenarios and possibly exposures to the general public are affected by these rates, it was suggested that an experimental program aimed at obtaining conversion rates under realistic reactor hall, tritium facility and external environmental conditions be undertaken. If conversion rates in the fusion facility prove uncomfortably high, surface conditioning and/or other methods of reducing them should be investigated.

In-plant tritium releases during normal operation would primarily result from leaks, particularly around valves, greatly exceeding contributions from permeation. One cause of leaks is the damage to elastomeric seals resulting from tritium exposure. The identification of tritium-resistant materials should proceed. For maintenance purposes, every tritium handling component should be designed so it can be purged. Components contaminated by tritium alone, however, do not require remote maintenance; a combination of glove boxes, plastic tents and bubble suits with independent air supply will be adequate for maintenance operations.

Some discussion of tritium releases to the environment did occur. The point was strongly made that care must be taken not to lock in on unrealistically low release goals based on reasonally achievable levels in experimental devices. In particular, the projected releases of TFTR (high population zone, very low inventory, no tritium processing) and of TSTA should not be arbitrarily applied to succeeding generations of fusion reactors which will likely have much larger inventory and processing requirements.

## BLANKET AND STRUCTURE ACTIVATIONS

D-T fusion reactors, as copious sources of neutrons, will activate structural, blanket and shielding materials, with profound effects on overall machine design, operational planning, and costs. In particular, maintenance operations on components within or proximal to the fusion device will be affected. For devices employing stainless steel or niobium structure, substantial remote maintenance capability was agreed to be necessary. Because most near-term concepts project the use of stainless steel, a substantial effort directed at developing the requisite remote maintenance capability is perceived to be necessary. Remote maintenance problems are being studied vigorously for TFTR and many of the solutions developed for that facility are expected to have applicability for future devices.

The use of aluminum structure with solid breeding materials for advanced reactors was suggested as a way to greatly reduce maintenance problems. Possibly (though there was disagreement on this point) the need for fully remote maintenance capability could be eliminated by proper choice of materials. The minimum activity blanket design of Brookhaven National Laboratory was cited as an example. For this design, the total specific activity for an aluminum structure was calculated to be a factor of $10^6$ lower than for a comparable steel structure. Impurities were found to be the major contributors to the activation. Unresolved problems affecting the feasibility of aluminum use include uncertainties about the effects of irradiation, including helium formation, on the mechanical properties of aluminum and the questionable sufficiency of the data base for aluminum to allow its confident use in near term machines.

Other low activation materials, such as graphite and silicon carbide, were also suggested as possible major constituents of fusion reactor blankets and structures.

## CORROSION PRODUCTS

Since most activated materials in a fusion device are formed in components and structures that are actively cooled, the transport of activated corrosion products throughout the coolant system must be considered. Among the possible consequences of this transport are: heat transfer fouling; heat exchanger tube and instrument line plugging; and fouling of tritium extraction components. Maintenance operations to relieve these conditions or for any other reason would be complicated by a high corrosion product activity.

The amount and specific activity of corrosion products generated will depend strongly on the coolant system structural material and the coolant itself.

The worst case discussed involved a stainless steel structure and lithium coolant, such as proposed for UWMAK-I. For UWMAK-I an estimated 2500 kg/yr of corrosion products would be transported around the primary coolant loop. To illustrate the implications it was noted that a dose of 1-15 R/hr near certain coolant system components in FFTF is estimated to result from a corrosion transport rate a factor of $10^3$ lower. Other coolants found to have the potential for moderate to large activity transport (either by being corrosive or by direct activation) included Na, flibe and $H_2O/D_2O$. Organic coolants would transport little activation and helium virtually none. The discussion strongly favored helium as the preferred coolant for this reason, although it was brought out that other factors, such as bred tritium recovery rates, may influence this position.

## AIR ACTIVATION

Activation of reactor hall air constituents by neutrons penetrating the primary shield of an operating fusion device is a potential safety problem that has been largely neglected heretofore. The total activity produced (mostly $^{41}$Ar), while small, presents a hazard to plant personnel because of its mobility. Fortunately, the short half-life (1.83 hr) of $^{41}$Ar and the small amounts produced make it a minimal hazard to the general public. Results were presented which indicated an $^{41}$Ar concentration still five times the occupational MPC (for a tokamak) 24 hours after shutdown. Rapid changing of the reactor hall air would reduce the time to reach the MPC but the likelihood remains that entry into any part of the reactor building (not just the reactor proximity) would be delayed for several hours. An unrelated, but significant, source of $^{41}$Ar could exist if the plasma is shut down by the addition of Ar. $^{41}$Ar introduced into the fuel cycle would become a concern for the tritium systems designer.

