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IFMIF, its facility concept and technology

Tatsuo Kondo *

Tohoku University, Aoba-ku, Sendai, Japan

Abstract

The historical background and the current status of the high energy, flux neutron irradiation test facility for fusion materials development are described focusing on the recent progress of the International Energy Agency (IEA) Conceptual Design Activity (CDA) on IFMIF. The reference design incorporated the results of the past international collaboration intended to select an optimum source concept, validate relevant technologies and identify requirements for the mission. Throughout the design period, the international design team closely followed the requirements with the guide of an authorized users group. The entire process was promoted by an international steering group based on an assumed material development plan and schedule to be phased with the design and construction of the DEMO reactor. The facility is able to satisfy the requirements for hypothetical test matrices using current candidate materials and includes a flexibility for future upgrading. Options for the next required steps are also discussed. © 1998 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

During the last two decades of fusion materials research, our inability to study high energy neutron damage in materials has been a persisting concern. From both scientific and engineering aspects, the problem arises from lack of a key experimental tool, a source of neutrons for irradiation experiments that are specific to a fusion reactor environment.

Since the beginning of fusion development, however, it was understood that controlling the neutron damage to materials was a critical prerequisite for fusion to be viable as an energy technology. This naturally generated an urgent need to construct and operate at least one adequate reliable experimental tool that could test materials in a simulated fusion neutron environment [1]. To optimize such a mission, the function and capability of the facility must have been defined carefully in terms of energy-spectral characteristics and the flux-fluence capacity for testing.

2. History and background

An apparent fatal contradiction exists in the strategy for testing materials for fusion reactor applications. Different from the situation in fission nuclear technology, there is little likelihood for obtaining a high flux, high volume source of fusion neutrons any time before successful operation of an advanced fusion reactor such as DEMO. Providing neutron environments of flux, and fluence levels higher than or similar to those expected at the first walls in DEMO reactor would be possible by the use either of neutron sources using accelerator-based or plasma driven designs that could achieve locally intense neutron fields.

The requirements for a neutron irradiation test bed for material testing in general are expected to be:

1. Spectra to produce irradiation effects in materials similar to that expected to occur in fusion reactors.
2. Test volume, with sufficient size and flux uniformity, to adequately accept the specimens or test rigs that are needed for R&D programs.
3. Neutron flux intensity for dose rate simulation sufficient for analyses of phenomena critical in predicting material performance.
4. Ability to provide tests to life-time fluence levels within a realistic time period, which would require operational stability of the facility.

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* Address: Department of Materials Science, Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken, Japan. Tel.: +81 29 282 6146; fax: +81 29 282 5551; e-mail: kondot@popsvr.tokai.jaeri.go.jp.

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In the case of fusion, requirement (1) is of particular importance due to the unique spectral character of D–T fusion neutrons. The measure of how the spectra can be similar to fusion neutron spectra may be the ratio of the gaseous or solid nuclear transmutations (such as helium in atomic ppm) and the atomic displacement damage, expressed by the number of displacement events per unit volume of material, dpa. Accelerator-based neutron facilities can uniquely satisfy such requirements, but because they are basically point sources, solutions for requirements (2)–(4) are difficult to achieve.

2.1. Evolution of the technology

The pioneering work for an accelerator-based neutron irradiation facility was begun early in the 1970's in the USA [2] and the technology development was implemented in the period 1978 to 1984 by the Fusion Materials Irradiation Facility (FMIT) Project [3]. The project utilized a source based on the deuteron–lithium stripping reaction (D–Li source) with a high current linac injecting 100 mA deuterons on to a liquid lithium target at 35 MeV to produce neutrons with an energy spectrum peaked at around 14 MeV. In about 5 years of development, the project successfully reached the preconstruction stage, but the project was cancelled due mainly to lack of financial support. During an effort to rescue the project, a team of specialists was organized by the International Energy Agency (IEA) to review the viability of the technology in 1984. This international assessment yielded the conclusion that the technology and facility design were mature for construction, provided that a successful beam-on-target demonstration test was conducted. The team, however, pointed out a few problems that needed to be solved:

1. The need to clarify and avoid, any, possible adverse effects of the high energy tail, the portion of the neutron spectrum above 14 MeV, where reliable nuclear data were lacking.
2. The test volume needed to be at least 100 ml without steep flux gradients.

