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Preliminary assessment of the safety of IFMIF

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is a planned high-energy neutron source for the testing of candidate materials for future fusion power plants. Safety studies performed during the various stages of the conceptual design of IFMIF have been brought together in a preliminary assessment of the safety of IFMIF, identifying the principal hazards and the means to prevent or mitigate them. The design is based on dual high-energy deuteron accelerators delivering beams onto a flowing lithium target, in which neutrons are produced through a d-Li stripping reaction. The neutrons irradiate material samples in controlled conditions in a test cell. In all these systems, potential hazards arise, but analyses show that no postulated off-normal event can result in a significant risk of harm to the public. However, care must be taken in forthcoming detailed design development to minimise occupational radiation exposure during IFMIF operation and maintenance.

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1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) has an essential role to play in the development of fusion power. By characterising the behaviour of candidate materials in relevant neutron irradiation conditions, it will enable the development and selection of materials for DEMO and commercial fusion power stations. On a 'fast track' path to fusion, this development is urgent, and delays must be avoided. Thus, when the regulatory approval of IFMIF construction is to be obtained, a rapid positive appraisal of the safety and environmental issues will be essential.

With this background, a compilation has been made of the current knowledge about the safety of IFMIF, based on the design presented in the Comprehensive Design Report [1]. This study has addressed the potential hazards present, the means to eliminate or mitigate them, and the conceivable consequences for personnel and the public. The outcome is the IFMIF Preliminary Safety Analysis Report (PSAR) [2]. This is based on safety studies so far performed in the project, which have

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addressed the key issues but which are not yet fully comprehensive. It is based on a design that is still evolving and for which much detail is yet to be fixed. And it is based on a generic approach to safety requirements, as the regulatory framework in which IFMIF construction will be licensed cannot be anticipated until a site, or at least a host country, is chosen. For these reasons the safety analysis presented is preliminary, but is a basis on which a full safety analysis can be built, by adding the outcome of future studies, by replacing assumptions with design detail, and eventually by providing the information required by the specific regulatory body that will licence IFMIF.

The intrinsic safety characteristics of IFMIF derive from an extremely sound confinement of a modest radioactive inventory. Only relatively low energies would be available to mobilise this inventory in postulated incidents and accidents, and the integrity of the strong confinement is maintained without the need for complex active safety systems. This ensures that, from the viewpoint of public exposure, the IFMIF plant can be kept in a safe state with high confidence.

2. Safety approach

The approach to safety in the IFMIF project is based on the top-level objectives that it is to be designed, constructed and operated in a way that protects individuals, society and the environment from harm. Hazards to the public and to workers are to be minimised and kept below prescribed limits. Accidents must be prevented and the consequences of any abnormal event must be minimised, as must any hazardous waste arising from the plant.

Safety principles are adopted to help achieve those objectives, following well-established practice in the nuclear industry. They include the principle of maintaining exposures to hazards as low as reasonably achievable (ALARA), which applies throughout the IFMIF project. Safety criteria are employed to assess compliance with the safety objectives, as an interim until the actual regulatory requirements are established for IFMIF at a specific site. These include proposals for quantitative project limits for occupational exposure, and definitions of radiation access zones, as well as guidelines for limits on routine operational releases. For occupational radiation exposure, an individual dose limit of 10 mSv/yr is proposed. For zoning, restricted access applies to all regions where the dose rate exceeds 10 μSv/h, and requires nuclear-grade heating ventilation and air conditioning (HVAC) systems on all volumes in which airborne contamination may exceed 1 DAC[1]. Total environmental releases should remain below the equivalent of 0.1 g of tritium per yr.

3. IFMIF facilities description

It is convenient to regard the design of IFMIF [1] as three closely linked facilities: the accelerator facility, the target facility and the test facility. All are housed within a single building, about 170 m long and maximum height 26 m above ground; the overall layout is illustrated in Fig. 1.

The accelerator facility comprises two separate accelerators, each producing a 125 mA beam of 40 MeV deuterons. In each there will be a deuteron ion source supplying ions to a radio frequency quadrupole linear accelerator followed by a beam transport system. This guides the two beams onto a 50 × 200 mm area of a flowing liquid lithium metal target, the total 10 MW of beam power thus representing a power density of 1 GW/m^2 on the lithium surface. Interaction of the beam with the target produces an intense source of high-energy neutrons via d-Li stripping reactions.