Implications of $^{14}$C production ($^{14}$N(n,p)$^{14}$C) were briefly discussed. In this case, the 5730 yr half life and the pervasiveness of carbon in living organisms make the possible buildup of $^{14}$C a concern for the long term. A production rate of approximately 35 Ci/day was estimated.

Several options for dealing with air activation were discussed. One approach would remove the air being activated, for example, by evacuating the building (or reactor cell) entirely or by substituting a helium atmosphere.

Another would eliminate most neutrons by tight fitting shielding. Another would be to simply wait out the decay of $^{41}Ar$, accepting the possible addition of a few hours to the downtime. The possibility of stripping argon from incoming air was also mentioned, but was quickly dismissed as uneconomical.

## SESSION 2: ACCIDENTS

Participants: W. E. Kastenberg - Chairman
L. D. Muhlestein
J. R. Powell
A. Z. Ullman
J. M. Mintz
V. L. Teofilo

Examination of the accident potential in conceptual fusion power plants requires answering two questions:

1. Are there mechanisms for releasing or volatilizing potentially hazardous materials?
2. Are there mechanisms for violating containment?

Because fusion power reactors are still in the conceptual design stage, detailed accident analysis is not possible. However, potential accidents in conceptual reactor designs should be examined so that they can be prevented in actual designs through either design option or provision of a system to mitigate them, and so that residual risk to the public can be estimated.

The discussion of accidents focused on six aspects of fusion reactor safety: liquid metal spills; magnet safety; power-flow mismatch; hydrogen and tritium accidents; plasma disturbances; and external hazards.

### LIQUID METAL SPILLS

The consequences of a lithium spill are of major concern for a lithium-cooled fusion power plant blanket. The safety objectives, should a lithium spill occur, are to contain any released radioactivity within the plant, limit physical danger to personnel and limit physical damage caused by the spill. Experimental programs for sodium-concrete and sodium-steel-concrete interactions, in support of LMFBR safety, are available to illustrate methods for treating lithium spills. The likelihood of serious lithium spills can be reduced by utilization of a number of safety features, such as maintaining an inert atmosphere outside the lithium loops and providing double-walled piping.

Three major considerations determine the extent of damage caused by a lithium spill. The first is the condition of the spill area. The atmosphere (inert or noninert), the surface (protected or bare concrete), and whether or not a collection device, fire extinguisher, and materials capable of reacting with the lithium are present, determine the severity of the spill. Second, the type of spill is important. The total lithium inventory available and the radioactive and nonradioactive products available, plus the size of the spill (a leak, a heavy spray, or a large pool) define the type of spill. The temperature of the spill is also significant: whether the lithium is spilled below and remains below reaction temperatures, is spilled below but is heated above reaction temperature, or is spilled above reaction temperatures affects the degree of hazard.

The major radiation release occurs by coagglomeration of activation products with lithium. By controlling the lithium spill, radioactivity is controlled. To this end methods must be developed to control lithium spills and to contain lithium aerosols.

Major research projects in the following areas are suggested:

- Activation Product Coagglomeration
- Lithium-Concrete Reactions
- Lithium-Material Reactions
- Lithium Spill Extinguishment
- Lithium Aerosol Behavior
- Lithium Air Cleaning Concepts
- Water/Gas Release from Concrete
- Hydrogen Formation
- Liner Concepts
- Use of Sodium Safety Analysis Codes

Many of these areas are, in fact, planned for investigation in the current program at HEDL.

## MAGNET SAFETY

Magnet safety will be receiving significant attention during the research, development and demonstration of magnetically-confined fusion power reactors.

Components of magnet safety analysis are: collection and evaluation of safety data; performance of safety analysis and risk assessment; and development of guidelines for design, construction and operation of fusion magnet systems.

Present experience is limited to shorter operating times, smaller and simpler magnets and simpler safety systems than full-scale reactors will use. Failure rates have been relatively high in existing superconducting magnets, particularly for repair and subsequent operation. Thus the safety and reliability of fusion magnet systems cannot be judged directly based on experience with existing systems; it will be several decades before meaningful statistics can be derived from operation of fusion magnets.