Solutions to those issues were found after a decade of elaboration, and triggered the International Energy Agency Conceptual Design Activity on International Fusion Materials Irradiation Facility (IEA IFMIF-CDA). The essential basis for IFMIF reference design, however, was the FMIT concept and technology achieved in its design.

2.2. Post FMIT activities

The urgent need of building such an intense, high energy neutron source was repeatedly endorsed in the IEA's formal international assessments made before and after the unfortunate cancellation of FMIT, e.g. by the Cottrell Blue Ribbon Panel [1] in 1983 and by the Amelinckx Senior Advisory Panel in 1986 [4]. Those panels emphasized the importance of an immediate effort to construct such a facility in concert with the development of fusion power technology and its socially acceptable features.

In the last decade, a group of materials scientists working under the auspices of the IEA Fusion Materials Agreement followed those recommendations by examining and selecting a potential neutron source concept. Organized meetings in the form of repeated international workshops [5–7] were held for specialists in the fields of neutron irradiation effects, neutronics, and, specific facility technologies such as accelerators and radiation tests in order to reach a realistic neutron source concept guaranteed to provide high suitability and technical maturity.

The start of the IFMIF activity occurred in February 1989 when an IEA International Workshop was organized at San Diego, USA and produced the selection criteria shown in Table 1 [5]. It initiated active dialogues between the communities of materials research and facility design and operation. The process for the source evaluation based on this selection criteria has been re-

Table 1
Requirements for an intense neutron source [5]

1.	Neutron flux/volume ratio: equivalent to 2 MW/m^2 in 10 l volume [later revised to 1 l] (1 MW/m^2 corresponds to 4.5×10^{17} n/m^2 s for En = 14 MeV, producing 3×10^{-7} dpa/s).
2.	Neutron spectrum: – Should meet first wall neutron spectrum as near as possible. – Quantitative criteria: primary recoil spectrum, PKA, and important transmutation reactions (He, H).
3.	Neutron fluence accumulation: DEMO-relevant fluences of 150 dpa$_{NRT}$ in a few years.
4.	Neutron flux gradient: $\leqslant$ 10%/cm based on minimum dimensions of CT and Charpy-V specimens.
5.	Machine availability: 70%.
6.	Time Structure: quasi continuous operation.
7.	Good accessibility of irradiation volume for experimentation and instrumentation.

1 MWy/m^2 = 10 dpa$_{NRT}$ for Fe.

viewed elsewhere [7–9]. Also, a conceptual modification of the D–Li source was undertaken by the Energy Selective Neutron Irradiation Test (ESNIT) Program in Japan (1988–1992) [10–12] based on recommendations from the earlier FMIT exercise. Those activities helped to solve the key problems that had been the sources of criticism on the suitability of the D–Li source for this application.

3. Organization of IFMIF-CDA and its mission

3.1. Organization of the CDA

Persistent efforts eventually yielded a new activity when in 1993 the IEA Fusion Power Coordinating Committee (FPCC) requested that the Executive Committee for the Fusion Materials Research Implementing Agreement (FMRIA) to summarize the progress in selecting a neutron source concept. The planning then accelerated in 1994 with the organization of an international design activity. A proposed plan for the IFMIF was accepted in 1995 by the FPCC, with the organization structure as shown in Fig. 1 [13]. The details of the CDA operation since the onset of that official action appear in the summary report [13] with full lists of the associated workshop proceedings and the latest technical implications published in several papers included in this volume.

