JAERI-Tech--96-036 JP9701005

JAERI-Tech
96-036

JP9701005

ADDENDUM TO IFMIF-CDA INTERIM REPORT

August 1996

IFMIF-CDA team

日本原子力研究所
Japan Atomic Energy Research Institute

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編集兼発行　日本原子力研究所
印　　　刷　㈱高野高速印刷

JAERI-Tech 96-036

Addendum to IFMIF-CDA Interim Report

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(Received July 10, 1996)

During the second IFMIF-CDA Design Integration Workshop, the conceptual design and contents of "IFMIF-CDA Interim Report" were examined and discussed at both general and group meetings. Based on these discussion, the final IFMIF-CDA Report will be modified from the "Interim Report". This report describes the outline of these modification.

Keywords : Fusion Material, Neutron, Irradiation Damage, Irradiation Facility, Lithium Target, Linear Accelerator, IFMIF, IEA, Interim Report

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(Eds.) Hiroshi MAEKAWA and Mizuho IDA

国際核融合材料照射施設概念設計（IFMIF-CDA）中間報告の補足

日本原子力研究所東海研究所原子炉工学部・材料研究部
IFMIF-CDAチーム

（1996年7月10日受理）

核融合炉材料照射試験を目的とした強力中性子源，国際核融合材料照射施設（IFMIF）の概念設計活動（CDA）における第2回設計統合ワークショップにおいて，昨年作成された「IFMIF-CDA中間設計報告書」の概念設計の内容が再検討された。これら全体会合および各グループ会合での検討結果を基に，「IFMIF-CDA最終報告書」がまとめられる予定である。このレポートでは中間設計報告書からの追加変更される内容の概要が述べられている。

（編）　前川　洋・井田　瑞穂

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* Major modified sections only.

* 主な修正部分のみ示す

I. Introduction

An intense fusion-like neutron source, International Fusion Material Irradiation Facility (IFMIF) was planned under the International Energy Agency (IEA) co-operative program, and the Conceptual Design Activity (CDA) started in February 1995. Followed to the technical group meetings of "Test Cell/User", "Accelerator" and "Target", the first Design Integration Workshop of IFMIF-CDA was held in October 1996 at ORNL in order to prepare the "IFMIF-CDA Interim Report". The interim Report was published as ORNL/M-4908 (Dec. 1995) and JAERI-memo 08-108 (March 1996). The second Design Integration Workshop of IFMIF-CDA was held on May 20 - 27, 1996 at JAERI/Tokai. During the 2nd IFMIF-CDA Design Integration Workshop, the conceptual design and contents of "IFMIF-CDA Interim Report" were examined and discussed at both general and group meetings. Based on these discussion, the final IFMIF-CDA report will be modified from the "Interim Report". This report describes the outline of sections to be modified.

II. Addendum to Interim Report

2. Project Description

2.3 Operational Requirements

Some modification will be done in the several sections based on the suggestion from the Accelerator, Target, Test Cell/Users and Design Integration groups along with the missing parts (TBD). A sammple is shown below:

2.3.1.5 Hot Test of Test Assembly

Performance testing of the VTAs will be combined with the target testing program. During the hot test phase the test modules will be equipped with a sufficiantly high number of thermocouples and dosimetry foils to measure accurately the temperature and neutron flux distribution as function of times and beam current. These investigations are indispensable for the assessment how close the actual irradiation conditions meet the initial user´s requirements and the verification of the overall test module concept. Similar to the Li-target test phase, the structural integrity of the test module will have the highest priority. Therefore
it is intended, to analyze within short time periods the dimensional stability and any surface (frack initiation and propagation) of the test module and its interior.

2.3.2.4.2 Normal VTA Change-out Operations

Figure 2.3.2-x shows the specimen change-out cycle for the initial facility operation with a single test cell and Figure 2.3.2-y shows the two Test Cell operation. The change-out process is summarized in **Table 2.3.2- 1** assuming NaK as the coolant. It is assumed that Helium will be an easier and quicker change-out option. Appendix E provides a more detailed listing of the basic steps required to changeout the VTAs.

During the initial operation of IFMIF only one Test Cell will be functional. As a result, a delay of approximately 8 days will be required to accommodate the removal of the completed VTA, replacement of the target and the reloading of the new VTA.
A basic assumption has been made that all NaK cooled modules are attached with ferrule tube connectors. This may not be possible for the high temperature units (800&1000℃). For such temperatures the reference concept provides a helium cooled high flux test module with rigs and an additional gas gap between the rig and the specimen encapsulation to ensure that the temperature of all structural components can be kept well below the nominal specimen irradiation temperature.

Table 2.3.2-1. Summary of Specimen Changeout process.

	Operation	Time (Days)
1.	Shutdown Test Cell Operations	1
2.	Remove Vertical Test Assemblies	1
3.	Remove test modules from VTAs,	2
4.	Remove specimen encapsulations from test module	1
5.	Cut encaplsulations and retrieve specimens	2
6.	Sort and reload test modules,	30
7.	Install modules on VTAs,	1
8.	Test of instrumentation and seals, VTA Checkout	1
9.	Install VTAs in Test Cell,	1
10.	Startup Test Cell and VTAs	1

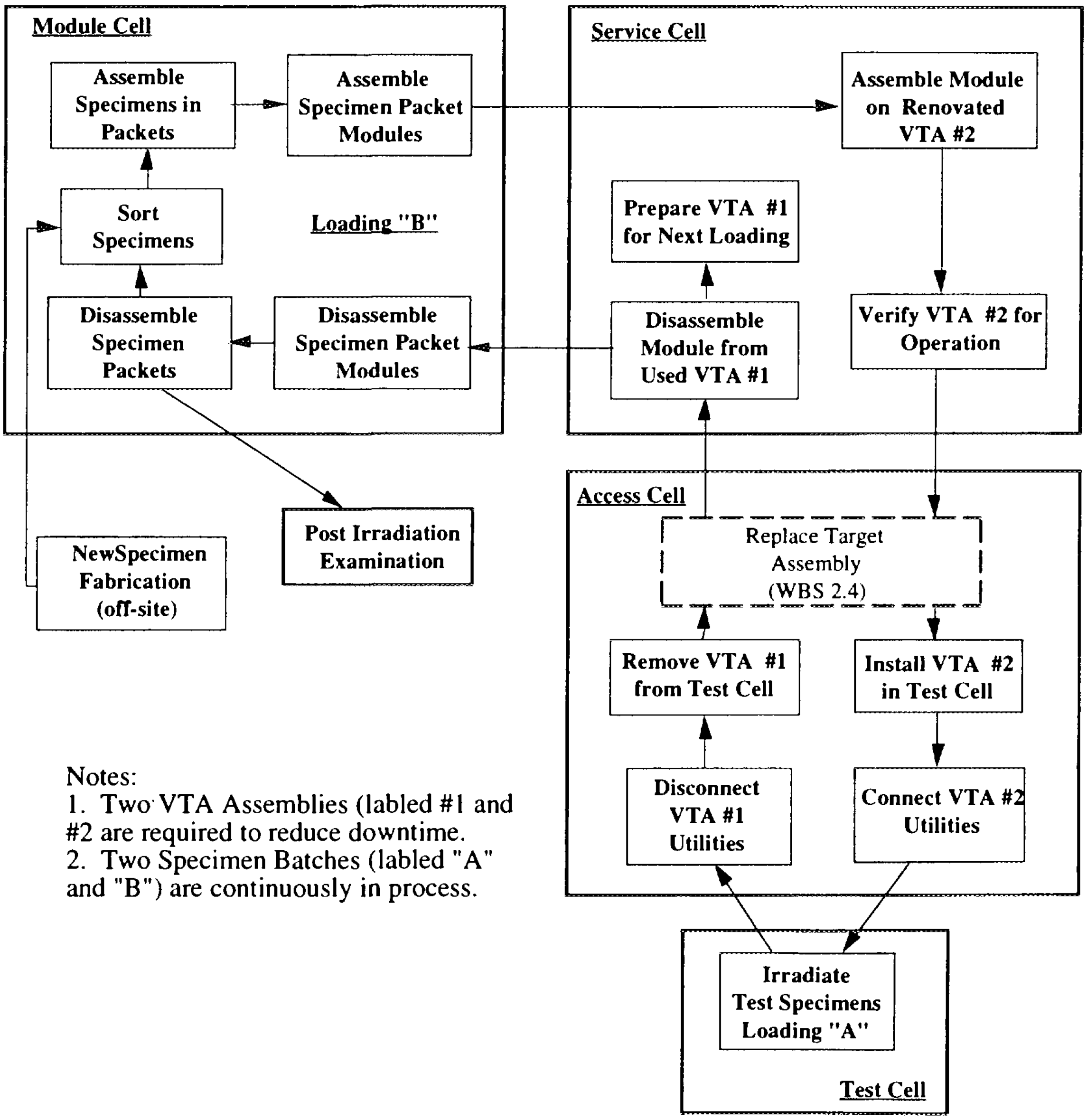


Figure 2.3.2-3. VTA change-out cycle for one Test Cell operation.

2.4 Test Facilities

The information that follows is intended to supplement the previously published IFMIF-CDA Interim Report based on items discussed at the 2nd IFMIF Design Integration Meeting held in Tokai, Japan from May 20-25, 1996. Specific items that are discussed below include (1) design revisions to the Test Cell, VTAs, Access Cell, PIE Facilities, Tritium Laboratory, and the Test Facility Ventilation System, (2) revised inputs on operations and maintenance, and (3) initial inputs on the Test Facility cost estimate. The numbers listed above each section are intended to indicate the section of the Interim Report that is addressed. Since this new text is intended to be supplemental, it is not necessarily meant to replace the entire section of the Interim Report.

The elements of the Test Facilities portion of the Work Breakdown Structure as revised and used to compile the cost estimate are attached to the end of this addendum. Costs were estimated for all fourth level (e.g. 2.x.x.x) subelements under the Test Facility WBS 2.0.

2.4.1.1 Operating Requirements

2.4.1.3 Nuclear Waste Production and Decommissioning

2.4.2 Facility Configuration

The plan and elevation views of the IFMIF Test Cell and post irradiation specimen-testing areas have been revised to reflect the latest information.

2.4.2.1 Test Cell

2.4.2.1.1 Test Cell vessel and heat shield

The thickness of the Test Cell Liner required to sustain the 1 bar external pressure loading has been determined to be about 20 mm. Active cooling using gaseous helium is provided along the internal surface of the vessel. This will maintain the interior surface of the vessel to less than 50℃.

The Test Cell Heat Shield is placed between the exterior surfaces of the Test Cell Liner and the interior surfaces of the Concrete Shielding surrounding the Test Cell. This arrangement reduces the neutronic heat loads in the concrete shielding to a level that can be tolerated with only edge cooling of the concrete, i.e. no internal cooling required. Gaps of 25 mm thickness are provided between the Test Cell Heat Shield and the Concrete Shielding and Test Cell Liner. With the use of the TCHS, the shielding concrete and the Test Cell Liner can be simply cooled from the edges adjacent to the TCHS using the Test Cell Cooling System. This eliminates the need to use cooling passages embedded in the shielding concrete. A low-activation stainless steel is used to construct this shielding with a thickness of 500 mm needed along the surface facing the lithium target and 300 mm along the other Test Cell walls. The heat shield is cooled along its interior edge with circulating gas. With this arrangement, the stainless steel heat shield temperature can be maintained to be less than 200 ℃ on the surface facing the lithium target and below 100 ℃ on the other surfaces. With this heat shield the peak temperature of the concrete shielding surrounding the Test Cell is expected to be less than 40 ℃.

