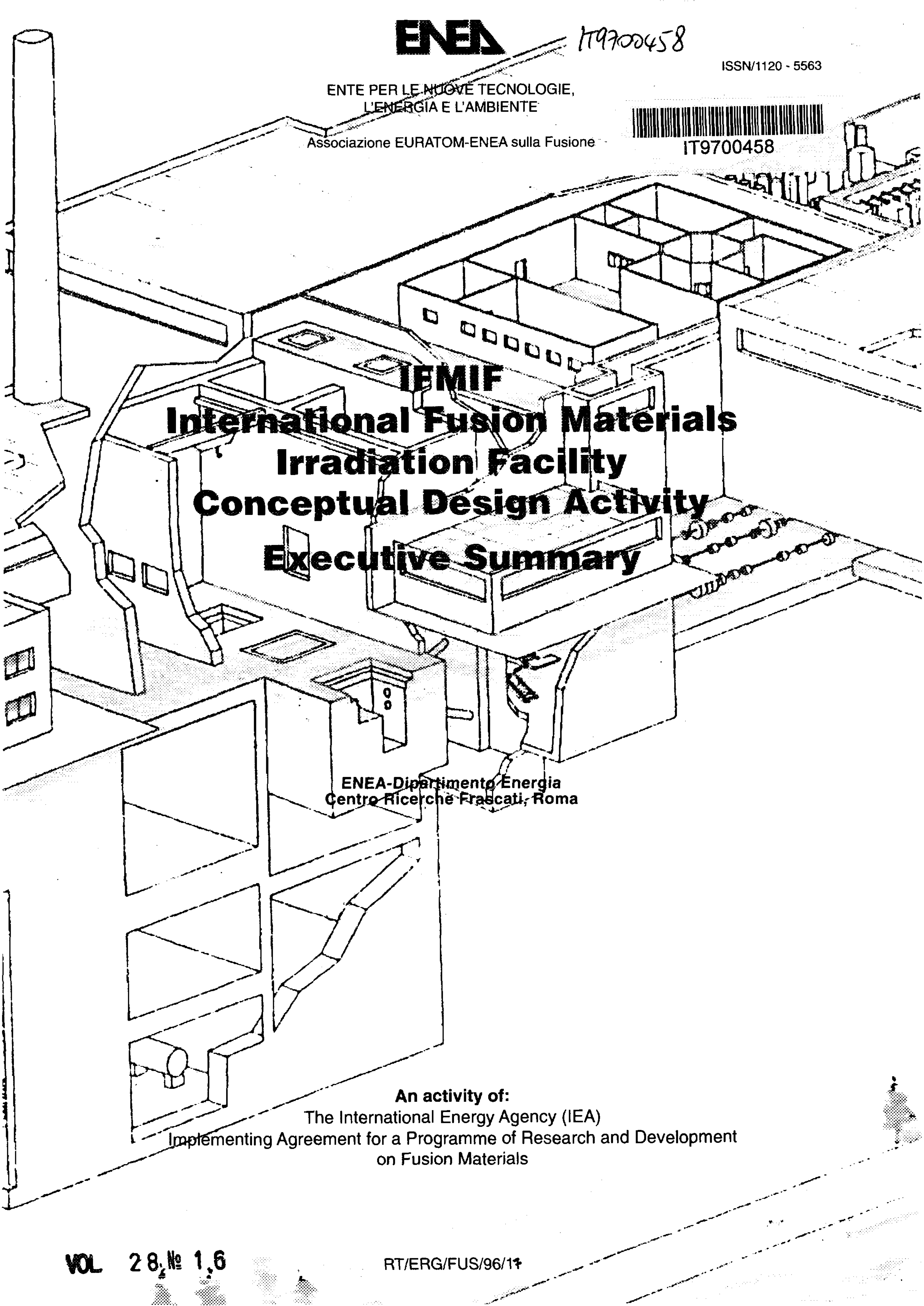

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L'ENERGIA E L'AMBIENTE

Associazione EURATOM-ENEA sulla Fusione

IFMIF
International Fusion Materials Irradiation Facility
Conceptual Design Activity

Executive Summary

ENEA-Dipartimento Energia
Centro Ricerche Frascati, Roma

An activity of:
The International Energy Agency (IEA)
Implementing Agreement for a Programme of Research and Development
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"IFMIF-International Fusion Materials Irradiation Facility Conceptual Design Activity, Final Report", IFMIF-CDA Team, edited by M. Martone, ENEA Frascati Report, RT/ERG/FUS/96/11 (December, 1996)