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 database of material-specific activation and radiological

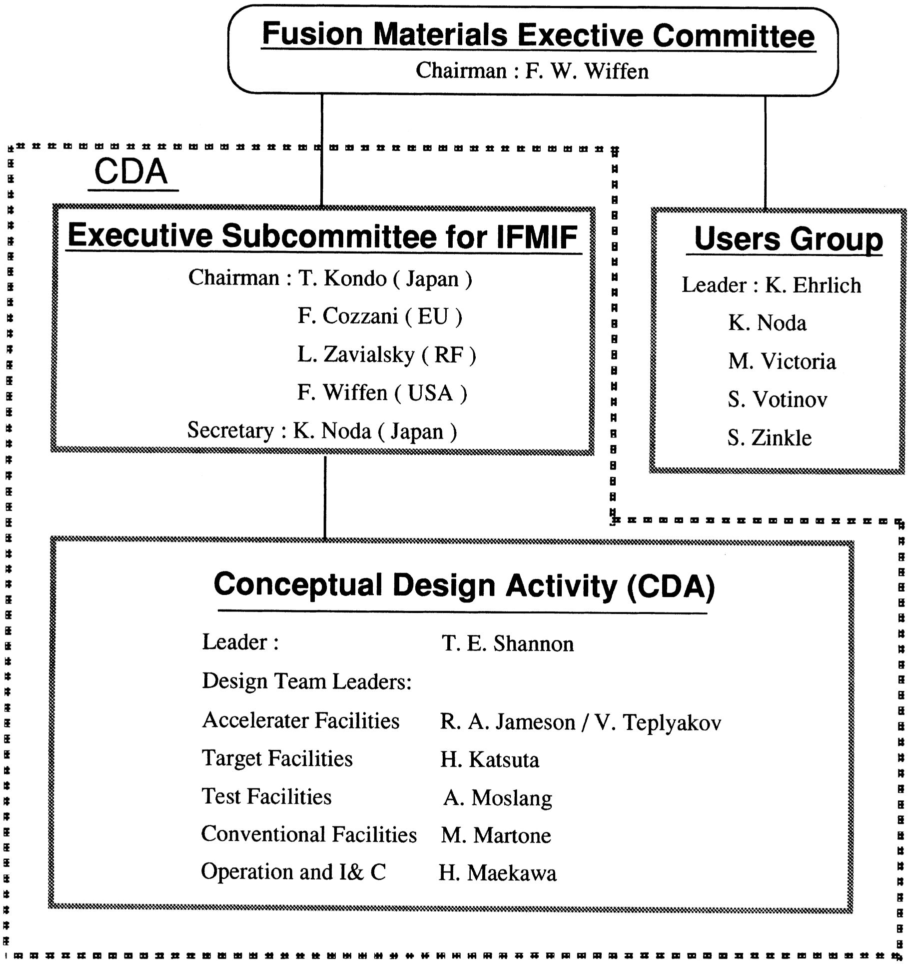

Fig. 1. Organization structure of IFMIF–CDA [13].

properties data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal systems. The direct objective of the 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 main effort of the CDA on the IFMIF was initiated in early 1995 and lasted for 2 years (implementing phase/April 1995–March 1997). The summary report completing the initial charter was published in early 1997 [13]. Most of the technical description presented hereafter is based on this report. The activity was under the auspices of the IEA FMRIA. An Executive Subcommittee organized under the Executive Committee of this agreement was charged with overseeing the IFMIF-CDA work. Participating parties in the CDA are the European Union, Japan, and the United States, with the Russian Federation as an associate member.

3.2. Execution of the CDA

The guiding principle referred to throughout this design activity was to meet the requirements of the expected users, i.e. the scientists developing materials for fusion systems. The Executive Subcommittee was to confirm that the final facility specifications achieved by the CDA was capable of fulfilling the user requirements, especially those on materials for DEMO-stage fusion reactors.

The design drawings were produced by the international specialists team composed of five specialist groups, including the Design Integration Group (T.E. Shannon, see Fig. 1). The international groups of talented experts from participating parties (with a total annual work force of 25 person per year shared by the participating parties) completed home assignments and reported results at workshops on each of the three major subsystems, i.e., test facilities, liquid metal target, and accelerator. The subsystem designs were then combined systematically at periodic design integration workshops.