2.4.2.1.2 Removable shield plug

The latest version of the Test Cell design includes a shield plug that is placed between the two VTAa and a separate Test Cell Removable Cover that is positioned along the top of the Test Cell to provide adequate shielding to protect the VTA access area from the test cell radiation. The Test Cell Removable Cover thickness of 2.2 M is adequate to protect the equipment in the Test Cell Access Room (i.e., the dose to the equipment is expected to be small enough to allow the use of organic seal, lubricating, and insulating materials). The Test Cell Removable Cover interfaces with the Test Cell Liner to provide a vacuum enclosure within the Test Cell and with gas cooling ducts that cool the upper surfaces of the Test Cell Heat Shield. Removal of the Shield Plug is required prior to removal of either of the two VTAs. Clear access to the entire Test Cell is achieved by removing the Test Cell Removable Cover.

2.4.2.1.3 Vertical test assemblies

The number of VTAs has been reduced from seven to two and a new system, referred to as the Vertical Irradiation Tube system, has been added. This new and simpler design concept significantly reduces costs and increases the flexibility for performing tests, especially in the low and very low flu regions.

NaK and helium cooled versions of the High Flux (> 20 dpa/a) VTA (VTA-1) remain as candidates, whereas, the two VTAs formerly used in the medium flux region (1 - 20 dpa/a) have been combined into a single VTA. Developing a medium flux VTA (VTA-2) concept that incorporates specimen packets for both in-situ creep-fatigue tests and tritium-release tests remains to be done.

The Vertical Irradiation Tube (VIT) system, which consists of an array of tubes, pneumatic pumps, valves and heat exchangers, is designed for rapid insertion and removal of test specimens in the low and very low flux regions of the Test Cell. The array of tubes contains pneumatic capsules that remain in the irradiation region until the specimens are irradiated to the desired dose. The pneumatic capsules are then transported back to the Loading/Unloading Station where they are removed and placed into a shielded container and transported to the PIE Hot Cells or Lead Boxes. A thermal control system is provided that can accurately maintain and control test specimen temperatures within individual tubes, each operating at a different temperature ranging from 4 K to 800 K.

<u>Helium Cooled Concept</u>

A detailed design concept for a helium cooled high flux test module and VTA has been developed meanwhile which is based on individual, temperature controlled rigs housing the encapsulated specimens. Although a feasibility study done by the industry shows together with initial thermo hydraulic calculations, that even for a peak heat deposition of about 40 W/cm^3 specimen temperatures down to 300 ℃ can be achieved and controlled in any high flux position, the present design should be experimentally verified before it is suggested as the reference design for all temperatures from 300 - 1000 ℃. Presently the baseline design incorporates NaK for temperatures below 600 ℃ and helium gas above 600 ℃.

2.4.2.1.4 Access Room, Service Cell, Test Module Handling Cell and Test Cell Technology Room

Detailed designs are meanwhile available. An additional room side by side with the Test Cell, called Test Cell Technology Room, was necessary. It houses the test cell cooling system, the test cell vacuum pumping system, the argon backfill system and the Test Cell diagnostic and control systems.

2.4.2.2 Hot Cells and Post Irradiation Examination Facilities

The mission of the PIE Facilities remained untouched. However, significant design changes has been made in order improve users flexibility and to reduce the costs significantly.

1. PIE Laboratory: In contrast to earlier considerations, a modular type design is being considered with of a smaller maintenance room for personal access, and the actual hot cell consisting of equipment tools, similar sized testing machines, and a removable exchange system with a small bridge crane and a transfer lorry. The removable testing machines are standing side by side in two arrays and can be rapidly replaced or exchanged to carry out service in the attached maintenance room. The bulk of the test equipment in this hot cell is dedicated to mechanical tests of specimens irradiated in the high flux region. Therefore, the PIE Hot Cell includes a laser profilometry for pressurized creep tube tests and several universal testing

machines equipped with vacuum furnaces and heating systems for tensile tests, push-pull creep fatigue tests, corrosion fatigue tests, fatigue crack growth and fracture toughness tests. Based on the preliminary test matrix mentioned in chapter II, the average yield per year from the high flux region is 220 specimens, and additional 370 TEM disk samples. The overall test capacity will ensure, that the examinations on these irradiated specimens together with necessary tests on unirradiated aged specimens will be less time consuming than the irradiation itself.

2. Shielded Glove Box Laboratory. Because only very small specimens sizes are necessary for the microstructural analyses, shielded glove boxes are sufficient. A completely new laboratory arrangement is proposed. According to the international standards, this Laboratory will be equipped with 10 bench-top glove boxes, modern scanning and transmission electron microscopes (SEM and TEM), TEM specimen preparation tools, an optical microscope, a microhardness tester, a temporary vacuum storage grid for TEM specimens, and an activation analysis system. The latter is important to confirm experimentally on low and reduced activation materials the predictions from activation inventory codes.

3. Tritium Laboratory. The existing design has been developed and an effective tritium retention system was included. The capsules irradiated in the medium flux region will contain highly activated ceramic breeders like Li_4SiO_4, Li_2ZrO_3 and other innovative lithium based ceramics with considerable tritium content. Retrieval of tritium containing or contaminated specimens from the subcapsules in the test module and post irradiation examinations (PIE) of high gamma-ray activated ceramic breeders (i.e., Li_2ZrO_3) require suitable hot cells. To minimize any cross contamination and to assure effective tritium retention, hot cells for tritium contaminated and containing materials are separated from those for other materials. Fig. 7 shows a bird's eye view of the main subsystems of the Tritium Laboratory: (i) The airtight tritium handling hot cells for disassembling of the subcapsules, preparation of specimens for PIE and PIE of high gamma-ray activated specimens, (ii) the airtight tritium glove boxes to analyze small pieces of ceramic breedrs or low gamma-ray activated ceramic breeders, (iii) the tritium removal / retention systems and temporary storage for tritium contaminated or containing specimens and devices.

2.4.3 Interfaces

2.4.3.2 Test Cell - Accelerator Interface

Suitable monitoring of beam profile, beam density and beam position is still a matter of concern.

Monte Carlo calculations with good statistics done bu the accelerator group indicate, that the beam shape is not an ideal rectangle, but can be described by a wafe shaped plateau with more than 10% density alterations. The impact of this profile on neutron flux contours, and damage production and transmutations rates will be calculated by the neutronics group.

2.4.3.3 Test Cell environment

Vacuum (10^{-1} Pa) is now generally accepted for the Test Cell. All systems including VTAs, removable test cell cover, shield plugs, steel liner etc. are designed to meet the vacuum requirements.

2.4.3.4 Test Cell - Facility Effluent System

Effluent gas from the test cell and tritium laboratory will be interfaced with the Conventional facility Nuclear HVAC. Reorganization of the effluent system in the entire IFMIF facility will be investigated in t he rest of the CDA.

2.4.4 Safety Considerations

No essential changes. Four different tritium sources have been identified: The Li-Target, the test module of the medium flux region containing the breeder materials, the test cell evacuated by a suitable pumping unit, and the Tritium Laboratory. All of them will be equipped with tailor-made tritium retention systems.

2.4.5 RAM Considerations

The design changes has to be included in the available RAM analyses.

WBS 2. Test Facilities Work Breakdown Structure Elements

2. TEST FACILITIES

2. 1. Test Facility Management

2. 2. Test Facility Subsystems

2. 2. 1. Vertical Test Assemblies
2. 2. 1. 1. VTA1-NaK
2. 2. 1. 2. VTA1-He
2. 2. 1. 3. VTA2-NaK
2. 2. 1. 4. VTA2-He
2. 2. 1. 4. 1. VTA2-He Concept 1
2. 2. 1. 4. 2. VTA2-He Concept 2
2. 2. 1. 5. VIT-System
2. 2. 1. 6. Shield Plug
2. 2. 2. Test Cell
2. 2. 2. 1. Test Cell Cover
2. 2. 2. 2. Test Cell Liner
2. 2. 2. 3. Heat shield
2. 2. 2. 4. Seal Plate
2. 2. 2. 5. Camera System
2. 2. 2. 6. Neutron Source Diagnostics
2. 2. 2. 7. Test Cell Diagnostics
2. 2. 2. 8. Emergency Shutdown Sys
2. 2. 3. Test Cell Technology Room
2. 2. 3. 1. Assembly and Testing
2. 2. 3. 2. Cooling System
2. 2. 3. 3. Vacuum Pumping System
2. 2. 3. 4. Ar backfill System
2. 2. 3. 5. Diagnostics and Controls
2. 2. 3. 6. Subsystem Power
2. 2. 4. Test Facility Control Room
2. 2. 4. 1. Assembly and Testing
2. 2. 4. 2. Data Acq - VTA 1 - NaK
2. 2. 4. 3. Data Acq - VTA-1 - He
2. 2. 4. 4. Data Acq. - Creep Fatigue
2. 2. 4. 5. Data Acq - Tritium Release
2. 2. 4. 6. Data Acq - VIT
2. 2. 4. 7. Supervisory Computer
2. 2. 4. 8. Subsystem Power

2.5 Target Facility

2.5.2.2 Target Assembly

Replaceable Backwall Design :

The current reference target assembly design is one with a replaceable backwall which is bolted to the target assembly. A new replaceable backwall concept has been introduced at the Second Design&Integration meeting (5/96). The new option uses a bayonet connection method, is based on the connection system depicted in Fig. A2.5-1. The figure shows that the replaceable backwall is insert/removed by a simple loading machine. The permanent structure is equipped with slide guides and hinges for secure locking of the replaceable backwall. The seal is inserted inside a cavity machined in the internal part of the backwall. This configuration seems to provide advantages to accommodate backwall thermal expansions and allows the possibility of good sealing. The feasibility of this new option will be evaluated in more details.

Sealing of Replaceable Backwall :

Proper sealing of the replaceable backwall is an important issue. A welding connection is one of the methods to realize a firm seal with no leakage. The welding/cutting device recently developed in Japan using a high average power YAG laser can perform sealing and welding for remote-replacement of the backwall. However, rewelding of material exposed to radiation field (as low as 0.01 dpa) may not be feasible due to helium effect. The feasibility of the welding technique, described below, for the replaceable backwall requires further assessment. **Figure A2.5-2** shows a schematic of the total system which consists of a high-power laser oscillator, an optical fiber cable for power transmission and a compact welding head being positioned by a manipulator. A distinct advantage of this system is the capability to maximize the laser output while keeping sufficient beam quality for coupling into the optical fiber cable. The silica-glass-made optical fibers with a core diameter of 1.0 mm enables transmission of 4.8 kW laser power with high transmission efficiency (> 90%) over a distance of more than 120m. As shown in Fig. A2. 5-3a and Fig. A2.5-3b, this laser system prevents lithium leakage by power-controlled fine lip-seal welding on the edge of the two thin-plate rims of the backwall and the target assembly. The pressing plate fixes the backwall onto the target assembly. By increasing the laser power, the system cuts the welded edge of the rims. For one pair of rectangular rims, more than five times of welding/cutting procedure are possible. The thin rims can be placed on the test assembly side for ease of backwall maintenance. Minimization of the amount of sputter during the cut operation is one issue to limit radioactive spread around the target assembly

This laser system is applicable to any parts of the target assembly including inlet piping, nozzle, diffuser, and so on. The remote-replacing flange with lip-seal structure is used to join piping as shown in Fig. A2.5-2, enabling the remote replacement of the whole target assembly without seal ring.

