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SAFETY DESIGN OF THE INTERNATIONAL FUSION MATERIALS IRRADIATION FACILITY (IFMIF)

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In the Conceptual Design Activity of the IFMIF, major subsystems, as well as the entire facility is carefully designed to satisfy the safety requirements that are anticipated to be reasonable for any possible construction sites under current and near future standards. Each subsystem is qualitatively analyzed to identify possible hazards to the workers, public and environments using Failure Mode and Effect Analysis(FMEA). Some important hazards, either frequent, or unlikely and accidental but extreme are further analyzed. The results are reflected in the design and operation procedure. Major technical issues identified include radioactivity and lithium fire hazards. Radiation safety is considered both in normal operation and off-normal events. Shielding of radiation, particularly neutron around the test cell is one of the most important issue in normal operation. Radiation due to beam halo and activation is a hazard for operation personnel in the accelerator system. For the maintenance, remote handling technology is designed to be applied in various facilities of the IFMIF. Lithium loop and target system hold the majority of the radioactive material in the facility. Tritium and beryllium-7 are generated by the nuclear reaction during operation and thus needed to be removed cotinuously. They are also the potential hazards of airborne source in off-normal events. Minimization of inventory, separation and immobilization, and multiple confinement are considered in the design. Generation of radioactive waste is anticipated to be minor, but waste treatment systems for gas, liquid and solid wastes are designed to minimize the environmental impact. Lithium leak followed by a fire is a major concern, and extensive prevention plan is made in the target design. One of the design option considered is composed of; primary enclosure of the lithium loop, secondary containment filled with positive pressure argon, and an air tight lithium cell made of concrete with a steel lining. This study will report some technical issues considered in the design of IFMIF. It was concluded that the IFMIF can be designed and constructed to meet or exceed current safely standerds for workers, public and the environment with existing technology and reasonable construction cost.

Keywords : Fusion Material, Neutron, Irradiation Facility, Tritium, Lithium, Linac, Safety Design, Waste Processing, Defence in Depth, FMEA

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国際核融合材料照射施設（IFMIF）における安全設計

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（１９９７年１０月８日受理）

IFMIFの概念設計においては、主要サブシステムおよび施設全体について、建設される可能性のある場所において現在及び近未来において想定される安全要求を満たすべく安全設計が行われた。各サブシステムについて、作業者、周辺公衆および環境にとって危険な可能性のある要因について、故障モード解析（FMEA）によって分析を行った。この結果、特に頻繁なものと、まれではあるが結果の重大な事故モードをさらに解析し、設計に反映した。放射線安全に関して、通常及び異常時の考察を行い、テストセルまわりの中性子遮蔽、加速器でのビームハローとそれによる放射化について考察を加え、メンテナンス作業のためには遠隔操作を採用している。リチウムループとターゲットは放射性物質については通常時は生成するトリチウムとベリリウム７のために、また異常時はそれらの放出を検討する必要のため、重要である。設計ではこれら生成する放射性物質の量の低減、分離固定処理と多重閉じ込めについて検討している。気体、液体及び固体放射性廃棄物の処理システムも設計した。リチウムの漏洩と火災は設計上考慮すべき重要な事象であり、加圧アルゴンガスによる二次閉じ込め、気密室と鋼ライニングによる多重防護を採用している。

本報告はIFMIF施設の安全設計上の特徴を記述するものである。結論としては、IFMIFは現在利用可能な技術で現行の作業者、公衆及び環境のための安全要求を満たすよう設計、建設できると考えられる。

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1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is an intensive fast neutron source based on deuteron accelerators and liquid lithium target. In the Conceptual Design Activity (CDA) from 1995 to 1997, each subsystems were defined and analyzed for its technical features and feasibility. The facility of IFMIF consists of unique subsystems, each are designed to have technical features beyond the performance and scale constructed in the past. They are, high energy particle beam of highest current ever, largest ever liquid lithium loop, and the neutron field of high energy and flux that has never existed. Large amount of tritium circulates in the system. Tritiated effluent gas and heavily irradiated materials are the source of rad-wastes. As a whole, IFMIF is an integrated plant that must satisfy the requirements for latest major nuclear facilities.

In the CDA of IFMIF, detailed quantitative safety analysis or assessment is not within the scope of the design. However, it was a common understanding that the each subsystems, as well as the entire facility must be designed to satisfy expected safety requirements. For this purpose, some reviews of the design and considerations were given to the subsystems in the aspect of safety. This report describes the summary of the safety considerations on IFMIF subsystems and some safety features unique in the design.