The target facility provides the lithium target as part of a loop containing 9 m^3 of liquid lithium. One surface of the flowing lithium is exposed at the target location, where it flows downwards over a steel backplate into a quench tank. This lithium surface is thus part of the accelerator vacuum boundary, although there are fast-closing isolation valves in the drift tubes. The loop contains electromagnetic pumps, a heat exchanger with an organic fluid secondary coolant, and a purification system to remove tritium and beryllium-7 from the lithium.

Neutrons produced in the target pass through the backplate into the test facility, where samples being irradiated are held in three vertical test assemblies (VTAs). The first is in the small-volume, but very high flux region, the second and third are in the medium and low flux regions. The complete test facilities and Li-target are contained within a test cell, approximately 3 × 3 × 6 m, the walls of which provide containment of the radioactive material as well as shielding from the direct radiation. This test

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[1] Derived Air Concentration, the airborne concentration of a radionuclide that would result in an inhalation dose uptake of 20 mSv in a year, assuming 2000 h exposure in the year.

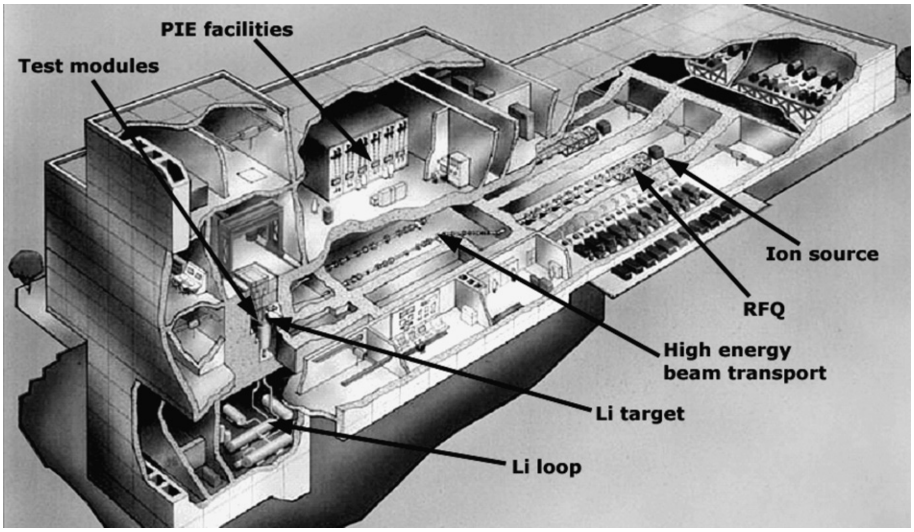

Fig. 1. Layout of the main IFMIF facilities.

cell is concrete with a stainless steel liner, and is maintained either under vacuum or with an inert gas slightly below atmospheric pressure. Above the test cell is an access cell into which the VTAs are withdrawn for exchange of test samples using remote handling equipment. The top section of each VTA includes shield plugs with steps to avoid neutron streaming paths.

A post-irradiation examination facility is also planned, comprising hot cell, glove box and tritium laboratories. In addition there are a number of service facilities, such as the control system, maintenance facility, power supply, cooling water supply, cryogenic coolant supply, and instrument air supply.

4. Potential hazards and their mitigation

In each of the IFMIF facilities potential hazards arise, including sources of radioactivity that could, in principle, lead to occupational doses or, in a postulated accident, an off-site release with public consequences. The occupational hazard is mitigated by operational practices including an access control interlock system, by the provision of radiation shielding, and by the use of remote handling techniques where appropriate. A fast shutdown system is designed to terminate the deuteron beams in an off-normal event within 10 μs of a shutdown signal, and a beamline isolation system separates the target from the beamline duct within 10 ms. An accidental off-site release is prevented by multiple levels of confinement, and by filtering systems to remove active material from discharges. These systems maintain the level of activity released in normal operation at an extremely low level.