Nuclear Heating in HEBT :

A preliminary neutronic analysis was performed to determine the nuclear heating deposition and generation in the backwall and HEBT. Nuclear heating during normal operation as well as decay heat generation were analyzed. Figs. A2.5-4 and A2.5-5 show the preliminary results for normal operation and decay heat, respectively. Although the total heat deposition in the HEBT was found to be small, about 1.5 kW, separate cooling of this component will be necessary. This can accomplished by diverting a small stream of lithium coolant (15 cc/s) from the main flow to the external coolant tubes around the HEBT. Decay heat generated in the backwall can be removed by a few percent of normal flow after beam shutdown. The main concern is in the case of loop failure, excessive temperature rise in the backwall may lead to melting if there was no cooling technique. One possible solution is to flood and circulate Ar gas in the test cell.

2.5.2.3 Lithium Loop

Revised Heat Exchanger Design :

The dimensions of the previous heat exchanger were based upon inlet and outlet temperatures of 220 and 270 degrees C, respectively. and the use of Syltherm as the organic coolant. At the first design integration meeting these temperatures were increased to 250 and 300 degrees C. In addition, information received from the vendor, Dow Corning, indicated that Dowtherm-A, another organic heat transfer fluid manufactured by Dow, has far superior radiation damage characteristics. This fluid has been demonstrated to be stable up to dosages of 10^{10} rads. Because of the high radiation field expected in the heat exchanger during operation, it was decided to change to this as the organic heat transfer fluid. The change in operating temperature and heat transfer fluid can be expected to have a significant impact on the performance of the heat exchanger. and therefore on its dimensions. Since the primary heat exchanger contains over 1/3 of the total loop lithium inventory, as well as being the largest single component in the lithium cell, it was considered important to redetermine the new dimensions.

The calculational methodology was similar to that used before, except that a more accurate and conservative heat transfer model was employed. The effect of all of the changes resulted initially in a design that had nearly 50% greater volume that the original one. This was considered unacceptable, and iterations performed to reduce the volume. The final design, which has 6% greater volume, was obtained by (1) reduction of the organic fluid temperature entering the heat exchanger from 220 to 190 degrees C, with a 50 degrees C temperature rise and (2) reduction in the tube spacing from 3.81 to 3.56 cm., and (3) doubling of the number of tube passes. A cross section through the heat exchanger is shown in Figure A2.5-6. For servicing, such as tube plugging in the event of a leak, access to the tubes is obtained by removal of the end opposite the tube side inlet/outlet.

The resulting heat exchanger has outside dimensions of 1.49m diameter and 4.24 meters in length, with a lithium volume of 3700 liters, compared to 3500 liters for the old design. This change is not great enough to justify any changes in tank volumes at this time.

Vacuum Turbopumps :

For the redundancy of the vacuum turbo pump, 4 additional pumps (5000 l/s x 2, 500 l/s x 2) are installed as spares. A total of 8 turbo pumps are installed in the differential pumping system of the Target-Accelerator Interface.

Cold Trap Economizers :

To avoid thermal shock on the lithium return lines from the Cold Traps, two economizers are set up on the lines for temperature control. Similar setup has been used for the Ti Hot Traps.

The additional turbopumps and cold trap economizers are included in the revised lithium loop diagram, shown in Fig. A2.5-7.

2.5.4 Safety Considerations

ENEA has carried out a detailed Failure Modes and Effects Analysis (FMEA) down to the component level for the Target Facility. The methodology of the analysis included a functional qualitative analysis of the entire plant and target systems/subsystems, as well as quantitative analysis using the Probabilitic Risk Assessment (PRA) method. Results of the FMEA analysis are being reviewed and will be included in the IFMIF Final Report.

2.5.5 RAM Considerations

Maintainability :

The preventive and corrective maintenance procedures were developed for the target system components. Details are included in a separate document which covers RAM analysis for IFMIF facilities.

2.5.7 Development Requirements

Planning for the Engineering Validation Phase activities has been developed. Three Target development tasks have been identified: (1) Target Assembly Development and Hydraulic Performance Validation, (2) Impurity Monitoring and Control, and (3) Lithium Safety. Task proposals, including estimated development costs, are shown in appendix T-1.

2.5.8 Summary of Alternatives

Lithium Loops Electromagnetic Pump :

A summary of the main EMP requirements is given in Table A2.5-1. While the actual design flow is only 120l/s, 150l/s has been specified to provide design margin, because of pressure drop uncertainties, the system pressure requirement has been set at 0.5 Mpa, about twice the anticipated requirement. A block diagram, illustrating the pump and its auxiliary control systems is shown in Fig. A2.5-8.

Cost Estimate of Target Facility :

Very detailed costing of the target facility was developed, and is reflected in separate documents.

Table A2.5-1 Summary of IFMIF Main Electromagnetic Pump Requirements

Basis of Estimate	One Pump & Set of Accessories	One Pump & Set of Accessories
Configuration	Annular Linear Induction Straight Thre Duct	Annular Linear Induction Return Duct
Design Flow	2300 gallons/min	2300 gallons/min
System Pressure	80 pounds/inch^2	80 pounds/inch^2
Input Power	3 Phase 60 Hertz 0 to 660 Volts Line-Line 90% Power Factor (Approx) Corrected	3 Phase 60 Hertz 0 to 660 Volts Line-Line 90% Power Factor (Approx)
Corrected	<200 kW (Approx)	200 kW (Approx)
Cooling	Natural Convection	Natural Convection
Pumped Lithium Temperature	300°C (Approx)	300°C (Approx)
Accessories	Motor Driven Variac Power Factor Correction Capacitors Pump Overtemperature Protection Phase Loss Protection	Motor Driven Variac Power Factor Corr. Capacitors Pump Overtemp. Protection Phase Loss Protection

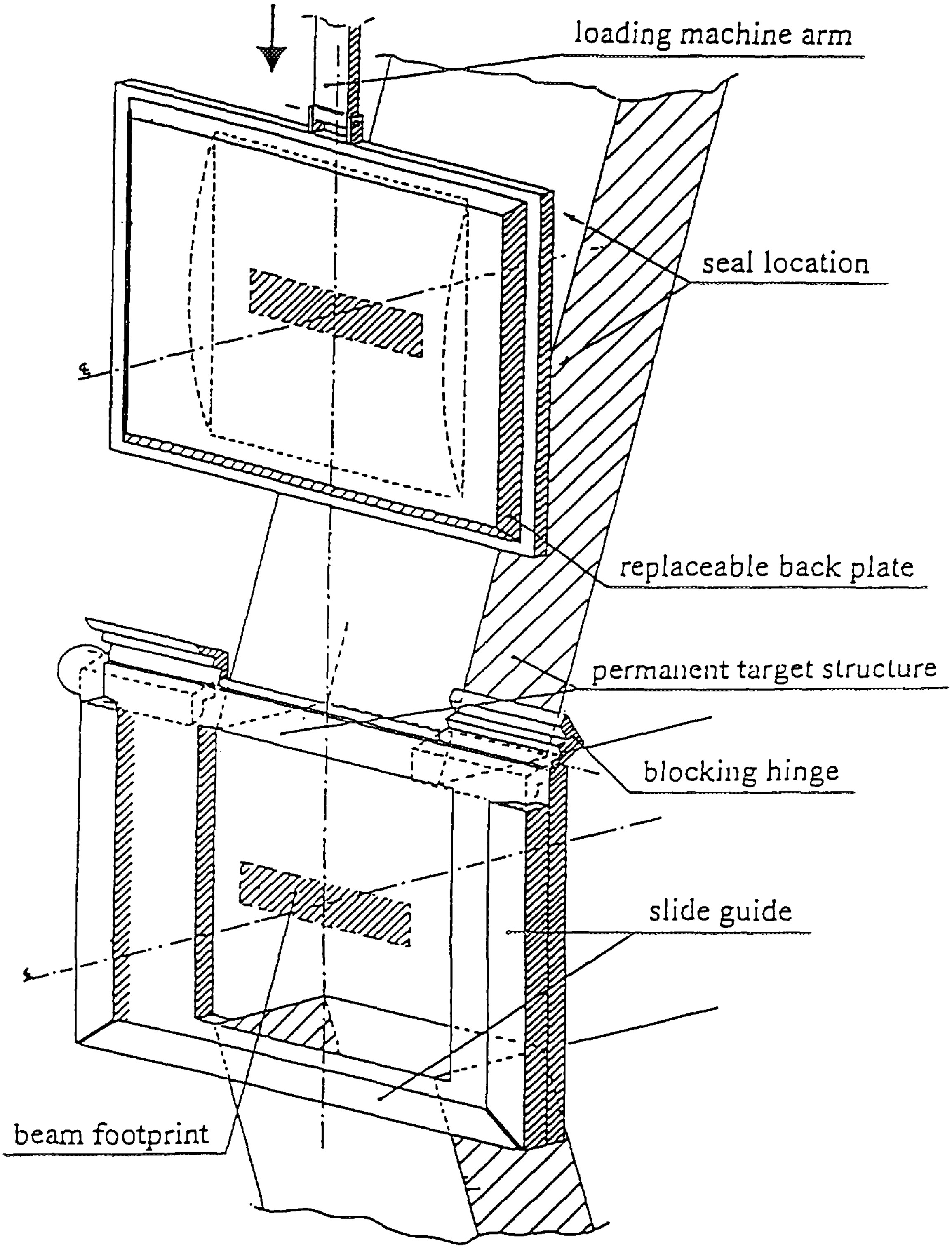


Fig. A2.5-1. The schematic of the bayonet concept.