For now, safety and reliability assessments for fusion magnets must be based on theoretical analyses and design safety factors. The major concerns of magnet systems relative to personnel safety include:

- Joule heating within a magnet or conductor sufficient to vaporize material.
- Sudden helium vaporization from heating resulting in destructive rupture of the helium coolant system.
- Thermal stress ruptures of magnets.
- Electric arcing with material vaporization and generation of high temperature flying material.
- Generation of eddy currents and stray electric fields.

As a result of magnet safety studies at BNL, various engineered safety features can be envisioned for these systems; these are shown in Table 2.

The major safety RD&D programs should include:

- Identification of potential accident initiators; whether they originate in the magnet or external to the magnet.
- Development of generic accident pathways and consequences using event trees or fault trees.
- Evaluation of safety systems by comparing alternate safety system options and examining performance requirements.
- Analysis of selected accident pathways, both mechanistic and probabilistic.

- Analyses of proposed magnet designs with integrated safety systems through:
  - Identification of potential failure modes;
  - Examination of design modifications; (additional safety systems or changes in design criteria); and
  - Analysis of interactive aspects with other reactor systems [blanket, etc.].

TABLE 2. Engineered Safety Features for Fusion Magnets

| Type of Engineered Safety Feature | Function |
|---|---|
| Detection systems | • Detect local hot spots in coil<br>• Detect lead overheating and failure<br>• Detect arcs in coil<br>• Detect loss of coolant or flow<br>• Detect excessive strain or movement |
| Temperature equilibration systems | • Drive all conductors normal early in a quench<br>• Remove coolant rapidly |
| Energy removal systems | • Dump coil energy in external resistance |
| Energy dispersion systems | • Prevent excessive local deposition of coil energy |
| Containment systems | • Prevent or minimize coil disruption consequences if coil winding fails |

## POWER-FLOW MISMATCHES

Power-flow mismatches describe events in which there is a lack of adequate cooling ability. In the fusion power reactor blanket, there are three general types of power-flow mismatch: a) overpower, with coolant flow at nominal flow rate, b) nominal power, with loss of coolant flow or loss of coolant due to pipe rupture, and c) after-heat or decay power with loss of coolant flow or loss of coolant due to pipe rupture.

To design a reactor which minimizes danger of power-flow mismatches, several questions need to be answered:

a) In what way can normal operations be disrupted?

b) What are the potential consequences of such a disruption?

c) How long does one have to detect the disruption and take corrective action?

d) What design changes or options could reduce the potential consequences or enhance one's ability to deal with the disruption?

A recent EPRI-sponsored program at UCLA has provided a preliminary assessment of a number of potential safety risks associated with fusion reactor designs. In particular, studies have been conducted for various postulated power-flow mismatch conditions; a particular goal was establishment of the characteristic time until, and the mode of, reactor failure. Published results available at EPRI[11-13] describe

- Loss-of-Flow Accidents (LOFA)
  a) Divertor LOFA: UWMAK-I lithium cooled plate
  b) First wall LOFA: LASL wetted wall LCTR
- Loss-of-Coolant Accidents (LOCA)
  a) Helium cooled hybrid
  b) Lithium cooled laser hybrid
  c) Modularized blanket design
- Heat Removal System Failure
  a) Steam ingress accident.

Power-flow mismatch analysis for fusion reactor designs should answer the following question. Are the consequences of a power-flow mismatch sufficiently great that: a) an auxiliary cooling system is needed? b) a redundant design is needed? or c) substantial design modifications are needed?

## HYDROGEN AND TRITIUM ACCIDENTS

A major concern is the explosive nature of hydrogen and its potential for releasing tritium. Hydrogen contains a great deal of potential energy; it contains 60,000 Btu/lb versus 20,000 Btu/lb for gasoline and 17,000 Btu/lb for dynamite. There is a 90% chance that hydrogen leaks will ignite spontaneously under certain conditions. Hydrogen will auto-ignite at 585°C.

The various design solutions suggested are:

- Use of surge volumes and/or rupture discs
- Double walled, inert atmosphere tritium transfer lines
- Explosion proof electric motors and coated wires in tritium facility buildings
- $H_2$ detectors, 1-1/2% turn-off source and sprinkler initiators
- Limit combustibles
- High hazard volumes - halon ($CBF_3$) explosion suppressors

The advantages and disadvantages related to the use of an inert atmosphere will have to be resolved.