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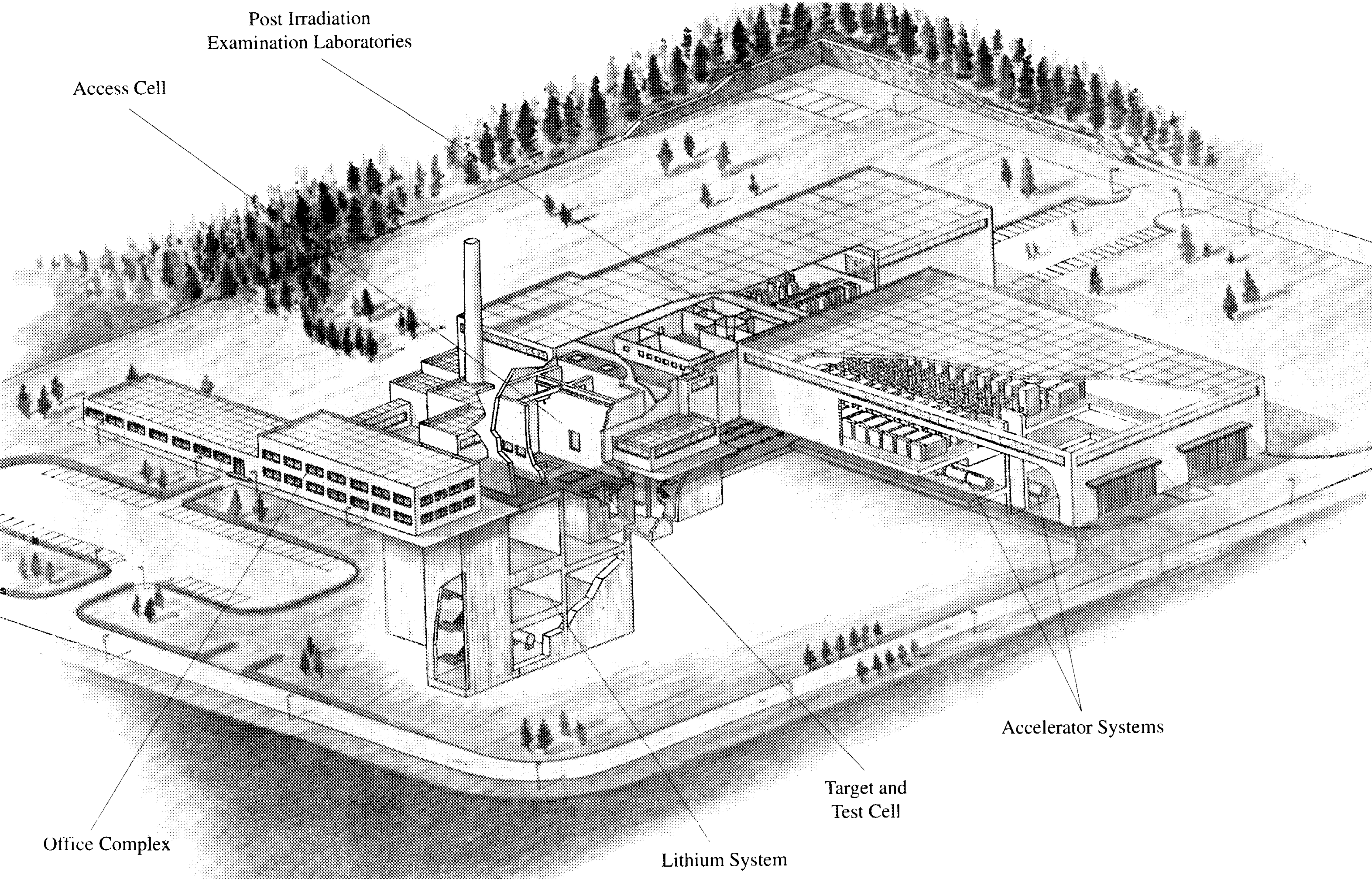


3–Dimensional View of IFMIF

PREFACE

This report is a summary of the results of the Conceptual Design Activity (CDA) on the International Fusion Materials Irradiation Facility (IFMIF), conducted during 1995 and 1996. The activity is under the auspices of the International Energy Agency (IEA) Implementing Agreement for a Programme of Research and Development on Fusion Materials. An IEA Fusion Materials Executive Subcommittee was charged with overseeing the IFMIF-CDA work. Participants in the CDA are the European Union, Japan, and the United States, with the Russian Federation as an associate member.

The guiding principle throughout this design activity has been to meet the requirements of the expected users, i.e. the scientists developing materials for fusion systems. The Executive Subcommittee confirms that the final facility specifications achieved by the CDA is capable of fulfilling the expected user requirements, especially to meet the needs of the research and development on materials for DEMO-stage fusion reactors. The conceptual design was mostly developed in the first year of the project. The activity has recently added assessments of the cost, safety and RAM (Reliability, Availability and Maintainability). The route to continuation of the activity from the current CDA stage to the eventual construction and operation of IFMIF has also been assessed. The supplementary research and development tasks that need to be implemented in the next phase, the Engineering Validation Phase, have been defined and documented in a separate report.