The framework of the reference design was generated in the first year of the project. The activity then added assessments for cost, safety and RAM (Reliability, Availability and Maintainability) in the second year after the mid-term interim report was published. Options for continuation of the activity from the current CDA stage to the eventual construction and operation of IFMIF were also assessed. Some supplementary research and development tasks were identified for implementation in future phases. Decision for the next step, however, has been delayed since the January 1997 FPCC meeting.

Table 2
Irradiation parameters for different materials to be tested in IFMIF [13]

High flux regime		
Materials investigated		
First wall and blanket structrual materials		
Material/Irradiation condition		
Ferritic–martensitic steels:	250–500°C,	150 dpa
Vanadium alloys:	250–600°C,	150 dpa
SiC/SiC-composites:	400–1000°C,	150 dpa
Type of experiments		
Mainly instrumented capsules for post-irradiation tests		
In a later stage fully instrumented in-situ tests on creep-fatigue and IASCC		
Medium and low flux regimes		
A variety of different materials has to be tested under different irradiation conditions		
Material/Irradiation condition		
Ceramic insulator materials:	RT–500°C,	0.1–10 dpa
RF-windows:	RT–400°C,	0.1–10 dpa
Diagnostic materials:	RT–400°C,	0.001–1 dpa
Ceramic breeder materials:	300–700°C,	1–50 dpa
Superconducting materials:	4–100 K,	<0.1 dpa
Structural materials:	Specific tests on low dose effects, etc.	
Fully instrumented in situ tests under irradiation, e.g.		
Fatigue and crack growth tests		
Stress-corrosion tests (IASCC)		
Radiation induced conductivity and electrical degradation (RIC, RIED)		
T-diffusion and release measurements		

3.3. Requirements and tests to be made by IFMIF

It is expected that a large variety of materials must be tested in order to develop materials for DEMO. In this CDA, several iterations were considered to configure possible test matrices into the available flux and volume options. The results are summarized in Table 2 [13,14]. As seen, much of the attention has focused on the structural materials for tests in the high flux, limited volume regions, whereas more space at limited flux was available for the tritium breeding and other functional materials.

4. Features in the reference design

4.1. The outline of the reference design

A schematic layout of the reference design is shown in Fig. 2. In the final reference IFMIF design, the two 125 mA deuteron accelerators shown will have a combined capacity of 250 mA at 32, 36, and 40 MeV.

(1) Flux–volume capacity

The beams impinge on a liquid lithium jet target which can provide a high energy neutron test field with flux–volume capacity of:

1. >5 MW/m^2 in approx. 100 cm^3
2. >2 MW/m^2 in approx. 500 cm^3
3. >0.1 MW/m^2 in approx. 6–10 l

As a function of damage rate the flux–volume relations for different material-coolant options are given in Table 3 [7]. The high flux zone of the test volume can achieve the neutron fluence corresponding to a radiation damage level of 100–150 dpa, which is required for lifetime testing of fusion first wall materials.

Table 3
Test volume available for various damage rate levels in standard loading modules (cm^3) [7]

Annual damage rate	Loading materials (Specimen/coolant)		
dpa/y	Fe/NaK	Fe/He	SiC/NaK
>40	35 (110) [a]	36 (112) [a]	86 [b]
>20	312 (520) [a]	320 (530) [a]	460
>10	800 (1080)	820 (1100) [a]	1060

[a] Volumes without and with parenthesis are for incident deuteron energies 35 and 40 MeV, respectively.
[b] Value calculated for pure Si.

(2) Satisfaction of the basic requirements

At 70% availability lifetime tests can be achieved in 3–4 years. Several other key items of the users' requirements including irradiation parameters such as continuous time-structure of neutron generation, experimental accessibility and future up-grade capacity are carefully incorporated in the design.