## PLASMA DISTURBANCES

A potential safety issue which has not been addressed in detail is the effect of plasma disturbances on safety. Plasma disturbances can be categorized into instabilities (magnetohydrodynanmic, anomalous, or thermal); operational disturbances; and disturbances to auxiliary systems (impurity buildup, neutral injection beams, ohmic heating coils).

The various instabilities are not considered potential safety hazards in themselves. However, they may initiate other system malfunctions. Thermal instabilities may result in power overshoots with resultant power-flow mismatch. Plasma thermal energy dump to the first wall may result in overheating and vacuum failure.

Operational questions have not yet been examined in great detail. The effects of system interactions, whereby an auxiliary system malfunction causes a plasma disturbance, may be a potential serious accident initiator. Since the plasma carries a large current, and is therefore part of the magnetic field configuration, a plasma disturbance may initiate sudden changes in the magnet system.

## EXTERNAL HAZARDS

External hazards can initiate accidents as well as lead directly to release of hazardous material. The major external hazards are: earthquake, tornadoes, floods, aircraft impacts, turbine missiles, tidal waves caused by hurricanes, missiles caused by hurricanes and tornadoes, and deliberate human acts.

Seismic design is of particular concern for fusion power plants. Thin-walled systems are likely in the vacuum dewars, cryogenic coolant dewars, in piping and first wall structure, and in the magnet windings. In addition, remote handling requirements may require quick-releasing pipe connectors instead of welded joints. These factors may require changes in the Seismic Class description adopted for fission power reactors.

Flooding will be of great concern for liquid metal cooled fusion power reactor blankets. The inventory of lithium in UWMAK-I is almost an order of magnitude greater than the sodium inventory in a power-equivalent LMFBR.

## SESSION 3: ENVIRONMENT

Participants: J. R. Young - Chairman
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W. Price

The session on the environmental effects of fusion power plants sought to define the significant changes in the environment which might be caused by fusion power plant construction and operation, and possible means to reduce or eliminate the adverse changes. First the general interactions with the environment were reviewed to determine the most significant ones. The four most significant impacts (tritium releases, magnetic field effects, natural resource utilization, and radioactive waste disposal) were determined; these are described and discussed in detail.

### General Interactions with the Environment

There are sixteen interactions between a power plant and the environment. Those interactions for a fusion power plant and their significance, are summarized in Table 3. A significant interaction is defined as one that could cause a larger impact than construction of a comparable-sized fossil or fission power plant or one that may be considered significant by opponents or licensing bodies.

This summary shows that most of the interactions probably will be trivial or comparable to those of fossil or fission power plants of the same capacity. Those interactions were not discussed further because research for current thermal power plants should adequately identify methods for reducing the effects if reduction is desirable.

### TRITIUM

There will probably be kilogram quantities of tritium ($T_2$) in the first generation of fusion power plants located in the reactor blanket, cooling systems, fuel recovery systems, and fuel storage systems. This tritium may escape to

TABLE 3. Fusion Power Plant Environmental Interactions

| Interaction | General Description of Interaction | Possible Significance |
|---|---|---|
| Land Use | 200 to 500 acres for the power plant. No fuel cycle land use. Small burial ground use. | Small, if properly located |
| Labor Use | Several thousand peak construction force--about the same as for a fission plant. | Small, if properly located |
| Material Use | Some design concepts requiring tens of thousands of tons of scarce materials. | Large |
| Heat Releases | About 60% of energy generated released as heat--about the same as for the best fossil or fission plants. | Small, no change from other types of plants |
| Chemical Releases | Primarily chemicals released in cooling water releases--the same as for the best fossil or fission plants. | Small, no change from other types of plants |
| Sanitary Wastes | No increase in total quantity--ample technology available for control. | Trivial |
| Noise Releases | No significant noises expected other than normal construction noises. | Trivial |
| Vibrations | No significant vibrations expected other than normal construction vibrations. | Trivial |
| Odors | No significant odors expected--ample control technology available. | Trivial |
| Magnetic Fields | Some design concepts have magnetic fields of many Gauss extending for hundreds of meters in all directions. | Large |
| Non-radioactive Liquid Releases | Only significant non-radioactive release is cooling system blowdown. | Small |
| Non-radioactive Solid Waste Disposal | Normal non-radioactive solids. | Trivial |
| Non-radioactive Gaseous Wastes | Trivial amount of non-radioactive gases. | Trivial |
| Radionuclide Releases | Tritium in cooling system blowdown. Tritium in ventilation air exhaust. | Large |
| Aesthetic Effects | Well-designed industrial buildings. | Small |
| Material Transportation | Construction material transportation to site. | Trivial |
| | Solid radioactive waste transportation. | Large |

the environment by diffusion through the power recovery systems, fuel system piping, and containment structures and by release to the atmosphere through leakage and during equipment maintenance. It may also be released during off-normal conditions such as cooling system disruptions, lithium fires and spills, pipe ruptures, fuel system accidents, and transportation accidents.