In the more than two decades of fusion materials research, a key concern has been the issues of materials damage with high energy fusion neutrons. Since the beginning of the study of materials for fusion, both scientific and engineering aspects of the evaluation have suffered from the lack of a key tool, i.e. a source of neutrons that adequately simulate a fusion environment. With the present CDA, the history of the materials development and thus the fusion power development will add a new page for a promising future, with the definition of the facility needed to fully quality materials for fusion systems.

The pioneering work for an accelerator-based neutron irradiation facility based on the deuteron-lithium stripping reaction (D-Li source) was implemented early in 1978 by the FMIT Project in the USA. This project defined the essential technology basis for the present IFMIF design. After the unfortunate cancellation of FMIT in 1984, the urgent need of building such an intense, high energy neutron source was repeatedly endorsed in the IEA's formal assessments, e.g. by the Cottrell Blue Ribbon Panel (1983) and by the Amelinckx Senior Advisory Panel (1986). Those international panels emphasized the importance of constructing the facility for the materials development aspects of fusion power development.

In the last decade, a group of materials scientists working under the auspices of the IEA Fusion Materials agreement continued their collaborative effort toward selecting a potential neutron source concept through a series of international workshops. At the same time, a conceptual modification of the D-Li source was undertaken by the ESNIT Program in Japan (1988-92). Those activities helped resolve a few of the key issues that had been the sources of criticism on the suitability of the D-Li source.

The essential kick-off of the IFMIF activity was made in February 1989 when an IEA International Workshop was organized at San Diego, USA. It began an important dialogue between the communities of materials research and facility design and operation. Such efforts eventually yielded a rewarding result when in 1993 the IEA Fusion Power Coordinating Committee (FPCC) requested the Executive Committee for the Fusion Materials Implementing Agreement to summarize the progress in selecting a neutron source concept. The planning then accelerated in 1994 to organize an international activity. A proposed plan for the IFMIF was accepted in 1995 by the FPCC, with additional advice on the organization structure. The details of the CDA operation since the onset of that official action appears in this text. I would simply point out here that the activity has been very successful because we were able to get the right people, i.e. people with the best available expertise, with high enthusiasm and with the ability to work together. It is strongly recommended that the fusion community maintain this group of people, the IFMIF-CDA team, for the future development of IFMIF. This is a valuable and rare collection of human talent.

The Fusion Materials Executive Committee and the Executive Subcommittee for the IFMIF-CDA have been highly impressed with the dedication and enthusiasm of the design team. This has been the major factor enabling the distinguished accomplishments of the CDA. The committees recognize that this effect has been created through the international collaboration under the experienced and talented leadership of Prof. Thomas E. Shannon. He has also had the strong support of reliable subleaders in the many different technical sectors. We should also remember the contribution of a number of dedicated people who had left the activity by their retirement before the CDA stage. Among the dozen unforgettable names, the contribution of Dr. Donald G. Doran must be singled out for his organization of the San Diego Workshop and the leadership of the IEA Working Group.

Finally, appreciation is given for the continued interest of the IEA-FPCC. Their encouragement has been a most effective external driving force for this activity.

Tatsuo Kondo
Chairman of
IFMIF-CDA Executive
Subcommittee

November 1996

EXECUTIVE SUMMARY

MISSION

Continued progress toward the development of a fusion power plant will require addressing a broad set of issues regarding environmental acceptability, safety, and economic viability. Among such issues, the development and qualification of radiation-resistant and low-activation materials will be a key factor. These low-activation materials must survive exposure to damage from neutrons having an energy spectrum peaked near 14 MeV with annual radiation doses in the range of 20 displacements per atom (dpa). 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.

The 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 International Fusion Materials Irradiation Facility (IFMIF) [1,2,3,4]. 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) [7,8,9]. 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 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.

CONCEPTUAL DESIGN ACTIVITY

The objective of IFMIF Conceptual Design Activity (CDA) is 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. After a joint technical preparation workshop held at FZK in Karlsruhe, Germany in September 1994 [12], specific area meetings were held during the spring and summer of 1995 in Europe (test facilities) [13], Japan (target systems) [14], and the United States (accelerator) [15,16]. The initial baseline design concept was developed during a 2-week design integration workshop, October 16 - 27, 1995, at Oak Ridge National Laboratory. The first draft of the CDA report was also produced during that workshop [17]. The second design integration workshop was held at the Japanese Atomic Energy Research Institute, Tokai, Japan, May 20-24, 1996 [18,19]. At this meeting, the baseline design was revised to reflect several changes discussed by the design team. The first draft of a cost estimate and schedule as well as a plan for the Engineering Validation Phase (EVP) was also produced. The third design integration meeting was held at the ENEA-Frascati Research Center, Italy, October 14-25, 1996. The final CDA report was prepared at this meeting and 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 Work Breakdown Structure (WBS) for the project has four major elements that defined the technical focus for the CDA as follows:

1. Project Management/Design Integration,
2. Test Facilities,
3. Target Facilities, and
4. Accelerator Facilities.

The schedule of meetings and activities for the CDA was as follows:

Start international preparation of CDA	June	1994
Formulate initial requirements and CDA tasks	Sept.	1994
Preliminary system design layouts		
- Test Facilities	July	1995
- Target Facilities	July	1995
- Accelerator Facilities	Sept.	1995
Design integration workshop		
- Design layout and establish baseline design	Oct.	1995
Interim report	Dec.	1995
Preliminary project plan and cost estimate	May	1996
Final design integration workshop		
- Update baseline design, plan, and cost	Oct.	1996
Conceptual design and cost report	Dec.	1996

The IFMIF program relies on an international electronic network system for communication among the project groups of various countries and institutions. To set up an efficient communication system, protocols and software have been specified. The basic set includes: EUDORA for e-mail, Microsoft Word 6.0 for text format, Microsoft Excel 5.0 for spreadsheet format, and AUTOCAD 12 (.DWG) format for drawings. A computer server has been set up at ENEA-Frascati Research Center, Italy, where project documents (reports, drawings, etc.) released from project management 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/).

In addition to providing up-to-date design information for future activities, the common server could provide the design team with a data base of supporting information, such as technical reports and results of research and development programs for possible future phases of the IFMIF project. Large databases such as the files from FMIT and ESNIT could be transferred to this system.

DESIGN CONCEPT

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.

An estimate of the test volume and the corresponding displacement rate in a test assembly with iron-based specimens per year of facility operation is as follows:

0.1 L > 50 dpa/fpy
0.5 L > 20 dpa/fpy
6.0 L > 1 dpa/fpy

Assuming a total facility availability of 70%, these displacement numbers which represent a full power year (fpy), have to be multiplied by a factor of 0.7.

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).

Because of the level of uncertainty in the amount of testing and development needed to characterize the damage effect of 14-MeV neutrons and to quantify materials for reactor lifetime service, the IFMIF facility has been designed from the outset to accommodate a possible future expansion in irradiation capacity and test volume. Two additional accelerators can be added so that two test assemblies could be irradiated simultaneously. The lithium system can be expanded so that both target systems can operate at the same time. At full-power operation, this expansion would double the test volume for the displacement rates as shown above. If needed, this additional volume would allow much more flexibility in the range of operating conditions within the test assemblies and thereby significantly reduce the time to characterize and test new material options.

OVERALL FACILITY LAYOUT

A three-dimensional view of the overall IFMIF facility is shown in Figure 1. The two parallel accelerators, each approximately 50 m long, produce a beam which is turned through approximately 90 degrees 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.

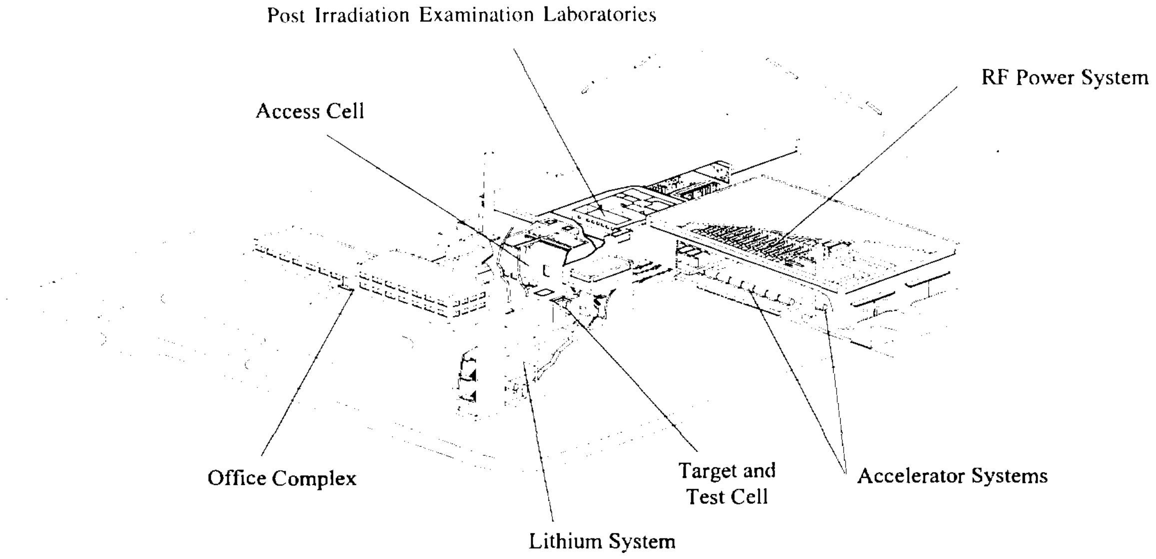


Figure 1. 3-dimensional view of IFMIF.