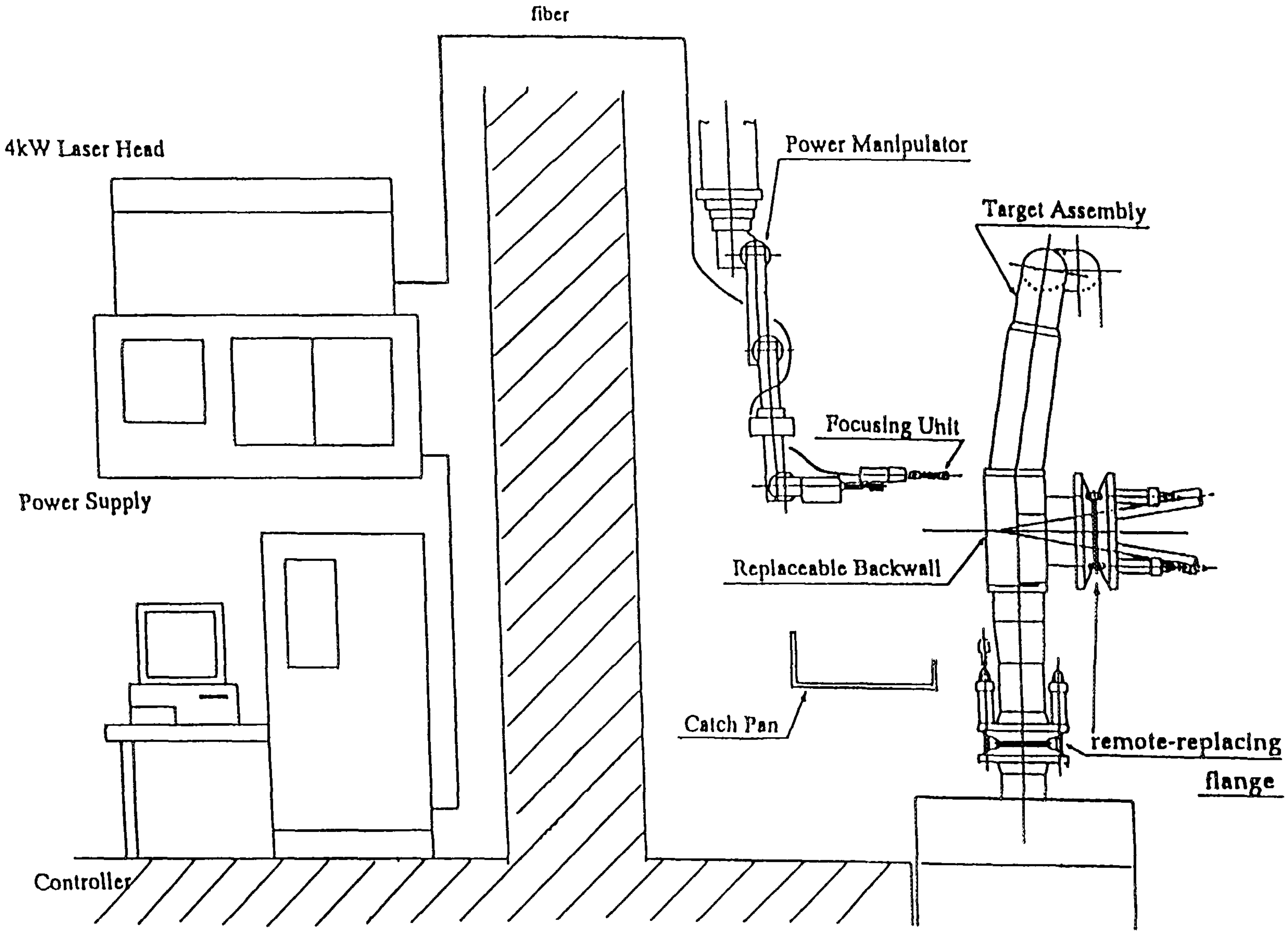


Fig. A2.5-2. Schematic of the YAG laser processing system.

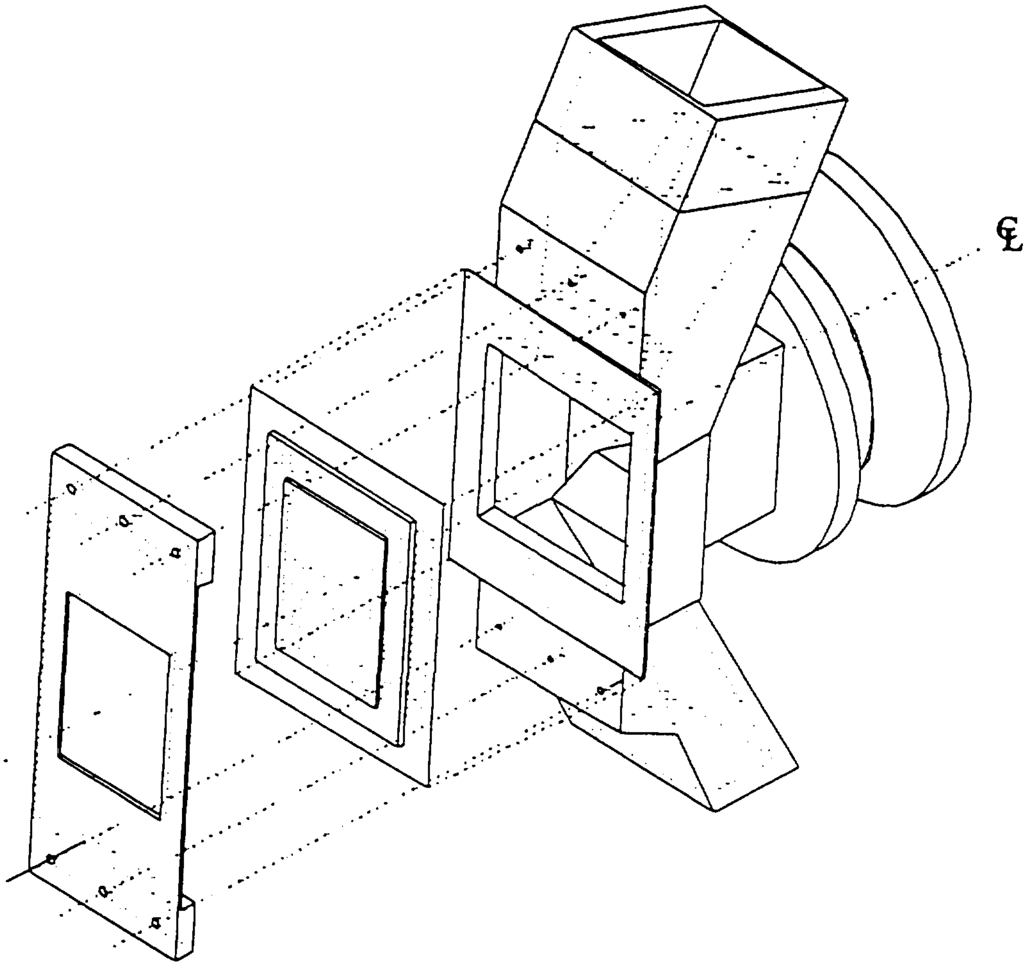


Fig. A2.5-3a. Replaceable backwall attachment scheme.
(Bolt-fix, welding-seal type)

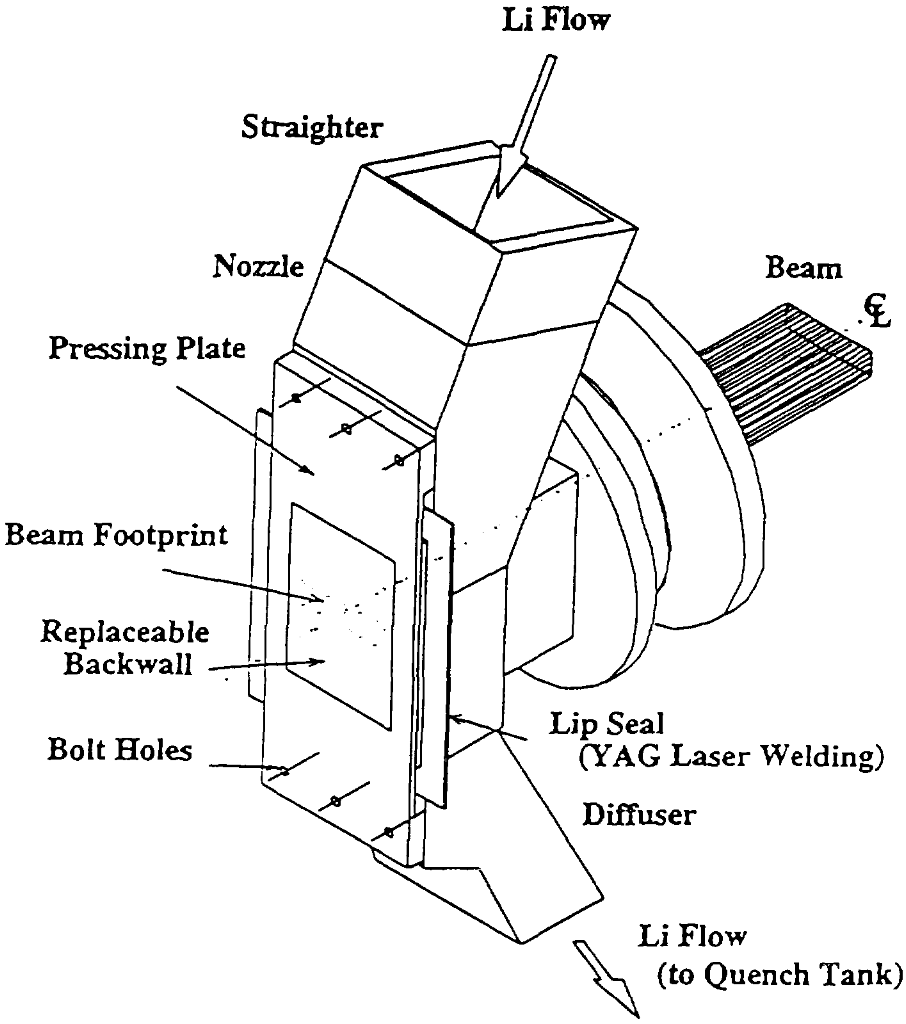


Fig. A2.5-3b. Replaceable backwall attachment scheme.
(Bolt-fix, welding-seal type)

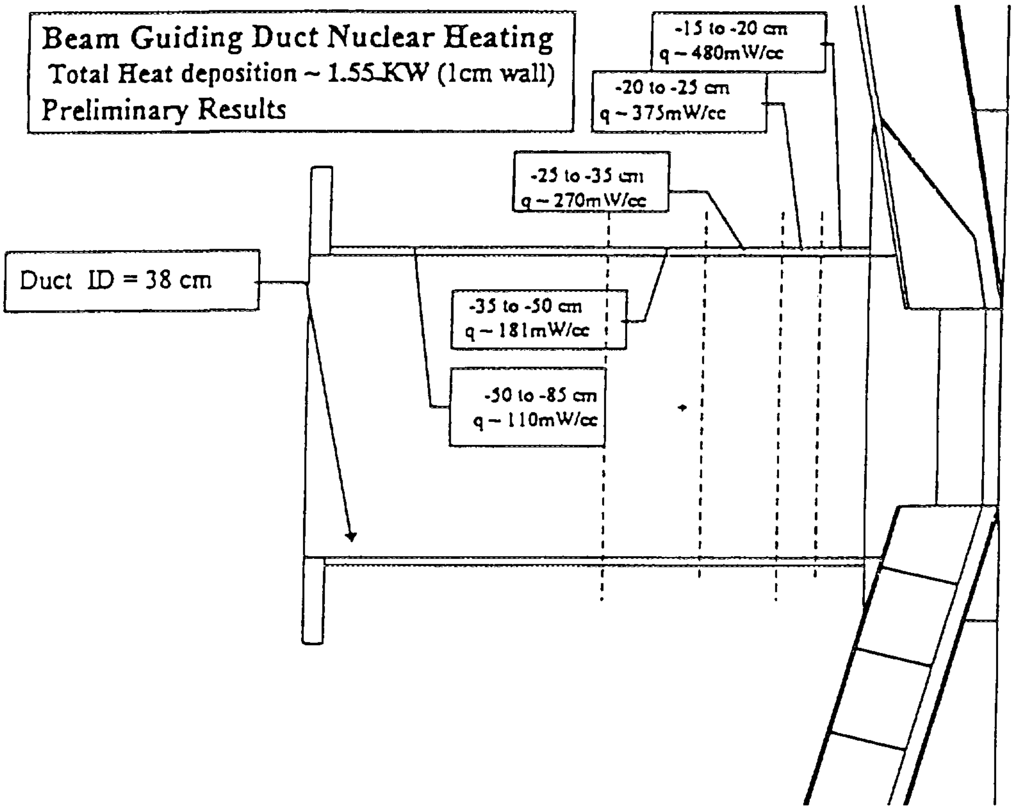


Fig. A2.5-4. Nuclear heating in the beam-tube.