In the accelerator facility the radiation hazard is similar in nature to that arising in existing accelerators, differing in magnitude due to the unusually high beam current and energy. There are two components: prompt radiation and residual radiation. Prompt radiation arises from the deuteron beam and high-energy particles and gamma-rays emitted from interactions between the beam and accelerator components, principally the beam tube. Shielding is provided to protect personnel from exposure to this source. Residual radiation is that which arises from direct deuteron activation of components, again mainly the beam tube, and also activation by secondary neutrons generated in deuteron reactions. These neutrons may activate not only structure, but also coolant fluids and air. There has yet been no quantitative analysis of these sources for IFMIF; this will depend initially on the magnitude and distribution of beam losses.

The lithium target facility is the main source of radiation in IFMIF. The intense neutron source from the d-Li interactions will induce activation in surrounding structures, particularly the backplate and parts of the accelerator drift tubes. Amongst the direct products of d-Li reactions in the target are tritium and beryllium-7. The T generation rate is about 7 g/yr and ^{7}Be (half-life 53 days) 1.5 g/yr (assuming 95% availability). Both of these will be removed from the circulating lithium and maintained at a low level by hot and cold traps in the loop. The traps themselves become a potential source of these isotopes – if they are replaced annually the maximum inventories are 6.7 g of T and 0.31 g of ^{7}Be.

In addition to these direct products, the lithium will contain impurities and the products of corrosion of the steel components of the loop. These will become activated in the neutron flux as they pass through the target region, and probably also by direct deuteron interactions. Analyses of the neutron activated corrosion products have shown that there is the potential for significant occupational doses from these [3,4]. It may be possible to substantially reduce this potential radiation source by providing additional trapping to remove these products from the loop.

Liquid Li is very reactive with air, water, concrete, carbon dioxide and nitrogen. The potential for these chemical reactions or a lithium fire is prevented in the IFMIF design by multiple confinements and inert atmospheres (using argon gas).

In the test facilities, samples are exposed to the neutron flux in controlled conditions. They are housed in vertical test assemblies which may be removed for replacement of samples etc. All of this structure, in addition to the test specimens themselves, will become activated, providing a substantial mass of active material – principally steel – well-confined within the test cell [5].

5. Environmental impact and waste

Cells and rooms in IFMIF which may contain radioactive material are served by nuclear-grade HVAC systems, which treat the air and argon atmospheres by a series of filters including detritration systems and high efficiency particulate air (HEPA) filters. Liquid waste, arising from coolant systems, also passes through a treatment system to remove activation products and tritium. By these means, the routine effluents from IFMIF operation can be maintained at a very low level, with present estimates less than 5 GBq/yr (equivalent to about 14 μg of tritium) [6].

Solid material that has become activated by neutron irradiation, particularly the structure and shielding of the test cell, represents a significant mass of active material at the end of life of IFMIF. However this activity decays relatively rapidly, and within 50 yr most of the material could be released from regulatory control as non-active waste, if IAEA guidelines on Clearance criteria were implemented. Most of the remaining material, around 500 tonnes, would be classified as low level waste, and only a very small quantity would require long-term repository storage beyond 100 yr (about 200 kg in the initial assessment) [7].

6. Occupational safety

Protection from occupational radiation exposure (ORE) is to be provided by access control based on a zoning scheme in all IFMIF facilities, restricting access everywhere that dose rates may exceed 10 μSv/h or an airborne concentration exceeds 1 DAC. Personnel intervention into restricted zones will be controlled and monitored, allowed only for maintenance tasks where there is no remote handling option. In regions where the dose rate exceeds 100 μSv/h, only short maintenance tasks (less than one hour) will be permitted. Since maintenance procedures have yet to be developed, and detailed design is yet to be completed, influencing the specifics of radiation sources and their shielding, it is not possible at this stage to perform a full evaluation of ORE.

Despite this lack of detailed information, a preliminary estimate of ORE has been made by making assumptions [8]. This led to an estimated possible total collective dose lying in the range 0.46–4.5 person-Sv/yr. Another estimate was made of ORE in the accelerator facility by extrapolating from actual operational experience on another high-energy accelerator, TRIUMPH [9]. This led to a range of dose estimates with an average of 1.8 person-Sv/yr for the total collective dose. These estimates are rather high, and if confirmed by more detailed analyses, will imply that additional measures may be necessary to reduce personnel doses. Since this would include optimisation of maintenance procedures not yet developed, it is not possible to comment on how readily the collective dose may be reduced.