TEST FACILITIES

Three Vertical Test Assemblies (VTAs) are provided for a wide range in neutron flux. That is, test beds for instrumented and/or in situ experiments in metals and nonmetals can be provided for any loading regime from 50 dpa/y to 0.01 dpa/y. Detailed test matrixes have been defined for the high and medium flux regions, showing that on the basis of small specimen test technologies, a database for an engineering design of an advanced fusion reactor can be established for a variety of structural materials and ceramic breeders. Design concepts for VTAs with instrumented capsules for post irradiation and in-situ experiments using either NaK or helium gas as coolant have been developed together with the design concepts for remote handling and hot cell facilities with capacity for investigating all irradiation specimens on the IFMIF site.

The test cell (Figure 2) 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 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 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.

Major engineering efforts have been undertaken to completely remote control any maintenance and assembling/disassembling activities in the test cell, the access cell and the service cell during normal and off-normal operation scenarios. Once the specimens are retrieved from the capsules in the test module handling cell, they will be mechanically tested in the Post Irradiation Examination (PIE) hot cells followed by microstructural investigations like Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM) in the glove box laboratory (Figure 3). Tritium containing or contaminated specimens will be analyzed in detail in the tritium laboratory. Any tritium exposure to personal or environment will be avoided by effective tritium retention systems.

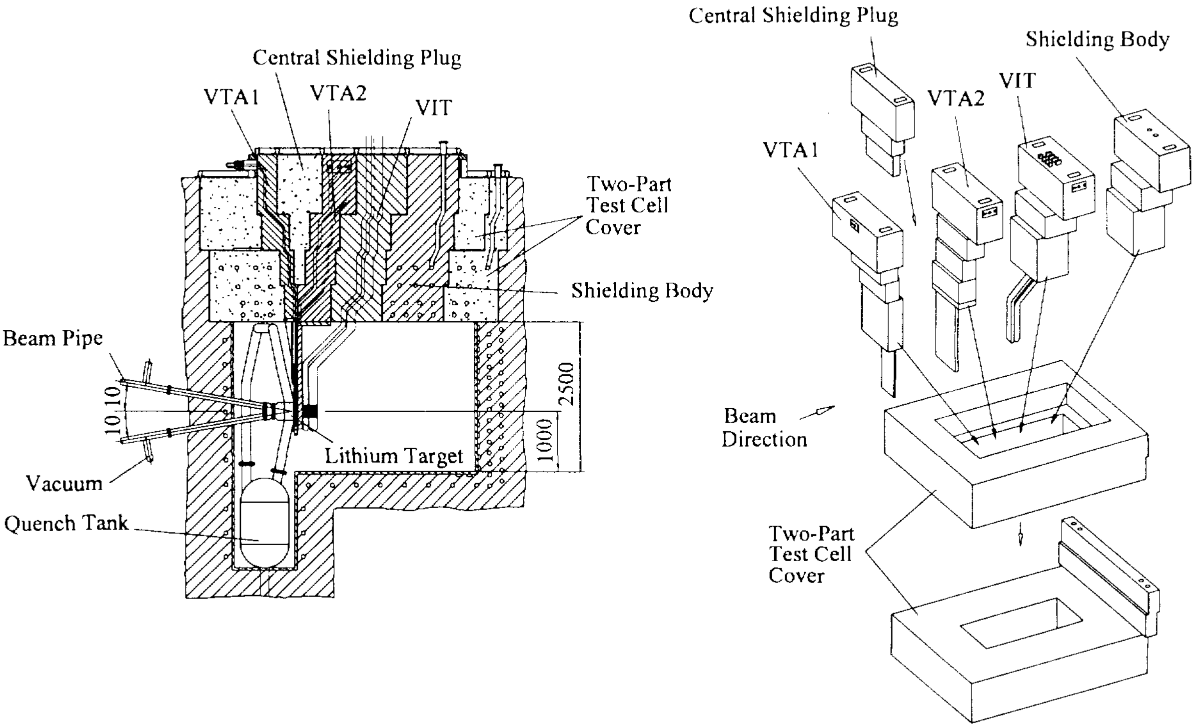


Figure 2. Test cell arrangement (all dimensions in mm).