4.2. Features in the reference design

Some typical features of the design in addition to the accelerator layout described above were innovated in response to the Users' Requirements;

(1) *High energy tail and energy selectivity*: The issue of the high energy tail effects was covered by making the incident deuteron energy selective in 3 steps. Reduction of the incident beam energy will shift the average neutron energy distribution to a lower level in return for lower neutron yield. The choice of the lower level is

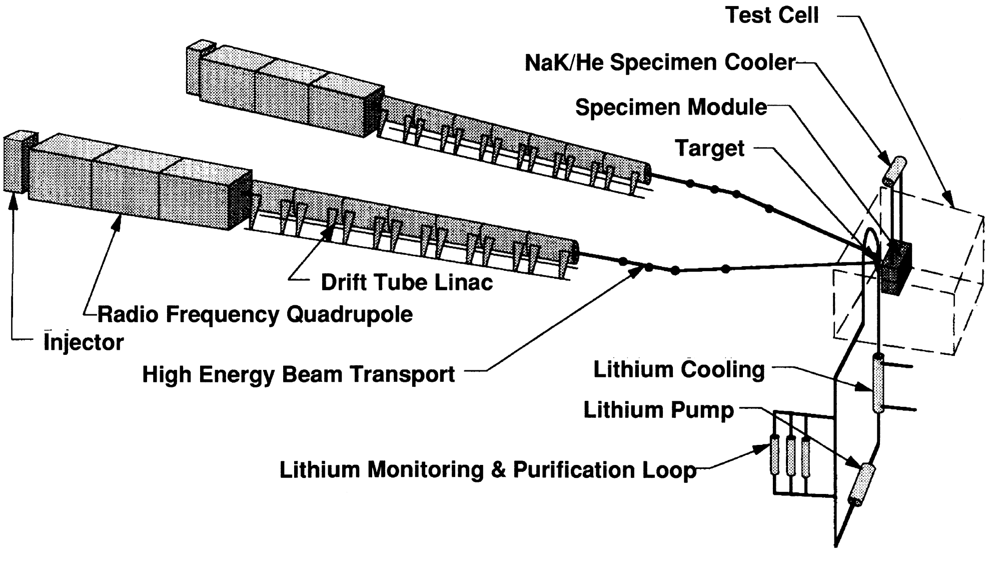

Fig. 2. Schematic layout of IFMIF [13].

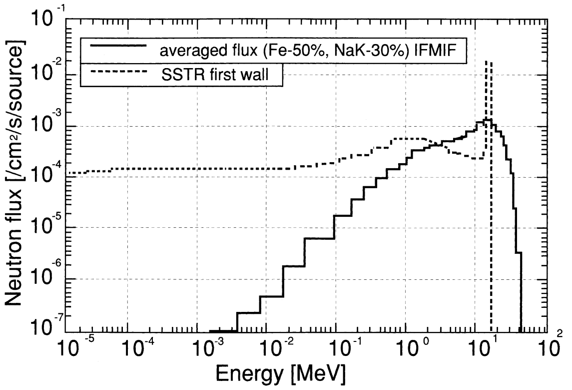

Fig. 3. Comparison of neutron flux spectra for IFMIF and an SSTR first wall [17].

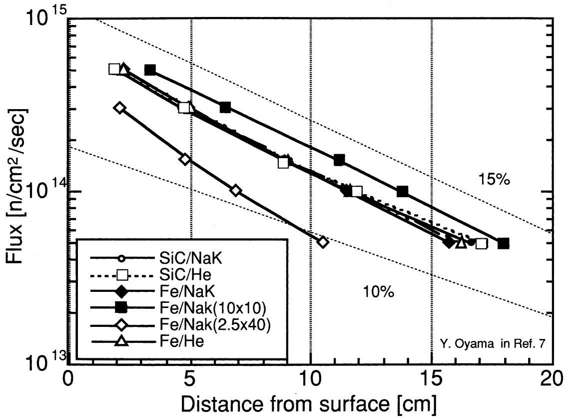

Fig. 4. Neutron flux gradient inside the test cell for different beam shapes and material loadings [7].

needed in order to test ceramic carbon based materials in which ratio of transmutation versus displacement damage is critical under 40 MeV operation. For the tests on structural metals, 40 MeV operation for high efficiency can be used with lower risk.