To conform with the ALAP (As Low As Practicable) philosophy which guides DOE radioactive emission standards, it was pointed out that, for fusion reactors, it will first be necessary to identify what the major tritium source terms are likely to be. Once the source terms are known, it is then necessary to consider what alternatives are available to restrict the release of tritium and how effective they may be developed. These research directions should serve as guidelines for defining acceptable levels of release if the fusion community and its regulatory institution use ALAP as the appropriate tritium release standard.

The environmental effects of tritium releases depend on the chemical form, temperature, and timing of the release. In particular, the environmental effects of a release in the oxide form (tritiated water) are several hundred times as great as the effects of release as unoxidized gas. The oxide easily enters a living body and may be rapidly brought down to the earth's surface by rain. The unoxidized gas, on the other hand, does not readily enter the body and generally is not deposited on the earth's surface until oxidized. As a result, oxidation prior to escape should be avoided; high-temperature releases should be avoided to minimize oxidation.

Computer codes have been developed which calculate the paths of released tritium through the environment and the resultant radiation doses. These codes simulate the deposition of tritium in the soil; the uptake by grasses, vegetables, and fruits; the consumption of these plants by humans and cattle; the transfer of the tritium to milk and meat; and the consumption of these foods by humans. The integrated radiation doses then are computed using numerous empirical relationships and assumptions for dispersion of the tritium downwind and meteorological conditions.

Dose calculations with these codes show, for example, that the total integrated dose as a result of consuming milk, meat, and vegetables, at any location outside the site boundary, decreases with an increase in duration of release of a fixed amount of tritium. On the other hand, the total integrated dose due to inhalation or drinking water is the same regardless of the release time for a fixed amount of tritium. The opinion was expressed that even large releases of tritium to the atmosphere are difficult to detect at ground level, so that the hazards due to this accident are probably over-rated.

Of particular importance to calculation of tritium releases is the correlation used for tritium permeation of metals. Recent experiments at PPPL have identified a transition range at low pressures ($10^{-4}$ to $10^{-5}$ torr). At pressures above $10^{-4}$ torr the diffusion rate correlates with the one-half power of the pressure. At lower pressures, diffusion correlates with the first power of the pressure. If these correlations are representative, the permeation rates of tritium will be much lower than has been estimated in the past when it was assumed that permeation at all pressures is related to the one-half power of the pressure and the calculations had to include extrapolations from higher pressures.

The surface condition of metals appears to be an important parameter affecting tritium diffusion rates. In particular, oxide films inhibit diffusion. As a result, creation of oxide layers could reduce tritium loss rates. However, such oxide layers might also make permeation windows for tritium removal inoperable.

An important mechanism for tritium release is escape into the building atmosphere and then transport with that atmosphere to the outer environment. Studies currently are being made at LASL and LLL of the effectiveness of methods for removing the tritium from ventilation air.

## MAGNETIC FIELDS

The magnetic field resulting from operation of fusion power plants may have strengths of up to 100 kilogauss, pulse durations from msec to hours, and duty cycles of up to 80% for commercial plants. Specific machines, such as UWMAK-1, could have a field strength of as much as 500 Gauss at the biological shield

(50 meters from the reactor center). This field would decrease geometrically with distance to about the earth's normal surface field strength at about 600 meters from the reactor center.

Other systems that generate large magnetic fields are bubble chambers, cryogenic electrical energy storage systems, accelerators, communication systems, levitated trains and magnetohydrodynamic generating systems.

Fusion plant employees could be subject to magnetic fields of up to 500 Gauss throughout their work periods. However, use of moderate size exclusion areas would prevent exposure of the general public to field strengths signficantly above normal.