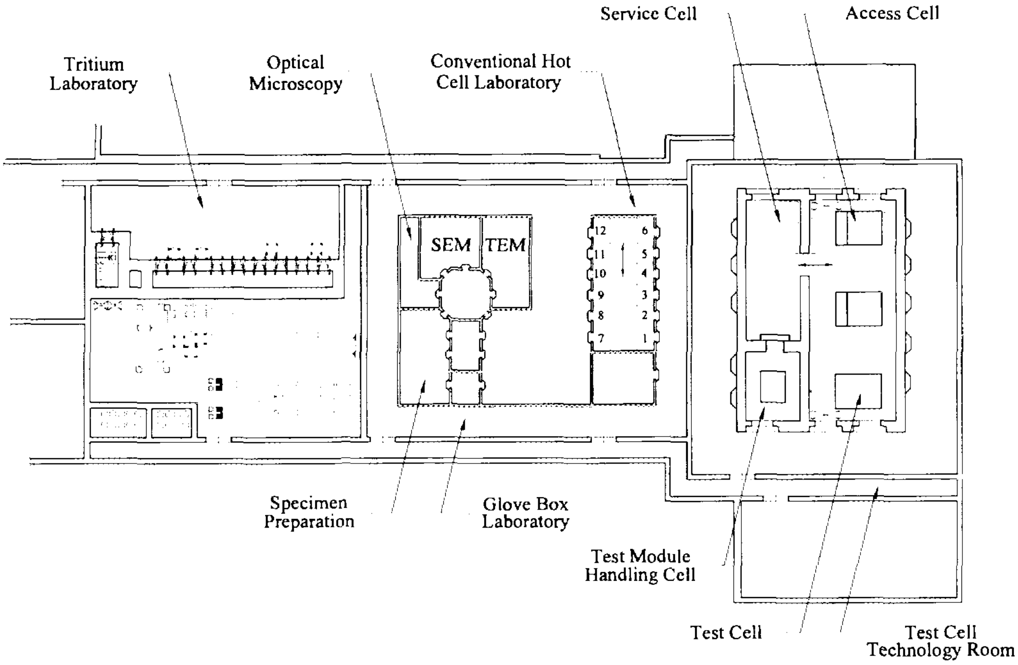


Figure 3. Testing facilities.

LITHIUM TARGET SYSTEM

The lithium target may be divided up into two basic components. The first is the target assembly itself, 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 target assembly and lithium loop will be briefly described.

The target assembly, shown in Figure 4, consists of the inlet pipe, the transition component from inlet pipe to flow straightener, the flow straightener, the nozzle, the backwall, the downstream diffuser with built-in drain baffles, and a vacuum port for connection to the deuteron beam tube. The total vertical distance from the highest point of the inlet pipe to the beam centerline is about 1.5 m. For a 40-MeV deuteron beam and a beam footprint of 5 × 20 cm^2, the nozzle lip dimensions will be 2.5 cm thick and 26 cm wide. Based upon a thorough assessment of various target designs, the modified FMIT-type target with a replaceable backwall has been selected for the baseline design. In addition there are two alternative options: (1) a scale-up version of the original FMIT target and (2) a free jet target.

The replaceable backwall is bolted to the back and sides of the target assembly. Seals around the edges will be needed to maintain different vacuum conditions in the target chamber (10^{-3} Pa) and in the test cell (~ 10^{-1} Pa). The target assembly, with the exception of the replaceable backwall, is designed to withstand neutron damage for a potential 20-years lifetime. To minimize the effect of neutron damage, permanent structural components are at least 10 cm away from the beam footprint. Part of the assembly side walls will be separately cooled on the outside by routing a small lithium stream from the inlet pipe. The replaceable backwall can be made of a different material if desired. For example a combination of ferritic steel target assembly and vanadium alloy backwall could increase the target system lifetime. The final backwall material choice will be determined by actual beam-on target testing during the initial 2-years of operation of IFMIF.

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

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.