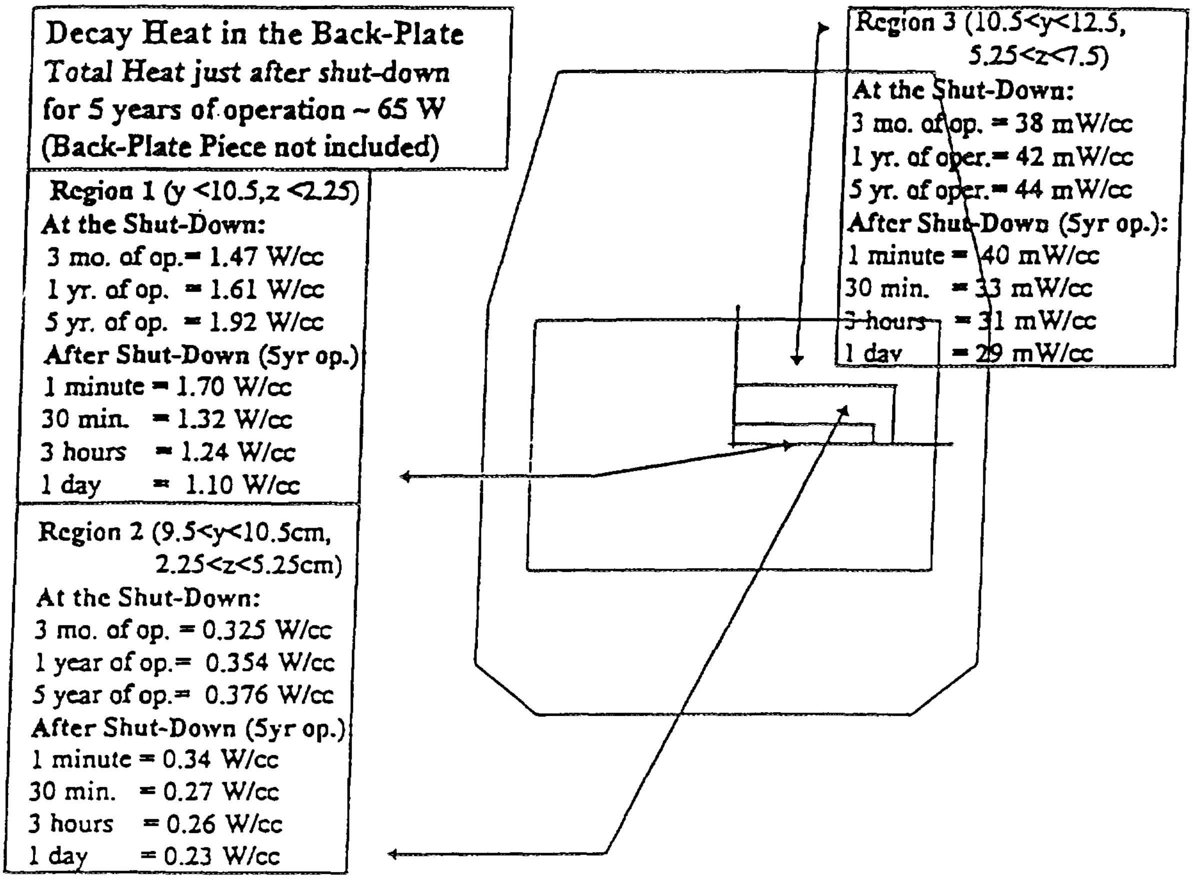
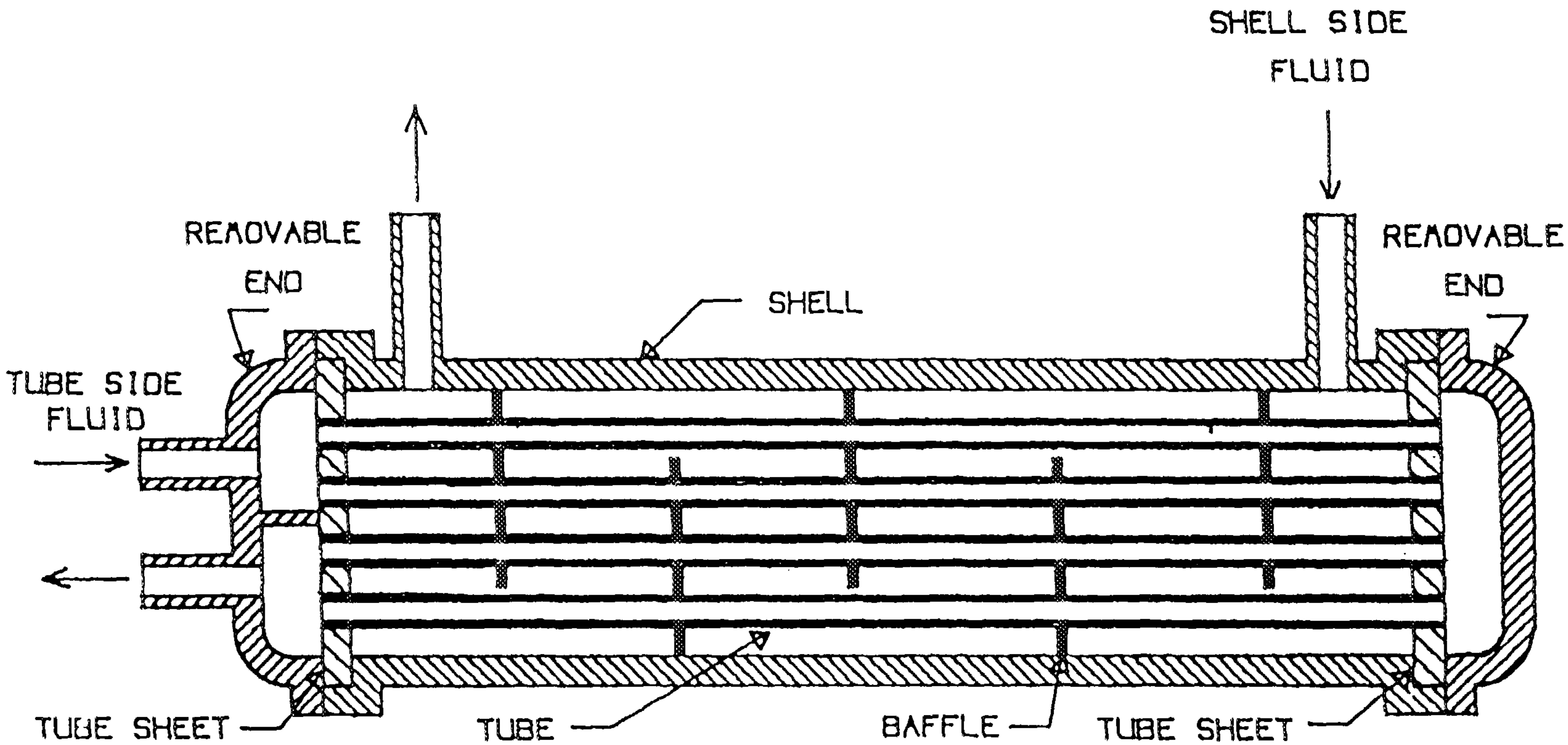


Fig. A2.5-5. Decay heat in the back-plate.



SHELL AND TUBE HEAT EXCHANGER
TWO TUBE PASSES - FIVE SHELL BAFFLES

Fig. A2.5-6. Cross section of heat exchanger.

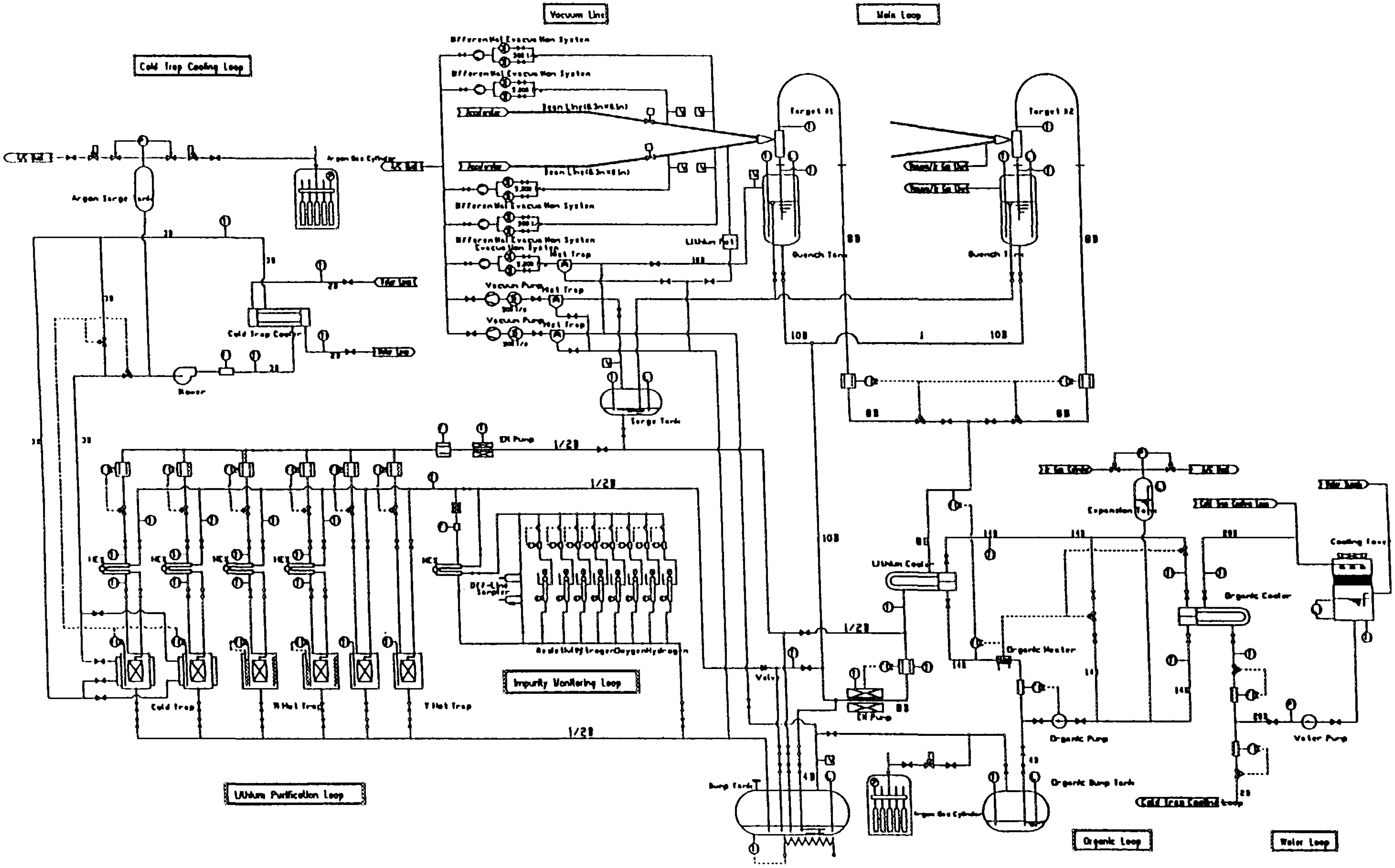
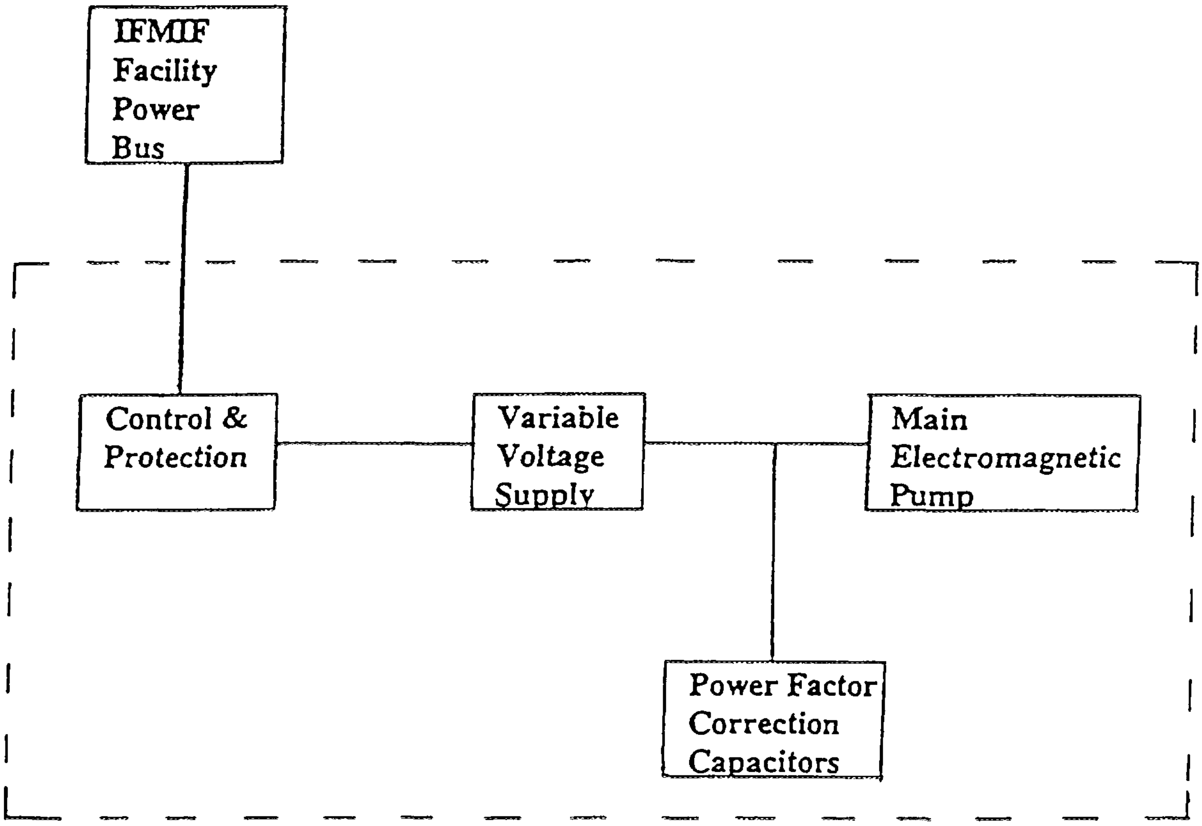