(2) *Modular accelerator arrangement*: The total beam current of 250 mA was the starting basis for the reference design, which was a compromise between the test capacity required and the state-of-the-art of the technology for the facility. The use of a set of two 125 mA accelerator modules (See Fig. 2), delivering 250 mA of deuterons at 40 MeV on a single target, provides operational redundancy by allowing the operation to continue at 125 mA when one or the other of the two accelerators is temporarily removed from service for repair.

(3) *Spectral similarity and test field characterization*: An IEA Neutron Source Working Group, established in 1990, evaluated physical damage parameters which are necessary to quantify the radiation characteristics [15,16]. Quantitative criteria are the displacement rate, the primary recoil spectrum and important gaseous and solid transmutations. This work concluded that differences in damage parameters among typical high energy tails generated by various sources could be tolerated. Fig. 3 and Table 4 compare respectively the energy spectra of a typical averaged case of specimen loading in IFMIF and the formation of gaseous transmutants as compared to fusion reactors.

The above described energy selectivity procedure for the incident deuteron energy given to the Reference IFMIF Design is expected to moderate the spectral "high energy tail" effects intrinsic to a D–Li source. A set of conceptual R and D tests for possible DEMO reactor materials was developed by the Users' Group, and it was adapted to the design of the test system.

The original requirement that the flux gradient be less than 10% was not fulfilled as shown in Fig. 4. The recent progress in the development of miniaturized specimen test technique, based on the IFMIF needs are providing solutions.

(4) *The interface between the liquid lithium target and accelerators*: The optimized design of the interface structure for a deuteron beam with a 5 × 20 cm footprint brought substantial tolerance for the high accelerator beam current. This widened footprint design is not only suitable to provide a uniform neutron flux distribution but it is also effective in solving the intrinsic critical problem of a high energy deposition rate. The impinge of the deuteron beams with increased current otherwise could cause lithium boiling or surface sput-

Table 4
Comparison of gas production rates for a first wall loading of 2 MWY/M^2 [7]

Facility →	DEMO [a]		IFMIF [b]					
			30 MeV		35 MeV		40 MeV	
Product → Element↓	He	H	He	H	He	H	He	H
V	89	374	131	570	227	905	350	1280
Fe	189	709	260	1505	386	2220	528	3050
Cr	282	722	240	1410	401	2310	604	3470

[a] U. Fischer.

[b] I. Gomes, Ref. [7].

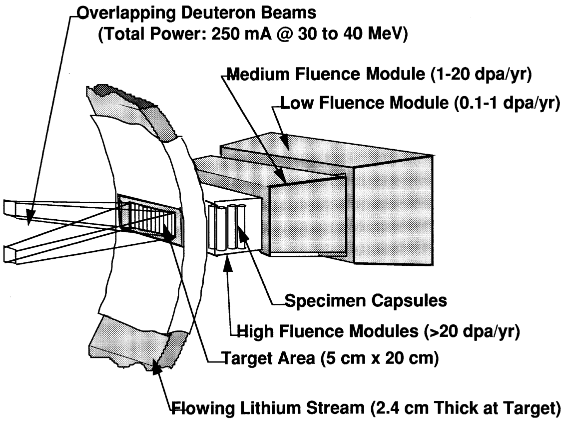

Fig. 5. Interface of IFMIF facilities in the test cell [13].

tering. The improvement in the interfaces between accelerator, target and test facilities made possible an efficient cascade arrangement from high to low flux regions as illustrated in Fig. 5.

The back plate of the target is designed to be removable. Prompt replacement of this component, when damaged by neutron bombardment, should minimize the down time.