In the target facility, a potentially important contributor to ORE is the activity carried by the lithium loop. While tritium and beryllium-7 are expected to be maintained at low levels by the hot and cold traps, the additional contribution of activated corrosion products and impurities may be of importance. Assuming that these are not filtered out, two analyses have been performed of the potential doses arising [3,4]. There are a number of uncertainties, related mainly to the corrosion rates of steel in liquid lithium, and its solubility, but initial results show a dose rate in the region of 100 μSv/h in the vicinity of a 20 cm pipe for the first week after shutdown, or up to 320 μSv/h adjacent to a large component such as the lithium heat exchanger. Not included in this figure is the contribution of corrosion products and impurities directly activated by deuterons as they pass through the target.

The test facilities rely on adequate shielding provision to ensure that radiation from the active samples and structure within the test cell does not give rise to excessive ORE. Analyses have shown that the shield design can maintain doses below 10 μSv/h in all zones requiring access [5]. However, further detailed studies of possible streaming paths will be required, as well as potential doses during remote handling operations to replace test assemblies.

Post-irradiation examination (PIE) facilities are another source of potential personnel exposure. This has not yet been studied, but since the PIE facilities are not unusual, the conventional means of radiation protection should be effective.

7. Public safety

The potential for abnormal events in IFMIF to lead to a public safety hazard is expected to be extremely low. Sources of radiation within the facilities are modest and very well-confined. To confirm this expectation, safety analyses have been started which aim to identify potentially hazardous event sequences and analyse the possible consequences.

A systematic approach has been taken to the identification of fault conditions that could in principle initiate a sequence of events leading to an off-site release of radioactivity. This has used failure modes and effects analyses (FMEA) together with fault tree and event tree analyses [10]. Eight postulated accident sequences have been selected for further analysis. These are: ingress of cooling water into the accelerator beam duct; beam overpower; air ingress into the beam duct; lithium discharge in the lithium loop area; loss of lithium into the test cell due to backplate break; lithium loop pump stoppage; loss of lithium loop heat sink due to organic coolant pump stoppage; and loss of vertical test assembly coolant into the access cell. So far, only the first two of these have been the subject of analyses [11], results indicating that they do not lead to an off-site hazard.

Table 1
Conservatively-calculated 7-day doses to the most exposed individual (MEI) at site boundary following a hypothetical accident sequence

Component	Source term	MEI dose
T	3 g	2.2 mSv
^{7}Be	2.5 mg	0.70 mSv
Activated corrosion products	Calculated inventory at $t = 0$	0.36 mSv
Solid activation products (in steel)	Calculated release up to $t = 7$days	11.2 μSv
Total		3.3 mSv

In order to assess the bounding consequences of a postulated accident in IFMIF, a study was also performed of a hypothetical sequence representing a bounding case, in which several failures of very low likelihood are postulated to occur simultaneously, with conservative assumptions throughout the analysis [12]. The hypothesis is a lithium fire in the test cell, combined with a failure of the test cell integrity as well as other confinement barrier leaks, leading to the release from the building of the entire inventory of the lithium loop (including a maximum 3 g T and 2.5 mg ^{7}Be, based on the assumed efficiency of the purification system) together with some of the fixed activation products in structure, activated corrosion products and impurities, etc. Even in this bounding case with no effective confinement, the maximum 7-day dose to an individual at the site boundary is just 3.3 mSv (see Table 1), well below the guideline of 50 mSv avertable dose that may trigger the need for public evacuation.

8. Conclusion

At this stage in the development of the design of IFMIF, insufficient detailed information exists to permit a thorough safety analysis. But the preliminary studies performed so far have enabled the reporting of a broad picture of the safety issues, the main hazards and their means of prevention. This indicates that the safety provisions built into the IFMIF design are more than adequate to ensure safe operation. The likelihood is very low for an accident sequence in which there could be an off-site release of radioactive material, resulting in an very low risk of harm to the public.

To ensure safety of IFMIF personnel, and to maintain occupational radiation exposure as low as reasonably achievable, it will be necessary to take care in the detailed design to minimise exposure pathways and to optimise shielding. The very preliminary estimates of doses should be revised by a full ORE assessment once sufficiently detailed information is available.

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