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Journal of Nuclear Materials 258–263 (1998) 106–112

journal of nuclear materials

Conceptual design of the international fusion materials irradiation facility (IFMIF)

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) conceptual design is complete. The two-year effort was carried out as an activity of the IEA Executive Committee on Fusion Materials. Specialists from Europe, Japan, the United States and the Russian Federation came together in a series of meetings and workshops to define the concepts for the technical systems and the overall design and cost estimate. The goal of the IFMIF is to provide an irradiation facility for use by fusion material scientists in the search for low activation and damage resistant materials. An accelerator-based neutron source has been established through a number of international studies and workshops as an essential step for near-term materials development and testing. IFMIF would also provide calibration and validation of data from fission reactor and other accelerator-based irradiation testing. The design concept consists of a deuteron accelerator producing particle energies in the range of 30–40 MeV. The deuterons interact with a flowing liquid lithium target (D–Li) producing high energy neutrons with a peaked flux around 14 MeV. The resulting high energy neutrons will interact with a test assembly to irradiate test samples of candidate materials up to full lifetime of anticipated use in future fusion energy reactors.

1. Introduction

To test and fully qualify candidate materials up to the expected doses of a fusion power reactor, a high flux source of high energy neutrons, presently not existing, has to be build and operated. A test facility suitable for such purposes has been explored through a number of international studies and workshops over the last decade. Under the assumption that such a facility should be available early in the next century, a neutron source from the Deuterium–Lithium (D–Li) stripping reaction has been selected as the basic concept of the IFMIF [1–4]. The technology of the accelerator-based D–Li neutron source concept was first developed by the Fusion Materials Irradiation Test (FMIT) Project (1978–84) [5,6] and later by the Energy Selective Neutron Irradiation Test Facility (ESNIT) Program (1988–92) [7–9]. Major worldwide advances in accelerator technology over the past decade have further added to the credibility of this approach.

The mission of IFMIF is to provide an accelerator-based, D–Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to about a full lifetime of anticipated use in fusion energy reactors. IFMIF would also provide calibration and validation of data from fission reactor and other accelerator-based irradiation tests [10]. It would generate an engineering

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base of material-specific activation and radiological properties data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal systems.

2. The IFMIF conceptual design activity

The objective of the IFMIF Conceptual Design Activity (CDA) was to provide a reference design and a project basis, including a schedule and cost estimate, satisfying the mission and the requirements for a facility as described above. The CDA was carried out under the direction of a subcommittee of the International Energy Agency (IEA), Executive Committee on Fusion Materials [11]. A users group of materials scientists was organized by the Executive Committee, outside of the CDA envelope, to provide requirements, guidance and review of the design. The design team consisted of specialists in all technical areas relevant to IFMIF, working, most of the time in their home institutions in Europe, Japan, the United States and the Russian Federation. The work was coordinated by a technical leader, assisted by deputy leaders who were responsible for the major technical areas. The CDA was done over a 2-year period, 1995–96, through a series of technical meetings and workshops in which tasks were defined and discussed and then completed at the home institutions [12–16]. The overall design concept was developed during three design integration workshops [17–19]. The final CDA report was published December 31, 1996 [20]. The entire CDA effort was accomplished with a professional work force of approximately 25 person years per year.

The IFMIF program relies on an international electronic network system for communication among the project groups of various countries and institutions. A computer server has been set up at ENEA-Frascati Research Center, Italy, where project documents are stored and easily accessible to all the project participants. An IFMIF home page may be accessed by Internet on the world-wide web (http://www.frascati.enea.it/ifmif/).

3. User requirements

The design concept for IFMIF is based on input from the materials community on the estimated test volume required to obtain useful irradiation data in a reasonably short operating time. Detailed design studies of the test assembly indicate that a test volume of about 0.5 L is required in a region producing a flux equivalent to 2 MW/m^2 (0.9×10^{18} n/m^2 s, uncollided flux) or greater. A fraction of this volume, about 0.1 L, is available at a flux equivalent to 5 MW/m^2 for accelerated testing.

Two accelerator systems combined will provide a continuous wave of 250 mA of deuterons at 32, 36, or 40 MeV. Neutronics calculations indicate that 40 MeV deuterons provide the maximum high-flux irradiation volume and provide a reasonable simulation of the fusion energy gaseous and solid transmutation rates in most metallic components. Some of the transmutation components in ceramic materials are best simulated with 32 or 36 MeV deuterons. The flexibility of choosing deuteron energies between 32 and 40 MeV during irradiation campaigns allows experiments designed to establish the influence of certain transmutation products to be conducted.