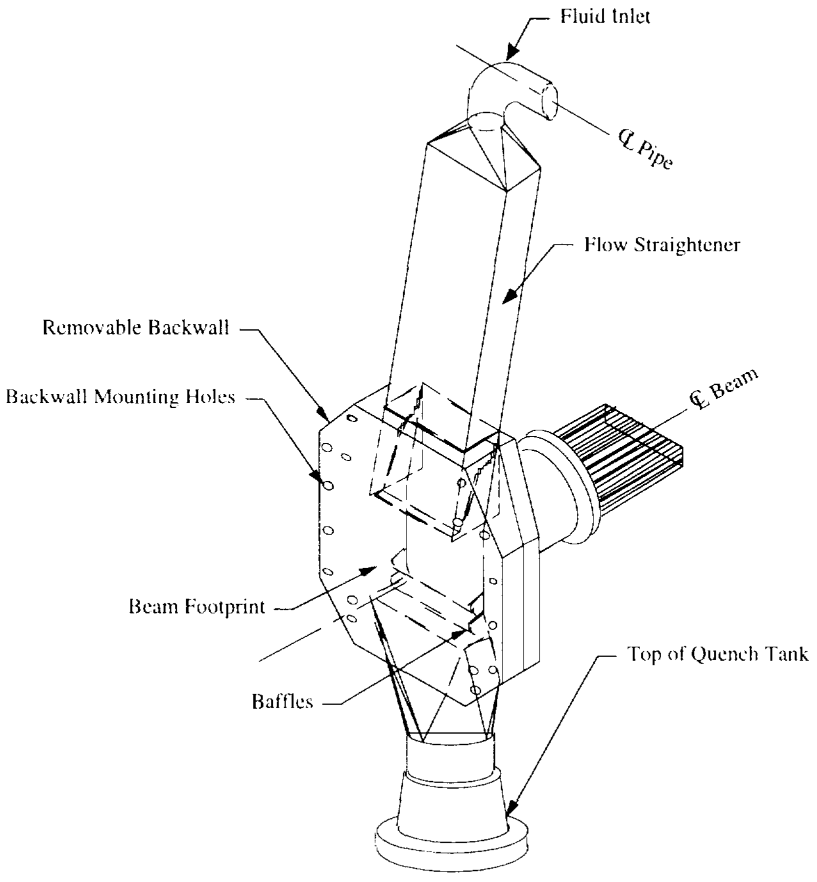


Figure 4. Target assembly with removable backwall.

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 Figures 5 and 6 (elevation and plan views), 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 Figure 6, 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 (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.

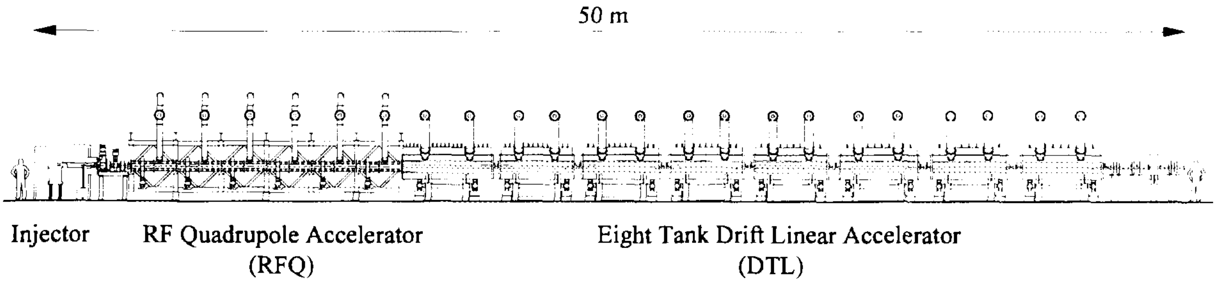


Figure 5. Accelerator configuration (elevation view).