Numerous studies have been made to determine the biological effects to humans of magnetic fields. These studies include cardiac function, respiratory function, behavioral changes, food consumption and growth, fetal development, brain electrical activity, pathologic changes in spleen, liver, adrenal and bone marrow, metabolic rates, hematology (red blood cells and leukocytes), antibody production, wound healing, tumor growth, cell culture (growth and function), cell division, genetics, enzymes, neuromuscular function, and survival. However, the results from these studies are ambiguous; for example, the results for several experiments on cell culture growth are about equally divided between no effect, increased growth, and decreased growth. Such results could be due to the normal range in experimental results, failure to control or measure important variables, or some unknown reason.

If magnetic fields are of concern, they can be reduced to normal background strength by use of shielding. As examples, a spherical shell with a 3 meter inner radius, installed at 50 meters from a tokamak reactor would have a mass of 110 tonnes. The mass of the shell required for the same degree of shielding decreases with distance to a typical 2 tonnes at 200 meters distance.

Another possible method for reducing the magnetic field strengths is to install bucking coils around a facility. For a relatively low cost, such coils can reduce the local fields to satisfactory levels.

Standards are needed for exposure of personnel to magnetic fields. Some U.S. facilities and some foreign nations have established standards, but there are several orders of magnitude difference between the standards. The U.S. federal standards probably should be re-evaluated since they are far less stringent than comparable foreign standards.

Closely-controlled experiments should be made to determine the effects of magnetic fields. Typical biological effects that should be studied are:

- Neurological and Behavioral Studies
- Life Span Exposures
- Effects on Development
  - Teratologic Studies
  - Reproductive Performance
  - Postnatal Performance after Prenatal Exposure
- Studies of Combined Insult
  - Radiation
  - Drugs or Dietary Alterations
  - Smoking
  - Chemical Carcinogens
- Epidemiologic Studies
- Avian Studies
- Mechanistic Studies

In addition, there is a need for development of a personnel dosimeter.

## NATURAL RESOURCES

Fusion power plants may use large quantities of construction and operational materials. Fuel material supplies are not expected to be a problem. Ample deuterium is available in the oceans to fuel fusion reactors for thousands of years. Ample lithium probably is also available for hundreds of years although more costly sources may have to be used.

Construction of fusion power plants could aggravate expected shortages of structural material in the 21st century. An example is the use of beryllium. If fusion reactors use as much beryllium as is currently projected by some designs there will not be enough beryllium for $10^6$ MWe of capacity unless it is recycled. On the other hand, as technology increases and more effort is expended to find ores, the material shortage should be mitigated. If fusion reactors are to be economically competitive, the quantity of material needed per MW of capacity has to be decreased. This should occur as a result of advances in material technology. Similarly, the available resources for many materials are poorly defined because of lack of incentive to find more ores. As shortages develop (and prices rise), increased exploration should discover more ore deposits.

A primary reason for large uses of construction materials is the relatively low power density in the reactor systems. The current designs have engineering power densities, which include the volume of the entire nuclear island, of about 1 $MW/m^3$ in comparison to about 3 $MW/m^3$ for fission plants and 5 $MW/m^3$ for coal plants.

The current development of lithium waterfall designs for fusion reactors may cause a significant decrease in material usage. Such designs may substantially reduce or eliminate replacement of the reactor inner walls. Larger inventories of lithium may be needed, but the consumption of lithium should not increase.

Particular emphasis should be placed on reducing use of materials in the nuclear island because such irradiated materials may not be recyclable.

In summary, early reference designs have illuminated materials requirements which would significantly deplete the world's inventory of certain known resources. This fact would lead to substantial impact on the environment if plants were actually built according to these designs and no further resource exploration occurred. However, further exploration is expected to increase the world's resources of these materials. Reactor design improvements and material recycle should reduce the requirements, and substitution of materials might alleviate some critical needs.

## RADIOACTIVE WASTE

Fusion power plants are expected to generate gaseous, liquid and solid radioactive wastes. Such wastes will probably include:

- activated air and tritium;
- cleaning fluids, heat transfer fluids, and chemical process fluids; and
- housekeeping trash, maintenance trash, reconstruction wastes, and decommissioning wastes.

These wastes will be disposed of by usual processes:

- dilution and dispersion for gaseous or aqueous wastes;
- solidification for chemical fluids;
- burial for low-level trash, packaged solids, and major components;
- storage; and
- recycling whenever economically attractive.

The primary environmental effects due to these wastes are expected to be:

1. Commitment of resources (burial sites, contamination of land and water, and use of materials);
2. Radiation exposures to biota during operations, transportation, and accidents; and
3. Economic and resource costs of the waste management.