A quasi-continuous operation is mandatory. Annealing times of point defects shorter than the repetition time of pulses and rate effects in the case of low duty-cycle sources would introduce unacceptable uncertainties in the observed radiation effects. It is planned that IFMIF will operate with two accelerators providing identical overlapping beam footprints on either one of two lithium targets. This configuration minimizes flux perturbations caused by a beam-off transient in one of the accelerators (i.e., the maximum likely temporal variation in the flux would be a factor of 2).

4. Overall facility layout

A three-dimensional view of the overall IFMIF facility is shown in Fig. 1. The two parallel accelerators, each approximately 50 m long, produce a beam which is turned through approximately 90° where it is directed to one of the targets where the two beams overlap. The accelerator systems along with the lithium loop and processing systems are located below ground level. Major power systems, access cells and hot cell facilities are located at ground level. The first floor level contains laboratories for the handling and testing of the irradiated components and specimens.

5. Test facilities

The test cell has an actively cooled steel liner and a removable shield plug with ports which allow flexible installation of two Vertical Test Assemblies (VTA1 and VTA2) for the high and medium flux regions, and a Vertical Irradiation Tube (VIT) system for the low and very low flux regions. The VTAs (Fig. 2) penetrate through the test cell ceiling and include the primary coolant, instrumentation and the test modules to be irradiated. This concept maintains a high degree of flexibility with respect to any future needs. In the present reference design the high flux region consists of either NaK cooled test modules for low and medium irradiation temperatures or helium gas cooled test

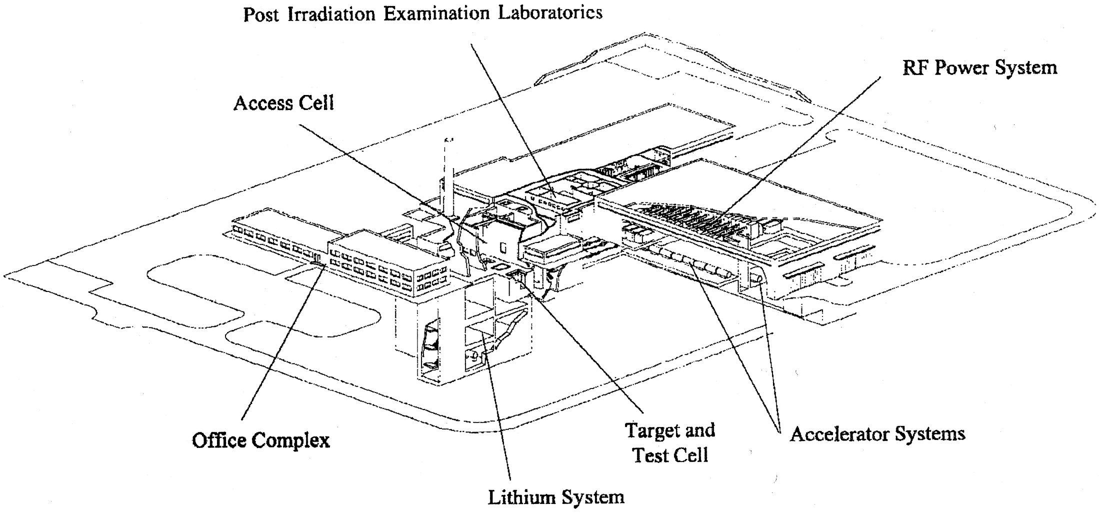

Fig. 1. 3-dimensional View of IFMIF.