2. Methodology

IFMIF is regarded as a unique facility that requires particular safety consideration that have little previous model to follow. In the CDA, possible hazards of the facility for ES&H were identified in the each subsystems. The major subsystems are; test cell where material specimens are irradiated, target and liquid lithium system, accelerator and conventional facility. A uniform analysis of safety was applied to each major facility. The analysis used a standard failure modes and effects analysis (FMEA) format in which failures are identified and evaluated by considering three factors:

- ease of detection,
- frequency of occurrence, and
- risk potential.

This methodology is used to identify processes and elements that can then be considered in the design process. It is a continuing process that will be updated and reviewed in all phases of the IFMIF program. The findings resulting from the FMEA safety analysis of each facility were further studied for design improvements. Table 1 shows the example of the FMEA analysis conducted on the target system.

1. Introduction

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3. Findings and Consideration

3.1 Test Facilities

Test cell has a passive nature in the facility, although significant amount of radiation particularly fast neutron exists. It is concluded that the test cell does not have significant potential hazards during operation. Failure modes in this subsystem have relatively less importance compared to other systems. Safety consideration on the test cell is therefore made mainly on the static characteristics of the system. Shielding design was thus identified as the most important subject to be studied and analysis of radiation field was conducted[1]. A major possible accident identified by the safety analysis is a rupture of a boundary between the lithium target and the test cell region called backwall, and resulted Li spill. Test cell vacuum atmosphere and shield plug construction is the unique features of the IFMIF test cell when compared with the conventional irradiation facilities. Vacuum atmosphere provide a safety in the events of possible lithium leak caused by a break of the back wall of the target to prevent loss of vacuum in the target and beam transport that will blow radioactive lithium.

Post irradiation facility PIE is a part of the system where activated and contaminated materials are handled for the purpose of analysis and measurements. Safe handling of such materials against the beta/gamma radiations and prevention and isolation and confinement of the contamination were designed based on the experiences of existing nuclear facilities.

Test cell is a major contributor of personnel dose and environmental release in the maintenance operation of IFMIF. Both the designed and controlled to be minimal and far below regulatory limits. Administrative control such as personnel training, well documented operation procedure is important to minimize these hazards. Additional work is needed to improve and clarify the design and function of the remote handling systems, because these have an immediate impact on reducing the risk of personnel exposure.

3.2 Target Facilities

The target system that holds large amount of lithium poses major safety concern in the IFMIF, because of its chemical activity and radioactive inventory. The FMEA identified that some of the system failure and operational deviation could lead to a substantial impact to the facility and possibly to the environment. The major feature of the hazard related to the target is its chemical activity and the mobility of the radio activity. Failure in confinement of lithium could lead to significant results if appropriate measure is not taken in design and operation procedure. Followings are identified hazards and safety design against them.

Lithium loop hazard:The most important event to be considered is a major leak of the liquid Lithium and the resulting fire if the Lithium loop components are installed in an environment that would not suppress combustion. The largest impact is related to the release of radioactive materials to the environment. A significant amount of the radioactivity in the target system could be in an airborne form such as aerosol of lithium and its compounds, some are chemically active and hazardous. In the events of lithium fire, no effective measure is known to immediately extinguish it and protect the building and its confinement function intact. Particularly it is technically difficult to clean and process radioactive lithium aerosol. Therefore to prevent ignition of lithium in the case of leak incidents is supposed to be essential for safety. Propagation of the event to the accelerator or Test Cell region is of major concern, and thus isolation between these subsystems were considered in the design. Containment of the Lithium loop and its major components was found to be essential for safety requirement for the Lithium system , and the multiple confinement with inert atmosphere and dedicated circulation systems as shown in the Fig.1 was worked out.

Target stability and back wall: Minor instability of the Lithium flow is identified as frequent and potentially serious. Instabilities that generate thinning in the liquid jet and a sudden stop in loop flow are possible, and the overall probability of such an event cannot be estimated at this time. The result of the exposure of back wall to the beam is anticipated to be catastrophic and typical time constant of the phenomena when a material is exposed to 100 kW/cm2 of power is in the range of milliseconds. From a safety point of view, isolation of the target from the beam line is difficult, and thus vacuum environment of the test cell was selected so that the target and the test cell be tolerant in such an event.