Fig. A2.5-7. Revised flow diagram of lithium loop.



NOTE : Dotted lines indicate limit of estimated hardware.

Fig. A2.5-8. Block diagram of EMP system.

2.6 Accelerator Facilities

Design activities in the six months between the Oak Ridge and JAERI Tokai meetings have made significant progress, which is reflected in several changes and additions to the accelerator baseline design. These changes usually affect many of the interrelated sections of the report. In the following annotations to the interim report, the major issues are noted in the section where they first occur, without repetition in the notes to other sections.

2.6.1 & 2 Requirements and Description

The major changes are highlighted:

- H_2^+ beam for testing may be limited to ~50 mA unless there is a major development program on H_2^+ sources. At this time, it is felt that 50 mA H_2^+ may be adequate for tuneup purposes prior to turning on the deuteron beam.

- A major decision was made at the Tokai meeting to reduce the rated output of the 175 MHz rf power amplifiers from 1.3 MW to 1.0 MW, to increase confidence that the cw power output can be achieved after the EVP development program. This has a number of consequences, including the need for larger number of amplifiers and accelerator tanks.
  The new tank layout may result in a different energy step to the lower energies (achieved by turning off acceleration in the last one or two tanks). Instead of 35 MeV and 30 MeV, it may be more natural to provide 36 MeV and 32 MeV. While further evaluation is required, this information is provided so it can be determined if this energy step size could be acceptable to the users.

- Design work on the high-energy beam-transport (HEBT) to accommodate detailed specifications established at the ORNL meeting shows feasibility but the HEBT is now a very complex design problem and further interface discussion may be required. Close interaction will be maintained with the target and test cell groups.

2.6.2.2 Injector

CDA work on ECR- and volume-ion-source injector development has continued as anticipated and is on schedule. The LANL work on a high-intensity ECR source has demonstrated that the RF window is not a key issue. Nevertheless, substantial development remains to prove the requirement on beam noise and to produce an engineered injector.

The dual injector concept, adopted earlier for RAM reasons, has been dropped. A major reason is that increasingly detailed radiation analysis has shown that maintenance accessibility to the standby injector would be difficult. An in-line injector concept has been substituted to minimize the change-out time to meet overall RAM requirements.

The use of H_2^+ beam for tuneup purposes would reduce radioactivity buildup during these periods. However, additional assessment of the status of H_2^+ ion sources indicates that currents are probably limited in the near future to ~50 mA unless a substantial development program were mounted. At present it is felt that 50 mA should be adequate for tuneup before the deuteron beam is switched on.

A magnetically-focused low-energy beam-transport (LEBT) is used in the baseline design. Electrostatically-focused LEBTs have some advantages, but are less developed. Injector development will include consideration of the electrostatically-focused LEBT.

A substantial amount of new work has been completed on analysis of beam loss in the LEBT and subsequent RFQ accelerator, and conversion of this information to radiation source terms and consequences. This work will continue and will be extended to the high-energy portion of the accelerator.

2.6.2.4 Drift Tube Linac (DTL)

Earlier extensive discussions with rf tube vendors indicated that an upper bound of ~1.3 MW cw might be an achievable result from the major tube development program that is necessary in any case (the existing experience base is for operation from a few seconds to about one minute at generally lower rf frequencies). This level was used to scope the initial baseline design. However, as pointed out in the Interim Report, more margin should perhaps be provided, and further discussion resulted in the consensus of the accelerator team that the accelerator design should be based on a 1 MW tube. Nevertheless, the final unit size must be decided after the experimental test of a tube under cw operation, the prime objective of the EVP.

This decision also has the advantage of opening competition between two manufacturers, allowing a fixed price procurement after the EVP development and test program, and insuring a more stable tube supply in the future.

This decision must be reflected throughout the design. It probably results in eight DTL tanks instead of six, a somewhat lower accelerating gradient, perhaps 10m more length, no change in the rf hall width. The major change affecting the user interface was outlined above - a possible recommendation that the lower energy steps below 40 MeV be in steps around 4 MeV rather than 5 MeV; i.e., about 36 MeV and 32 MeV rather than 35 MeV and 30 MeV.

2.6.2.4 HEBT

Increasingly detailed specification of desired target and test-cell requirements on the beam spatial profiles and energy spread result in increasing complexity of the HEBT design. Increased emphasis on the vertical dimension flat-top uniformity was indicated, because this dimension if on the same order as the size of the small samples, across which uniform dosage is desired. Substantial further design work is necessary on the HEBT beam dynamics design, including tuning sensitivity investigation and compensation, and to incorporate steering magnets and diagnostics. Close liaison will be maintained with the target and test-cell groups.

An option for using a fast steering system to dither the beam in at least one transverse dimension will be explored to possibly ameliorate some of the pressures on the baseline design.

The HEBT configuration at present may have adequate natural energy spread to eliminate the requirement for the energy-dispersion sweeping cavities. The resultant energy profile will be coordinated with the target and test-cell groups.

2.6.3.3.3 Radiation protection interface

Work has concentrated on deriving a beam-loss model for the LEBT and RFQ, and converting the beam loss model to radiation source terms and consequences. Substantial progress has been made; this is new work, going beyond previous analyses.

2.6.3.4 Accelerator/Central Control System Interface

Continuing definition has resulted in considerably more detail.

2.6.7 Development Requirements

2.6.7.1 CDA 2nd year activities as outlined have been substantially accomplished as permitted by budget allocations.

2.6.7.2 Planning for the Engineering Validation Phase is reflected in a separate document.

2.6.8 Alternatives

2.6.8.1 Superconducting 8-40 MeV Linac Option

Work by Japan concludes that SC remains a strong option and that continued evaluation and tracking of development on other projects should continue. 100 kW solid-state rf amplifiers are also under development in Japan and could be attractive drivers if the technical objectives are met, costs can be made competitive, and efficiency improved.

2.6.8.2 CCDTL 8-40 MeV Linac Option

Evaluation was completed. This approach remains a low-priority option.

Accelerator Costs

Very detailed accelerator costing was developed, and is reflected in separate documents.

Facility Interface

The accelerator, major rf and ancillary systems and HEBT have been able to be reconfigured to achieve saving in building size and complexity.

2.7 Conventional Facilities

Since the last DI Meeting (Oak Ridge, October 14-26,1996), the activity has been mainly addressed to Building, Site Improvement and Plant Service cost estimates, and for General Layout updating .

The outcomes of this Meeting affects only marginally the content of Section 2.7. Almost all the paragraph must be however reviewed.

The major changes/additions are the followings:

2.7.2.1 Accelerator Building

The Accelerator, major RF and ancillary systems and HEBT will be reconfigured to achieve a saving in building size and complexity. New description will be provided by John Rathke.

2.7.1.3 & 2.7.2.3 Test and Examination Complex

Two Technology Rooms (6x4x2.5 m^3 each), close to the Test Cell to house Test Cell ancillary systems, are required .

2.7.2.4 General Plant Buildings

Room (10x5x5 m^3) close to the more contaminated area has been required, to house the HEPA filters and blowers of the HVAC system.

2.7.2.9 Other Plant Services

Radioactive waste processing / handling that was tentatively discussed and designed under the test cell tritium lab section is transferred to the conventional facility design. In the design integration activity, confinement of radioactivity and processing rad-waste are identified as outstanding design issues. Among them, tritium may not be a major radioactivity in IFMIF, but regarded as a major radiological hazard due to its chemical feature. It was pointed out that the processing systems for rad-waste would be a possible significant impact on cost estimation, although the ultimate waste disposal /burial is assubed to rely on an existing nuclear facility close to the future IFMIF site.