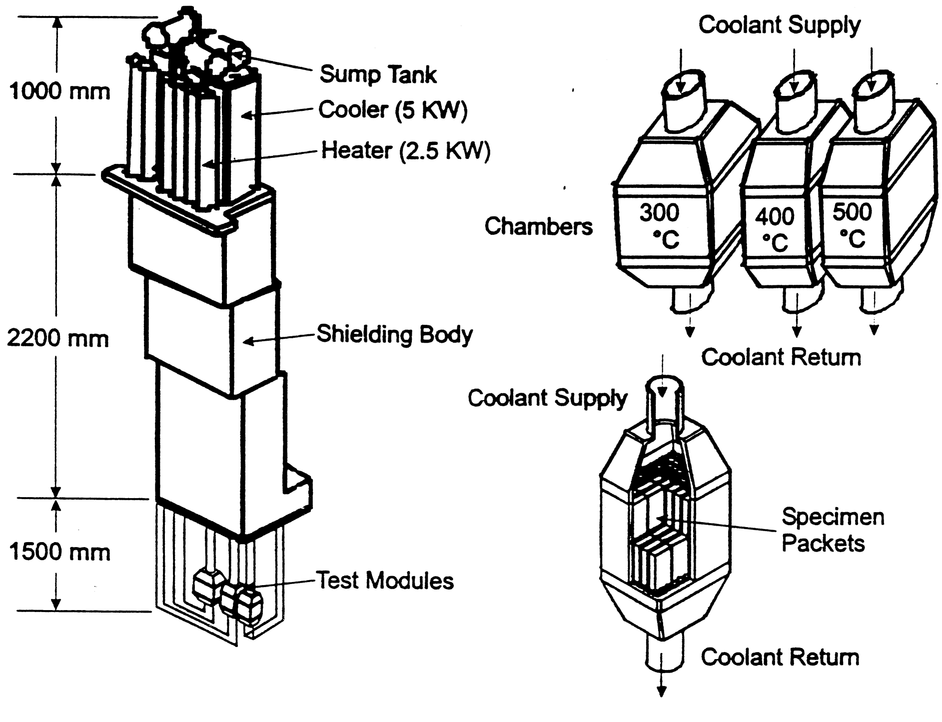

Fig. 2. Vertical Test Assembly (VTA1).

modules for high temperature applications with the strong option to replace the NaK cooled version after the feasibility of the helium concept has been shown experimentally mainly by thermal hydraulics tests. Major advantages of helium gas instead of NaK are flexibility with respect to irradiation temperatures as well as safety and maintenance considerations (NaK has more than 10 times higher decay heat than Fe during the first day after irradiation). Either simultaneous in situ push–pull creep fatigue tests on three individual specimens or in situ tritium release tests on breeder materials are foreseen in the medium flux region. The VIT system in the low and very low flux region is presently dedicated to special purpose materials like ceramic insulators, rf windows, diagnostic materials or superconducting materials.

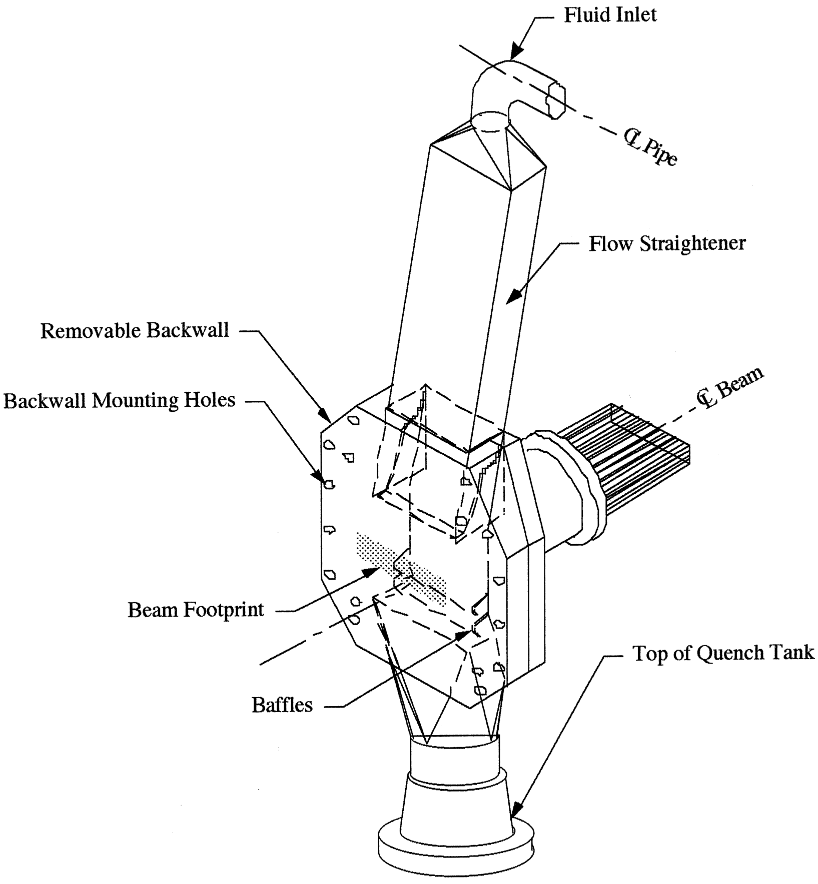

Fig. 3. Target assembly with removable backwall.