Tritium is identified as a most important radionuclide generates in IFMIF in the aspect of safety. Approximately 1 g/y of tritium is produced in the target and designed to be removed continuously. Due to the nature of tritium, multiple confinement systems were designed where substantial tritium exists. Although the total inventory of tritium will be maintained as low as possible, it is very likely that the IFMIF is regarded as a major tritium handling facility.

Radioactive Beryllium-7 is anticipated to generate in the lithium. The chemical hazard of beryllium is expected to be negligible when compared to the hazard resulting from a leak of Lithium. However, in the leaked Lithium, the gamma activity of beryllium could possibly pose a significant hazard to personnel [2].

Another feature of the target system is, unlike other subsystems, its operation actively provides the safety. Because this system is required to safely receive the large amount of energy coming from the beam, and release to the environment through the several steps of heat transfer train, failures and off-normal incidents in the operation are regarded as the safety issues of the entire facility. The HAZOP (Hazard Operability) analysis to investigate the effects of the deviations of the target system from normal operating conditions on the total system safety. High reliability and stability of the target system is important for safety reasons as well as operational requirements. Prevention, safe recovery and interlocks of the off-normal operational status were found to be important for the safety design and analysis of the target system.

3.3 Accelerator Facilities

The accelerator handles significant electrical energy as a form of rf power and high energy particle beam. Due to the nature of the system that is energized only during operation, hazards related to the large energy is not a safety concern. Radiation resulted from the in the beam optics, and activation of the beam system caused by the nuclear reaction with beam , are however regarded as the source of hazard for mainly workers in operation and maintenance. No environmental effects is anticipated in any off-normal situations. Thus radiation protection against the operating beamline and activated materials are considered to ensure the safety of this subsystem.

Radiation generated by beam loss cannot be quantitatively estimated at this stage of accelerator design, but it is expected that the beam optics will keep the beam halo well below the value of that projected for FMIT[3]. Possible activated materials related to accelerator system will be;

LEBT/RFQ structure, especially vanes, due to beam loss with energy up to 8 MeV,
Drift tubes in DTL due to unintentional beam loss with beam energy 32-40 MeV,
HEBT components exposed to 32-40MeV deuteron, e.g. bending magnet chamber,
Last several components of HEBT and neutron backstream shield/dump due to neutrons back-scattered from target,
Accelerator vault, i.e. floor, wall, and ceiling, due to prompt neutrons.

Primary radiation protection will be achieved by the control and minimization of beam loss and resulting activation throughout the accelerator system. Adequate local and/or temporary shielding will be applied to further minimize the personnel exposure and unnecessary waiting time. Temporary housing to prevent the contamination and portable ventilation duct backed by the exhaust processing system is considered to protect the workers from contact, intake and inhalation of radioactive materials.

3.4 Conventional Facilities

Conventional Facilities of IFMIF provides building, utility, radioactive confinement and waste treatments. A number of malfunctioning events of the utility supply of the conventional facilities are found to cause serious safety problems in the entire facility. Interlocked actions are expected to be effective and an important measure against such events. Because the initiation events in the conventional facility can readily be detected and the consequences are not extremely fast and accute, it is expected that the conventional safety design for nuclear facility will be sufficient.

4. Waste Treatment

Waste treatment of gas, liquid and solid discharge is the most important function of this subsystem that limits the impact of the entire system to the environment. Although significant amount of radioactive nuclides are generated as the operation of IFMIF, they are all self-contained or retained and none will be processed as waste in the normal operation. Particular consideration was made on tritium, that is anticipated to be the most important nuclide to be processed in various form of waste. The waste processing system is designed to meet or exceed the current and near future requirements.

All the gaseous discharge from the IFMIF is under control of the conventional facility that is equipped with nuclear ventilation system with filters and monitors. Among the possible radionuclides, only tritium is identified as the species that cannot be filtrated by the conventional ventilation. Other possible radioactive gases such as nitrogen and argon activated by neutron irradiation were found to be negligible. Therefore, detritiation systems are designed for some effluent gases before going to the final treatment to discharge through the stack. Effluent gas treatment system consists of three detritiation systems, which are exhaust gas detritiation system, secondary exhaust gas detritiation system and temporary exhaust gas detritiation system.