Conventional facility of the IFMIF has a centralized Nuclear House Vacuum system that processes normal exhaust gases to the environment after filteration. Each subsystems are equipped with specific pre-treatment for effluents succh as Li-vapor removal from target Li system. Between them, IFMIF exhaust process will have a capability to process tritium and other possible source of hazards. Solid wastes, either/both tritiated /activated, will be packaged for the safe loading out from IFMIF so that transportation and ultimate disposal in the host facility will be possible. Tritium is again the major volatile nucride that requires special attention. Particularly the amount of tritium produced and recovered from the lithium loop is expected to be significant. No mixed waste, i.e. active and chemical, is anticipated except for discharges from lithium system. Active liquid waste is expected to be minor, thus regular processing system will be designed. In many cases, rough vacuum will be needed and their exhaust should finally be processed in the facility effluent processing systems. Oil-free vacuum manifolds and exhaust process will be designed. Some of the facilities may have dedicated atmosphere control, either as promary or secondary containment of the hazards. Exhausts from such multiple confinments will have to be optimized and centralized to avoid duplication. Solid wastes has not been given any design considerations so far. It is a general agreement that the IFMIF facility will depend some of the very fundamental infrastruacure upon existing nuclear research institutes in the world. As for the solid waste, its implication is that the ultimate disposal of the waste will not have to be considered in the CDA, however temporary storage and safe packaging of the wastes should be designed. Particular difficulty will again be in tritium handling and will be discussed in the final CDA report.

Moreover the IFMIF Site layout and the Power Station and HVAC diagrams will be included in the Sec.2.7.

2.8 Common Instrumentation and Central Control System

This document describes the changes about the Common Instrumentation and Central Control System (CI & CC) after IFMIF-CDA Interim Report. There are some changes in this portion.

We clarified the boundary of CC as shown in Figure 1. CC includes central computers, operator interfaces, status displays, local area network, sequence synchronizer, dummy substation (for monitoring and development of CC) and interlock logic. We did not modify the basic ideas of functions and requirements on CC. CC handles commands, status or diagnostics from the other subsystems. Other facilities (Accelerator, Test Cell and Conventional Facility) should have its own substation control system. The substation controls should manage its own devices and should be responsible for processing data from each sensor and selecting status and diagnostics data to send them to CC. The substation controls also should have pre-defined functions and sequences for remote control by CC. We also defined the coverage of CC interlock logic. CC manages only the interlock signals that should be exchange over facilities. Each facility should have its own interlock logic for safety of its own devices and send some interlock signals to CC for safety of overall IFMIF facility.

There are major changes in the Instrumentation part. In previously published Interim Report, the "Central" Instrumentation included sensors and analyzers of other facilities. We limited the Instrumentation hardwares into the following CI subsystems as commonly needed instrumentations.

- Beam Instrumentation (On-Target Profile Monitor)
- Radiation Monitoring
- Video Monitoring
- Access Control

Then we substituted the name of Instrumentation part to "Common" Instrumentation.

We revised the Work Breakdown Structure (WBS) into a component level and we estimated costs of items in WBS. The revised WBS and estimated cost will be attached elsewhere.

In this document, We will describe only modifications from the IFMIF-CDA Interim Report.

2.8.1 Requirements

Requirements for General Control System, Subsystem Control, Operator Interface, Communications Subsystem have no change. We modified the descriptions about the Instrumentation. We added the section of CI, and leveled down Accelerator, Test Cell and Facility Instrumentation under the CI section.

2.8.1.5 Common Instrumentation

CI manages all the commonly needed informations. This instrumentation comprises the component level hardwares about On-Target Profile Monitoring, Radiation Monitoring, Video Monitoring and Access Control, and supports the other instrumentation as a remote function. Each facility should manage the hardware and software of the other instrumentation.

2.8.1.5.1 Accelerator Instrumentation

CI supports the Accelerator Instrumentation as a remote function.

2.8.1.5.2 Test Cell Instrumentation

CI comprises the component level hardwares about On-Target Profile Monitoring and supports the other instrumentation as a remote function.

2.8.1.5.3 Facility Instrumentation

CI comprises the component level hardwares about Radiation Monitoring, Video Monitoring and Access Control, and support the other instrumentation as a remote function.

CI manages only the interlock signals that should be exchange over facilities. Each facility should have its own interlock logic for the safety of its own devices and send some interlock signals to CI for safety of overall IFMIF facility. Each facility also should have pre-defined sequence of safe termination of beam for fast beam shutdown signal provided from the CI interlock logic.

2.8.2 System Description

Descriptions for Central Control System have no change. We modified the descriptions about the Instrumentation. We added the section of CI, and leveled down Accelerator, Test Cell and Facility Instrumentation under the CI section.

2.8.2.2 Common Instrumentation

CI manages all the commonly needed informations. This instrumentation comprises the component level hardwares about On-Target Profile Monitoring, Radiation Monitoring, Video Monitoring and Access Control, and supports the other instrumentation as a remote function. Each facility should manage the hardware and software of the other instrumentation.

2.8.2.2.1 Accelerator Instrumentation

CI supports the Accelerator Instrumentation as a remote function.

2.8.2.2.2 Test Cell Instrumentation

CI comprises the component level hardwares about On-Target Profile Monitoring and supports the other instrumentation as a remote function. We suppose Optical/IR Viewing and Pinhole Neutron Imaging as the On-Target Profile Monitoring.

2.8.2.2.3 Facility Instrumentation

The CI comprises the component level hardwares about Radiation Monitoring, Video Monitoring and Access Control, and support the other instrumentation as a remote function. Video monitoring system is used for visually monitoring all over the IFMIF facility.

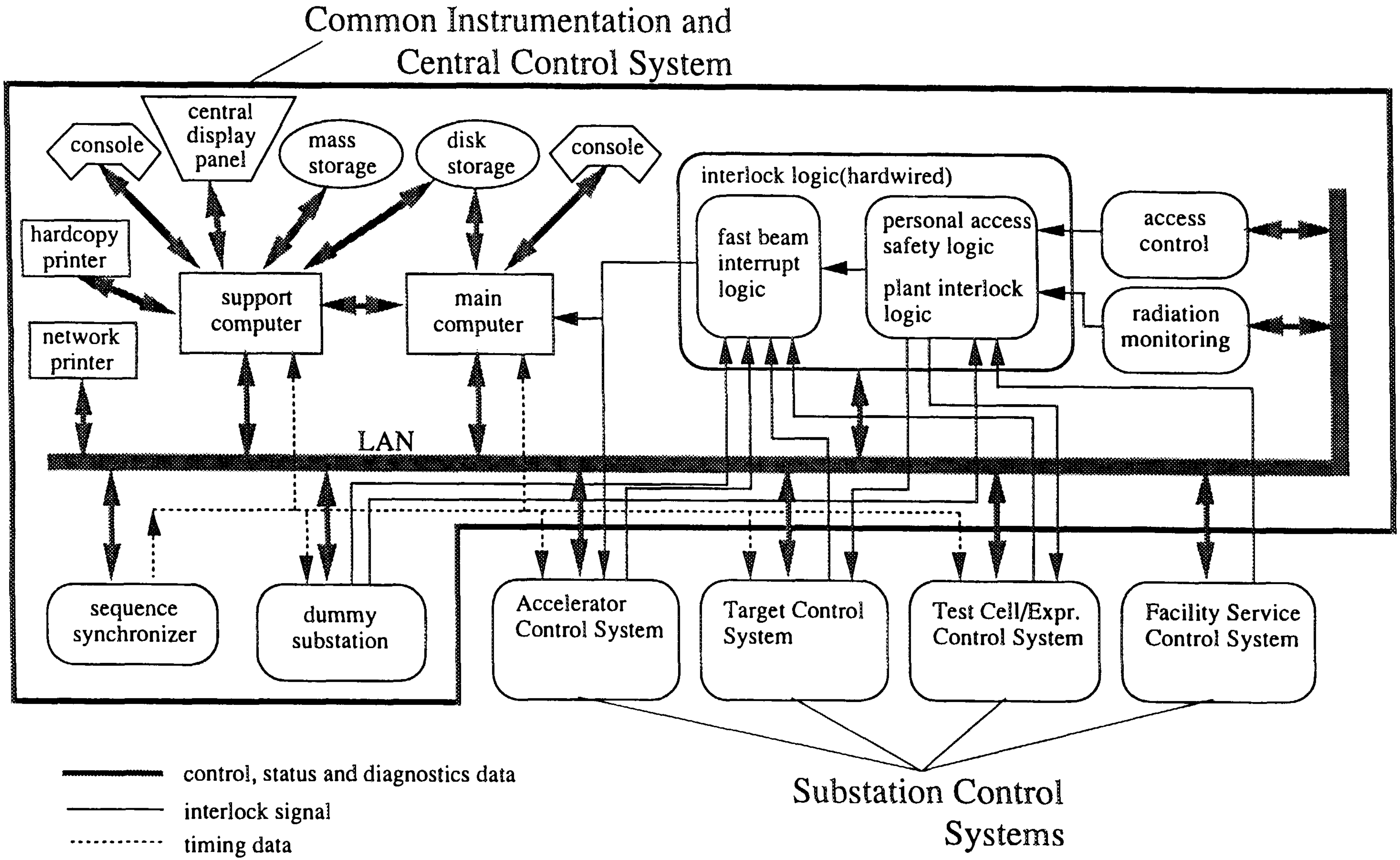

Common Instrumentation and Central Control System
console
central display panel
mass storage
disk storage
console
interlock logic(hardwired)
hardcopy printer
support computer
main computer
fast beam interrupt logic
personal access safety logic
plant interlock logic
access control
radiation monitoring
network printer
LAN
sequence synchronizer
dummy substation
Accelerator Control System
Target Control System
Test Cell/Expr. Control System
Facility Service Control System
control, status and diagnostics data
interlock signal
timing data
Substation Control Systems

Fig. 1

2.9 RAM

This document provides a summary of the group discussions on Reliability, Availability, and Maintainability (RAM) during the 2nd IFMIF Design Integration meeting in Tokai, May 20-24, 1996:

Overall : A general RAM overview presentation was delivered to the entire IFMIF team in the morning of Wednesday, May 22nd. The presentation included review of the reliability, availability, and maintainability methodology and recommendations for all facilities on the general level with detailed discussions of each individual facility deferred to the group meetings to be scheduled later. Updates to the availability models made since October 1995 were summarized: most of these were in the area of the accelerator system modeling where the most significant one was the transition to a single injector which was previously considered and which lead to difficulties with the beam dynamics in the LEBT . Higher than expected radiation environment made the previously planned on-line ion source replacements impossible anyway.

Target : The RAM meeting with the target group took place in the afternoon, on Wednesday, May 22nd. The meeting concentrated mostly on review of the maintainability aspects of the target. This included review of the preliminary list of preventive maintenance activities, with definition of their frequency and duration. The final list is presented in viewgraph form in the presentation supplied with this text in the section entitled "Maintainability". The most significant item on this list includes replacements of the target backwall. The frequency of such replacements cannot be determined at this time in view of the uncertainties of the backwall material behavior in the intense radiation environment of the beam. Further discussion of this issue is continued further down. Another area of uncertainty is associated with the possible need for periodic maintenance of the hot and cold traps depending on the limits on the tritium inventory imposed on the facility.

A limited number of corrective maintenance procedures were also reviewed, with emphasis on their duration which were analyzed into individual tasks to gain confidence in the estimates. These estimates will be used to obtain more accurate values of the MTTRs used in the availability analyses which will have to be reviewed and updated with the new numbers. Operational timelines for normal startup, normal shutdown, and off-normal shutdown were also defined. They represent the foundation for all the corrective maintenance procedures which will require facility shutdown. The final version of these timelines is included in the viewgraphs supplied with this text in the “Maintainability” section.