The total quantity of waste generated by a single large power plant could be several hundred cubic meters per year of spent equipment, liquids solidified by use of concrete or bitumin, oils, charcoal, mercury, zirconium, yttrium, coolant salts, and lithium. The activity could be as much as $2 \times 10^7$ Ci/yr.

Replacement of the reactor inner walls may require disposal of up to several hundred tonnes of material per year containing up to several million Curies of radioactivity. Use of minimum activation materials could reduce by several orders of magnitude the radiation doses during handling of these wastes. An important aspect of waste management is valve maintenance. Valves have many crevices that accumulate radioactive crud, resulting in high radiation doses and much radioactive release.

Several questions should be answered by waste management studies. Typical ones are:

1. How much waste results from housekeeping activities and process contamination?
2. Should the wastes be concentrated or diluted?

3. Can critical materials be reclaimed?
4. What are the hazards of specific wastes, particularly from the standpoint of environmental contamination and biological effects?
5. How does the choice of materials affect the cost-benefit balance for waste management?

## SESSION 4: PLANT SAFETY

Participants: S. H. Bush - Chairman
W. Lipinski
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Three topics are listed in the agenda (Table 1) for discussion under plant safety: safety criteria, safety instrumentation and maintenance, and operation requirements. Previous sections on radiation exposure, accidents, and environment have outlined existing and needed instrumentation and maintenance and operation requirements reasonably well. The following discussion concentrates on examination of safety criteria--standards, codes, regulatory requirements--for fusion reactors.

The issues that establish the need for standards in fusion design are 1) the potential for release of radioactivity under either routine or accident conditions, 2) the necessity to control tritium, and 3) DOE's need to "protect their investment."

The magnitude of the radioactive source and the severity of the design basis accidents for fusion plants are expected to be much less than those for fission plants. Therefore, existing safety standards for fission plants are expected to be relaxed to a degree that does not increase hazardous failure probabilities in fusion plant operation. It was assumed by those participants with fission reactor safety experience that standards applicable to fission plants will be used as a basis for fusion plant standards. There was considerable discussion on this point, with some participants expressing the view that safety criteria developed for fission will be applied to fusion, and some feeling that an independent design criteria philosophy should be developed. It seems certain that the latter course will not evolve without a concerted effort from within the fusion community.

Modification of fission standards can only occur after several questions have been answered with respect to fusion:

1. What is a reasonable list of design basis accidents?
2. What impact will standards have on design?

3. What is the effect of realistic releases on design?
4. What is the spectrum of realistic accidents?
5. What factors are controlling in fusion safety?
6. Will DOE add criteria to protect investment?
7. Can the relative consequences of fission and fusion accidents be compared?
8. What is a reasonable set of accident probability values for fusion comparable to fission values (but modified to account for lower consequences)?

Using answers obtained from this list, the fusion designers and safety researchers may develop less restrictive standards. Potential modifications in codes, standards and criteria must balance reduced conservatism because of lower hazards against economic risks of damage to the facility. Perhaps an ACRS-NRC review of a fusion prototype considered representative of a demonstration plant would indicate the level of regulatory control that will be needed. Any conclusions from such analyses should be incorporated as early as possible into contemporary fusion designs.

Guidelines which should be considered while developing an acceptable set of safety criteria are the following:

1. Build on existing codes, standards and criteria whenever appropriate by justifying changes on the basis of lessened safety consequences;
2. Consider economic as well as safety factors;
3. Careful attention to design for optimized maintenance should markedly reduce the down time.

A vital first step impinging on design basis accidents and their consequences is a quantification of the radioactive source term and of the significance of exposure to the various radionuclides comprising the source term. Since accidents require examination in the context of exposure of the public, the implications of large releases of tritium and the potential for release of activation products present as "crud" in the coolant--say, during a liquid metal fire--must be established. Such releases should be decoupled from both routine releases and from exposure of plant personnel to better assess the potential for relaxing various safety criteria. Any such approach must be highly directed and, preferably, should be decoupled from specific design aspects to permit generalization of the approach.

In general, the designers present appeared to recognize the need for design criteria, codes and standards. Rather than fighting the standards, their benefits should be examined; modifications can occur as necessary on the basis of available data.

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# WORKSHOP ON SAFETY AND ENVIRONMENTAL ASPECTS OF FUSION POWER PLANTS

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