4.3. Other key items

The site requirements for the facility of the reference design demonstrate the need for a 10 hector site within a nuclear facility zone with capacity for approx. 95 m^3/min cooling water and 52 MW electric power. An illustrative view of IFMIF is shown in Fig. 6.

The safety assessment indicated that 3–5 g of tritium and 5×10^{-4} appm beryllium[7] are the expected radioactive inventories in the continuously processed recirculating liquid lithium system.

The cost for construction of IFMIF in the reference design was estimated to be approximately 800 MUS$, while the total project cost including engineering validation and startup and commissioning amounted to about 900 MUS$ (US$ as of January 1996).

5. Perspective

Development of fusion materials naturally requires a long-term strategic approach which includes innovation and qualification of materials that are tailored for fusion applications. Fig. 7 illustrates such a strategic process in which different irradiation facilities are arranged in a sequence based on their potential capacity and timing.

At the start of the CDA, a schedule was prepared for work needed to start irradiation testing.

This plan included 2–3 years of Engineering Validation Phase (EVP) to deal with minor engineering issues that could affect the subsequent construction design. In order to be consistent with the ITER–DEMO process, the projected start of neutron test using IFMIF was expected in the first decade of 2000. This assumes that a decision for moving to EVP should be made before the beginning of the next century. Just as with ITER, the

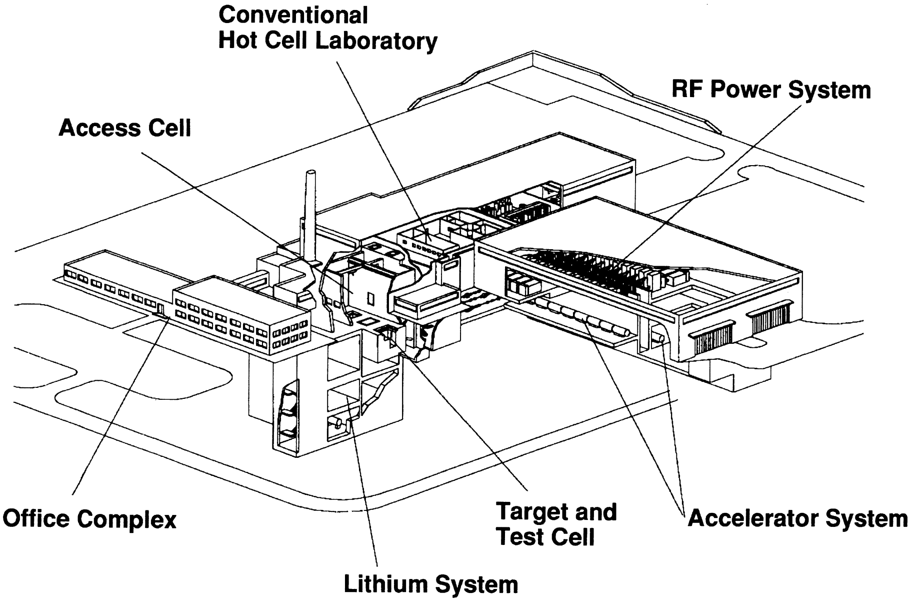

Fig. 6. Bird's eye view of IFMIF [13].

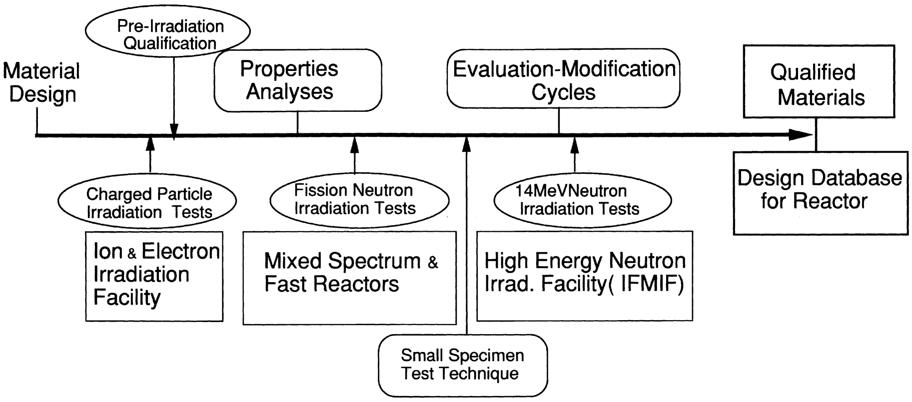

Fig. 7. Strategic process of fusion materials development.