6. Lithium target system

The lithium target may be divided up into two basic components. The first is the target assembly itself shown in Fig. 3 which must present a stable lithium jet to the beam, where the kinetic energy of the deuteron beam is deposited and where neutrons are produced. The second is the lithium loop, which circulates the lithium to and from the target assembly and removes the heat deposited by the deuteron beam. This loop also contains systems for maintaining the high purity of the loop required for radiological safety and for minimizing corrosion of the loop structure by the hot flowing lithium. A single lithium loop provides flow to either of the target assemblies in the two test cells. A maximum 10% flow is provided to the inoperative target for decay heat removal.

The main lithium loop circulates the lithium to and from the target assembly with the parameters shown in Table 1. Since two targets are assumed, the loop must be able to deliver flow to either of the test cells. The major components in this loop are the target quench tank, the surge or overflow tank, the lithium dump tank, the organic dump tank, the main electromagnetic pump, and the two heat exchangers. All of the piping and tanks are constructed of austenitic stainless steel (either 304 or 316). There are, in addition, a trace heating system, to maintain the temperature throughout the loop above the melting point of the lithium at all times the metal is present in the loop, thermal insulation, valves, electromagnetic flow meters, instrumentation, and connections to vacuum and argon headers. The total lithium inventory is 21 m^3.

Table 1
Lithium jet parameters (40 MeV, 250 mA)

Jet thickness, m	0.025
Jet width, m	0.26
Jet velocity, m/s	15 (range 10–20)
Inlet temperature, °C	250
Outlet temperature, °C	300 (for 15 m/s)
Surface temperature, °C	290 (for 15 m/s)
Peak temperature, °C	450 (for 15 m/s)
Beam footprint, cm^2	5 × 20

7. Accelerator system

The IFMIF requirement for 250 mA of deuteron beam current delivered to the target will be met by two 125-mA, 40-MeV accelerator modules operating in parallel. This technological approach is conservative with respect to the current capabilities of rf linac technology and provides operational redundancy by allowing operation to continue at 125 mA when one or the other of the two accelerators is temporarily removed from service for repair. Each 125-mA accelerator is designed with sufficient derating but not with a significant upgrade capability. Additional beam current, if desired, would be provided by adding additional 125-mA modules.

The IFMIF deuteron accelerator, shown in Fig. 4 (plan view), comprises a sequence of acceleration and beam transport stages. The ion source generates a cw 140-mA deuteron beam at 100 keV. A Low Energy Beam Transport (LEBT) guides the deuteron beam from the operating source to a Radio Frequency Quadrupole (RFQ). The RFQ bunches the beam and accelerates 125 mA to 8 MeV. The 8 MeV RFQ beam is injected directly into a Room-Temperature (RT), Drift-Tube-Linac (DTL) of the conventional Alvarez type with post couplers, where it is accelerated to 32, 36, or 40 MeV.

The rf power system for the IFMIF accelerator is based on a tetrode amplifier operated at a power level of 1.0 MW and a frequency of 175 MHz. Operation of both the RFQ and the DTL at the same relatively low frequency is a conservative approach for delivering the high current deuteron beam with low beam loss in the accelerator. The use of only one rf frequency also provides some operational simplification. Beam loss in the accelerator is to be limited so that maintenance can be "hands-on", i.e., not requiring remote manipulators. However, the accelerator facility will be designed in such a way that remote maintenance is not precluded.

As shown in Fig. 4, the DTL output beam is carried to either of the targets or to the tune-up beam calibration station by a High Energy Beam Transport (HEBT) that also provides the desired target spot distribution tailoring and energy dispersion.

Extensive trade-off studies have been conducted on this baseline design, using the Accelerator System Model