The item raising most concerns in the target remains the backwall with the uncertainty about its lifetime in the intense radiation environment. The approach currently envisioned is to open up and examine the target after the first 3 months of operation. The estimates of the lifetime capabilities of the backwall will not be available until then. This high risk situation is a concern from the RAM point of view and possibly safety as well. Failure of the backwall accompanied with large lithium spill occurring during this 3 month characterization period could render the facility unusable for a very long period. Preliminary analyses show that the temperature of the surface of the backwall would rise by several hundred degrees within 10 microseconds it takes to shut down the beam if the lithium flow were to be interrupted. Even though the melting point of the material is not exceeded, additional detailed analyses and tests are recommended before this approach is adopted.

The RAM model of the target facility presented in the viewgraph presentation supplied with this text in section "Target" has been updated with respect to the October 1995 version. The model now incorporates an updated availability calculation method with the off-line repair capability. It will, however, require review and updates to incorporate changes made to the design since October 1995. These changes are not substantial, but nevertheless necessary to keep the model up to date.

Test Cell : The RAM meeting with the test cell group took place in the morning, on Thursday, May 23d. The meeting concentrated mostly on the review of maintainability. This included a review of the preliminary list of preventive maintenance activities, with definition of their frequency and duration. A limited list of corrective maintenance procedures was also reviewed, with emphasis on their duration. These procedures were analyzed into individual tasks to gain confidence in the estimates. These estimates will be used to obtain more accurate values of the MTTRs used in the availability analyses which will have to be reviewed and updated with these new numbers. Operational timelines for normal startup, normal shutdown, and off-normal shutdown were also defined. They represent the foundation for all the corrective maintenance procedures which will require facility shutdown. The final versions of the preventive and corrective maintenance procedures were included in the attached viewgraph presentation in section "Maintenance".

Review of the RAM model of the test cell identified that the model may need to be modified in the modeling of the test modules in the VTAs, since no repair is planned for individual components (such as thermocouples) within the module. Rather, if all the redundant thermocouples failed, the entire module would be replaced. Thus, the module becomes a component rather than an assembly. A review and update of the RAM model of the test facility will be required to keep the model up to date in view of the changes made to the design since October 95. In particular, there is only one medium flux VTA now, instead of the two proposed previously. Also, the low flux VTAs were replaced with the He cooled VITs.

Also, the question of the spare VTA was discussed. It was decided that one spare VTA will be included. This spare VTA will reduce the unavailability in case of a VTA failure. Another additional VTA will be used to shorten the time required for specimen changeout during the annual shutdown. Without this VTA, the changeout process may exceed the one month currently allotted for the scheduled maintenance. The current test plan calls for nine month irradiation campaigns with one month scheduled maintenance periods in-between. This additional VTA will be prepared within the period of nine months while the other VTA is in the test cell. Only the items which will require continuation of the irradiation process would have to be moved from one VTA to the other during the scheduled maintenance period.

Accelerator : The RAM meeting with the accelerator group took place in the afternoon, on Thursday, May 23d. The meeting concentrated mostly on review of the maintainability aspects of the test cell. This included a review of the preliminary lists of preventive maintenance activities for the injector, linac, rf system, and HEBT, with definition of their frequency and duration. A limited number of corrective maintenance procedures was also reviewed, with emphasis on their duration. The procedures were analyzed into individual tasks to gain confidence in the estimates. These estimates will be used to obtain more accurate values of the MTTRs used in the availability analyses which will have to be reviewed and updated with these new numbers. Operational timelines for normal startup, normal shutdown, and off-normal shutdown were also defined for each subsystem. They represent the foundation for all the corrective maintenance procedures which will require facility shutdown.

The RAM model of the accelerator facility was also reviewed with the accelerator group in great detail. This model was updated since October 1995 to incorporate the changes that took place in the design: the dual configuration injector was replaced with a single injector without redundancy; individual cooling systems for each subsystem were eliminated and lumped into one common cooling system for the entire accelerator facility; the numbers of the drive loops in the RFQ and DTL were corrected; diagnostics in the RFQ were eliminated; diagnostics in the DTL were represented with redundancy (two failures are now tolerable); redundancies previously included in the vacuum systems were eliminated. A significant change in the analytical model of availability introduced into the model over the last six months was the incorporation of capability to compute the availability to repair off-line. The effect of this change was not large since there were only a few systems within the accelerator model were previously repair on-line was assumed and were it was not the correct assumption to begin with. The most significant change was due to the elimination of the redundant injector.

Additional updates to the RAM model will now be necessary due to the decision adopted during this integration meeting to reduce the rf high power amplifier output tube and the associated increase in the number of the tubes and other equipment.

Conventional Facilities : The RAM meeting with the Marcello Martone, the deputy for Conventional Facilities, took place on Monday, May 20th, 1996. We reviewed the preliminary list of preventive maintenance actions and updated it. Additional review will follow by the engineers in the conventional facilities group. Inputs in the area of corrective maintenance will be provided by M. Martone by end of June 1996. The RAM model for the conventional facilities will also be generated.

Instrumentation & Controls : The RAM meeting with Hiroshi Maekawa, the deputy for Instrumentation and Controls, and Y. Houjou took place on Friday, May 24th, 1996. We reviewed the preliminary list of preventive maintenance actions and updated it. We also reviewed the normal startup, normal shutdown, and off-normal shutdown timelines for the Integration and Control facility. Corrective maintenance information will be provided by H. Maekawa and Y. Houjou by end of June 1996.

2.10 Safety Considerations

In the CDA, detailed safety design is not within the scope. However, design will be expected to include some safety issues, and further consideration will be made toward the completion of the design. Technical issues such as environmental impact, possible hazard to public, site requirements / limitation will be discussed in the design to show IFMIF is designed to be a safe and attractive facility to construct not only for technical specialists, but also for local community, public and authority .

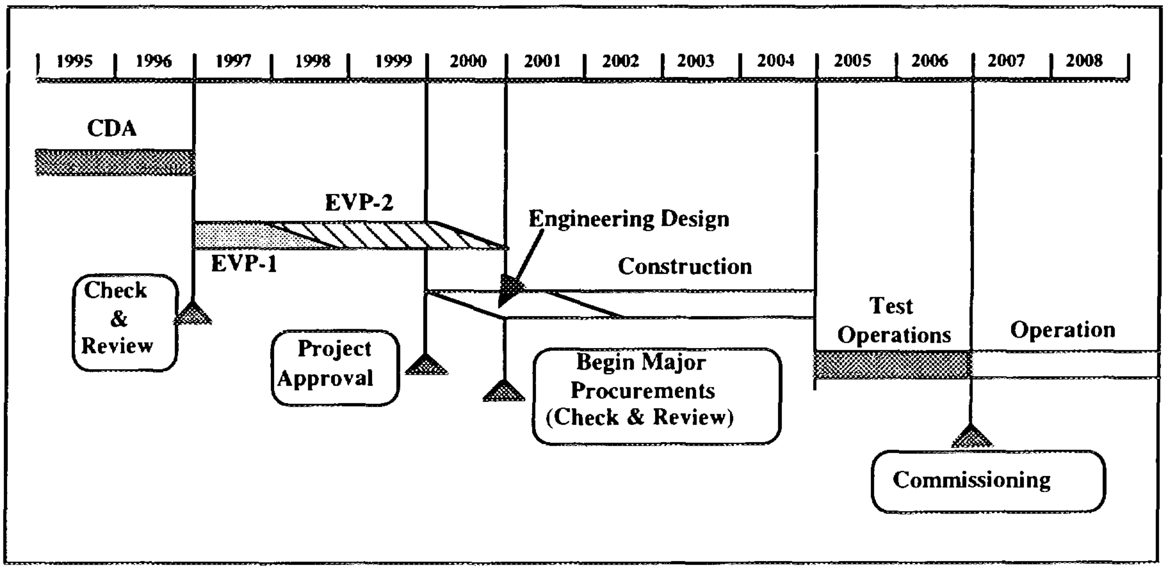
Each subsystems has FMEA to identify hazards. Review of the FMEA will be conducted to identify some important hazards, both frequent and unlikely but extreme accident will be further analyzed. Assessment, analysis, prevention and operation for these hazards will be studied. The results may require design changes with possible impacts on the cost. Major technical issues identified include; radioactive waste processing systems, IFMIF facility zoning, and lithium fire hazards. A special working group will be formed and some safety analysis subtasks will be issued. The results will be submitted to the next design integration meeting and will be included as a part of the final CDA report.

4. Project Schedule

4.1 Introduction

The basic top level schedule defining the key phases and milestones for IFMIF is shown in Figure 4.0-1. This schedule was used to guide the development of the detailed planning schedule provided in Appendix 4-A.

The planning schedule is organized according to the major facilities in order to collect the input from each of the major technical groups in logical sequence. Predictably, the accelerator dominates the timing of the construction project, thus, this Facility was developed first with the remaining groups adding detail within the Facilities to confirm the overall milestones.



CDA: Conceptual Design Activity

EVP-I: Engineering Validation Phase-1
Review of IFMIF Conceptual Design,
Design of Prototype Components for R&D
(Accelerator, Target System, Test Assembly, etc.),
Engineering validation of key elements,
Additional Safety analysis.

EVP-2: Engineering Validation Phase-2
Fabrication of Prototype Components,
Prototype Testing and Engineering Development,
Engineering Validation of Key Elements,
Advanced Procurement of Critical Path Engineering Services,
Site Selection.
Check & Review

Project Approval: Governmental Approval,
Award of Major Industrial Contracts,
Begin Final Design.

Figure 4.0-1 Proposed Top Level IFMIF Schedule

4.2 Costing Coordination

The detailed schedule is organized by WBS elements to eventually tie the cost and schedule together during the development of time distributions. It also shows the effort for each facility group in one section for easier understanding and editing. This accelerator estimate already considers the scheduling of all elements cost in the preliminary estimate. Since this system accounts for half the cost of IFMIF the process of completing a time loaded cost sheet is well underway.

4.3 Key Milestones

Several milestones are considered pivotal to the overall planning activity; delays in any of these will result in a delay in the completion of IFMIF.

* #31 Authorization For Advanced Procurement 1/1/99: This will allow the early designation of industrial contractors for the critical path elements (i.e., accelerator and conventional facilities). This a common technique used in large projects; however, it usually requires special approval by governmental officials.

* #32 Project Approval 1/1/2000; It is assumed that the necessary governmental agencies will give the go-ahead for full project support. This should result in significant budget support and authorization of complete placement of remaining industrial contracts.

* #97 Begin Test, Target and Control Facility installation In Main Building 9/26/03; This assumes that both the building and facility systems are ready.

* #106 Begin Operation Of First Accelerator 11/26/04; All systems are in operation; installation of the second accelerator continues.

国際単位系 (SI) と換算表

表 1　SI基本単位および補助単位

量	名　称	記　号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SIと併用される単位

名　称	記　号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$

$1\ \mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$

表 5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \text{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$

$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$

$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal} = 1\ \mathrm{cm/s^2} = 10^{-2}\ \mathrm{m/s^2}$

$1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad} = 1\ \mathrm{cGy} = 10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem} = 1\ \mathrm{cSv} = 10^{-2}\ \mathrm{Sv}$

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換　算　表

力	$N(=10^5 dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa \cdot s(N \cdot s/m^2) = 10\ P$(ポアズ)$(g/(cm \cdot s))$

動粘度　$1\ m^2/s = 10^4 St$(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	$lbf/in^2(psi)$
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）

　= 4.184 J　（熱化学）

　= 4.1855 J　(15 ℃)

　= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）

　= 75 kgf·m/s

　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

ADDENDUM TO IFMIF-CDA INTERIM REPORT