IFMIF will be a rate controlling step toward eventual commercial fusion power development.

5.1. International collaboration and programs

It has been very encouraging for us to have completed the multi-disciplinary design of IFMIF with very limited resources (2 years at 25 my/y) without a permanent working facility. Periodic interactions between home teams on tasks shared on an international level were successfully coordinated through frequent multi-channel communications and yielded effective workshops on individual tasks conducted at appropriate intervals.

6. Concluding remarks

The IEA Executive Subcommittee and Executive Committee confirmed that the final facility specifications achieved by the CDA was capable of fulfilling the expected users' requirements, in order to meet the R&D materials needs for a DEMO-stage fusion reactor. As these materials issues have already been recognized as generic to fusion engineering regardless of the design specification of reactors, the decision to proceed to an engineering stage can move forward. An achievement of the IFMIF design is to allow us to move toward construction once funding is identified.

Finally it should be noted that the CDA has been very successful because it was organized with highly dedicated members who had the best available expertise, and worked together with enthusiasm. 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 collection of rare human talents.

Acknowledgements

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References

[1] A. Cottrell et al., Report of the Panel on Fusion Materials Research and Testing, IEA, 1983.
[2] E.W. Pottmeyer, Jr., J. Nucl. Mater. 85/86 (1979) 463.
[3] A.L. Torego et al., Nucl. Technol. Fusion 4 (2) (1983) 695.
[4] S. Amelinckx et al., Materials for Fusion, Report of International Senior Advisory Panel on Fusion Materials, IEA, 1986.
[5] J.E. Leis et al. (Eds.), in: Proceedings of IEA Workshop on the International Fusion Irradiation Facility, San Diego, CA, 1989.
[6] A. Miyahara, F.W. Wiffen (Eds.), in: Proceedings of the International Panel on 14 MeV Intense Neutron Source based on Accelerators, Tokyo, Japan, NIFS-W2-2 Report, 1991.
[7] K. Ehrlich, E. Daum (Eds.), in: Proceedings of IEA Workshop on Selection of Intense Neutron Sources, Karlsruhe, Germany, KfK Report 5296, 1994.
[8] T. Kondo, H. Ohno, R.A. Jameson, J.A. Hassberger, Fusion Eng. Design 22 (1993) 117.
[9] T. Kondo, D.G. Doran, K. Ehrlich, F.W. Wiffen, J. Nucl. Mater. 191–194 (1992) 100.

[10] T. Kondo, H. Ohno, M. Mizumoto, M. Odera, J. Fusion Energy 8 (1989) 229.
[11] K. Noda et al., J. Nucl. Mater. 174 (1990) 319.
[12] K. Noda et al., J. Nucl. Mater. 191–194 (1992) 1367.
[13] M. Martone (Ed.), IFMIF – International Fusion Materials Irradiation Facility Conceptual Design Activity, Final Report, IEA Document, ISSN/1120 – 5563, 1996.
[14] T. Kondo, T.E. Shannon, K. Ehrlich, J. Nucl. Mater. 233–237 (1997) 82.
[15] D.G. Doran, F.M. Mann, L.R. Greenwood, J. Nucl. Mater. 174 (1990) 125.
[16] D.G. Doran, S. Cierjacks, F.M. Mann, L.R. Greenwood, J. Nucl. Mater. 218 (1994) 3717.
[17] Y. Oyama, K. Kosako, K. Noda, Neutronic Analyses of the IFMIF – Japanese Contribution — , JAERI-Research-97-065, Japan Atomic Energy Research Institute, October, 1997.