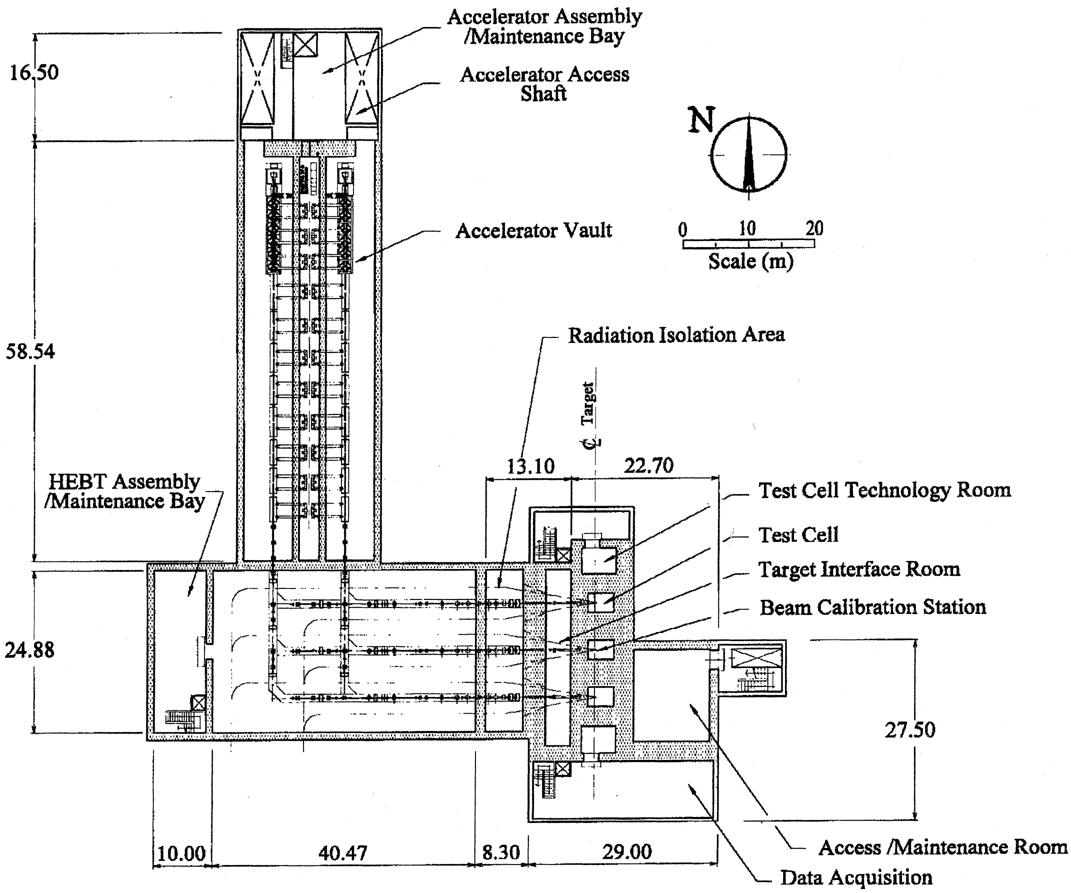

Fig. 4. Overall accelerator layout (plan view).

Table 2
Summary of IFMIF cost estimate

WBS	System	Estimated costs M$ (US) – Jan. 1996 values
1.0	Project management	52
2.0	Test facilities	107
3.0	Target facilities	115
4.0	Accelerator facilities	409
5.0	Conventional facilities	90
6.0	Central control system and common instrumentation	24
Total Estimated Construction Cost (TEC)		797
7.0	Startup and commissioning	63
	Engineering validation	49
Total Project Cost (TPC)		910

(ASM). ASM is a new code that allows consideration of physics, engineering, cost, and Reliability, Availability, Maintainability (RAM) information in a consistent framework for the first time.

8. Project cost and schedule

A construction schedule for the IFMIF program which was developed for the CDA required about 5 years from the start of Engineering Design to the start of Test Operations. A period of about three years (Engineering Validation) is required before the start of the Engineering Design and Construction for the development and testing of prototype components. It also includes time for the checking, review and approval by the individual possible parties to the IFMIF program.

Many of the individual estimates were developed by specialists from two or more countries. Rather than selecting an average cost within the range of the differences, the final estimate for the CDA was selected to be more representative of the cost for construction in Europe and the US. The Japanese have more rigid standards for construction of nuclear facilities at JAERI for both environmental and safety requirements. The estimate quoted internally by Japan is expected to be somewhat higher.

The present estimate is referred to as the baseline cost estimate. Each country may produce an internal estimate to best reflect the needs for construction within their national sites. A summary of the baseline cost estimate [21,22] is given in Table 2. The Total Estimated Construction Cost (TEC) of 797 M$ includes an allowance for indeterminates of 168 M$ which is distributed among the various systems.

The IFMIF operating cost will be strongly influenced by the cost of electricity. For the range in cost of electric power among the IFMIF parties, the total estimated annual operating cost is 56–78 M$.

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