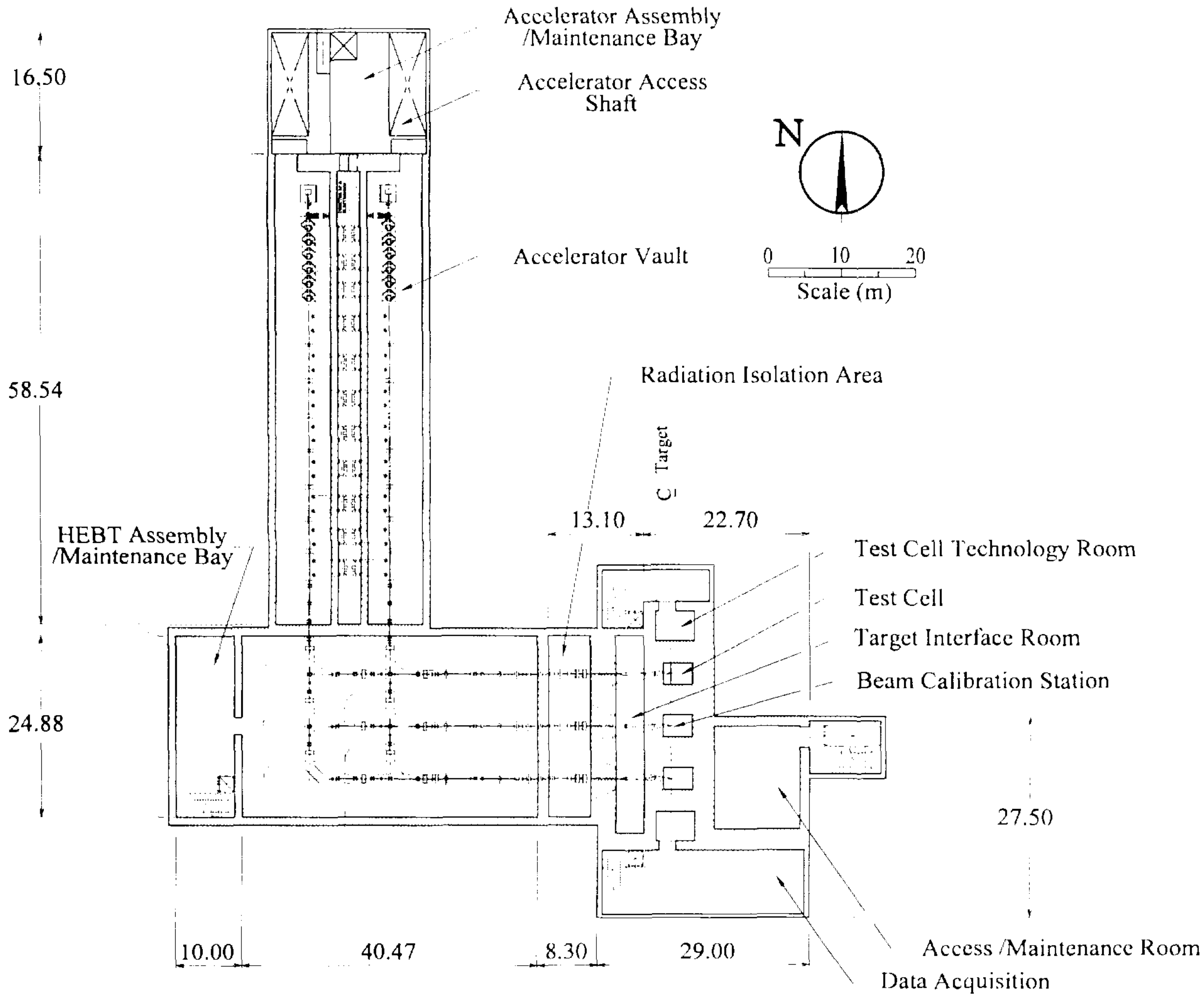


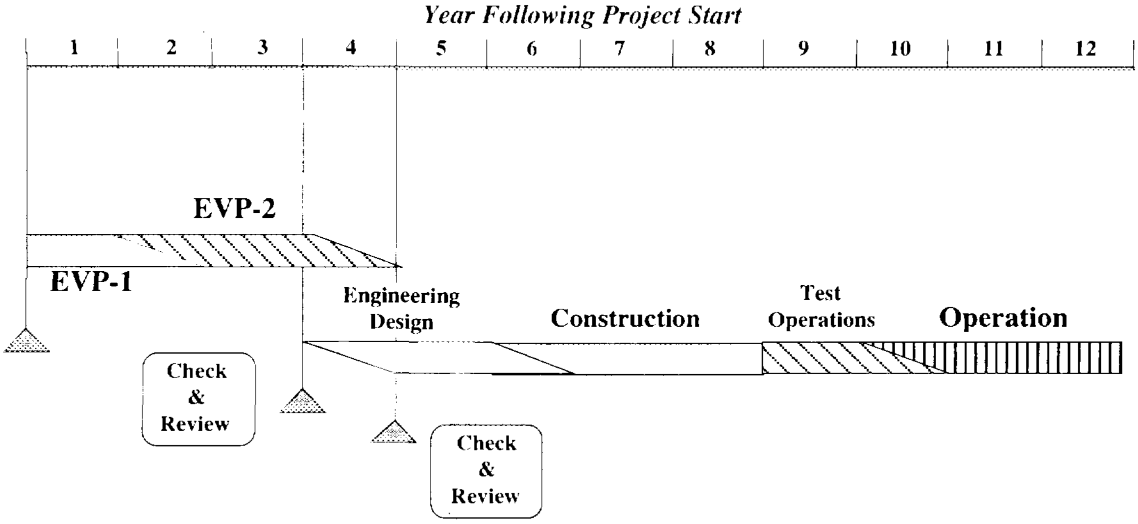
Figure 6. Overall accelerator layout (plan view).

PROJECT COST AND SCHEDULE

The long range schedule for the IFMIF program which was developed for the CDA is shown in Figure 7. The EVP is assumed to start in Year 1 of the pproject, sometime after the completion of the CDA. It includes the design, development and testing of prototype components necessary to prepare for engineering design and construction [21]. It also includes time for the checking, review and approval by the individual possible parties to the IFMIF program.

The cost of manufactured items including complex one-of-a-kind machinery is driven by international competition among industrial firms. Companies throughout the world are well aware of the market value of their goods and services and how to compete in the international market. Therefore, the cost of procured items for the IFMIF project such as power supplies, accelerator and target components and test cell equipment can be estimated by different countries within a similar range of uncertainty.

The cost of construction and operation is a much different matter. The host country must satisfy national requirements for building codes and standards, safety and environmental considerations and authorization for construction of nuclear facilities. It is clearly not possible to estimate a single project cost that would apply equally for the construction of IFMIF in Europe, Japan, Russian Federation and the United States.



EVP-1: Engineering Validation Phase-1
EVP-2: Engineering Validation Phase-2

Figure 7. Top level IFMIF schedule developed during the CDA.

The IFMIF design team developed the overall cost estimate in a very open way so that each country is aware of the areas where national considerations are different. 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 U.S. 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 [22,23] is given in Table 2. The total estimated construction cost of 797 M$ includes an allowance for indeterminates of 168 M$ which is distributed among the various systems.

Table 2. Summary of IFMIF cost estimate

WBS	System	Estimated Costs M$ (U.S.) - 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 Phase	49
Total Project Cost (TPC)		**910**

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