A processing system for the vacuum exhaust and other primary effluents of the IFMIF facility is designed. One of the major forms of the airborne contaminant removed from the IFMIF system is as solid particulates including solid lithium compounds that must be trapped/filtered before processing. The other form of the material from the primary loop to the outside is as a gaseous species, predominated by tritium. Simplified flow of the exhaust detritiation system is shown in the Fig. 2.(a) and (b). The tritium gas in the exhausted Ar gas is first removed by circulating Pd-permeator system with metal getter beds. The exhaust gas is oxidized while diluted with hydrogen, followed by cold trap, and further cleaned by membrane separator system. The exhaust is discharged at lower than 9Bq/cc, into the atmosphere via nuclear ventilation.

The current IFMIF facility design assumes a host nuclear facility that will be responsible for ultimate disposal of wastes. Solid waste processing system was designed for packaging of wastes for temporary storage and shipping, and decontamination of volatile contaminant such as tritium. Generation of liquid waste is anticipated minor, and will be processed for discharge at lower than $5x10^{-4}$Bq/cc.

5. Conclusion

The conceptual design of the IFMIF facility was reviewed for safety and some important issues identified were given more consideration for safety system design. Major technical issues identified include; lithium fire hazards, confinement of radioactive materials,

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The conceptual design of the IFMIF facility was reviewed for safety and some important issues identified were given more consideration for safety system design. Major technical issues identified include; lithium fire hazards, confinement of radioactive materials, shielding, personnel, protection and waste processing. It was concluded that the IFMIF can be designed to satisfy the safety requirements with currently available technology and reasonable cost[4]. The conceptual design is intended to provide the maximum achievable safety level at the present technology based on the ALARA (As Low As Reasonably Achievable) concept. Particularly the systems that include technical uncertainty, and/or requirements are anticipated to be more strict in the future, are provided with extra margins. It should be noted that in most of the nations requirements for nuclear safety have changed increasingly strict in the past, and this trend is anticipated to continue in the future. It is encouraged to apply modern technologies to improve safety features of the facility. Technical issues such as environmental impact, possible hazard to public, site requirements / limitation have to be investigated in the next phase, so that IFMIF is designed to be a safe and acceptable facility to construct not only for technical specialists, but also for local community, public and authority .

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Table 1 FAILURE MODES AND EFFECTS ANALYSIS FOR IFMIF TARGET SYSTEM

COMPONENT	PURPOSE	FAILURE MODE	EFFECT	DETECTION	MITIGATION OR PREVENTION	FREQUENCY	RISK
EMP	Circulate Liquid Lithium	Process Leak	Lithium in secondary containment	B. Pressure Flow	Leak Check	C	IV
		Stop	Lost Target Flow	A. Pressure Flow	Current Check Interlock	D	V
		Insufficient Flow	Low Target Flow	A. Current Flow	Periodical Check.	C	IV
Li Plumbing	Circulate Liquid Lithium	Process Leak	Lithium in secondary containment	B. Pressure Flow	Leak Check	C	IV
			Lithium in Air	B. Pressure Flow	Detect Minor Leak	D	V
		Plugging	Lost Target Flow	A. Pressure Flow	Impurity Control	D	V
Heat Exchanger	Remove Beam Heat	Internal. Leak	Lithium in Oil Possible Rad Release	B. Pressure	Alarm, Interlock	C	IV
		Stopped Oil	Loss of Cooling	A.Tempera- ture B. Pressure	Alarm, Interlock	C	III
		Oil Leak	Minor Contamina-tion		Leak Check	B	III
Cold Trap Hot Trap	Impurity Control	Plugging	Loss of Flow	A. Flow	Monitor Dp	B	III
		T Malfunction Breakthrough	Impurity in Li Possible Mail Loop Plug	B. Plugging Meter	Impurity Monitor	C	IV

FMEA factors

Ease of Detection		
A	Easy	Immediately detected and alarmed
B	Limited	Detected with delay or needs observation
C	Difficult	No detection available
Frequency of Occurance		
A	Operational Events	More than once per year
B	Likely Events	$1/y \sim 10^{-2}/y$
C	Unlikely Events	$10^{-2} \sim 10^{-4}/y$
D	Extremely Unlikely Events	Less than $10^{-4}/y$
Risk Potential		
I		Operational caution required
II	Danger	Limited function
III	Minor Hazard	Immediate halt and repair
IV	Major Hazard	Accident, damage of facility
V	Extreme	Possible environmental effect

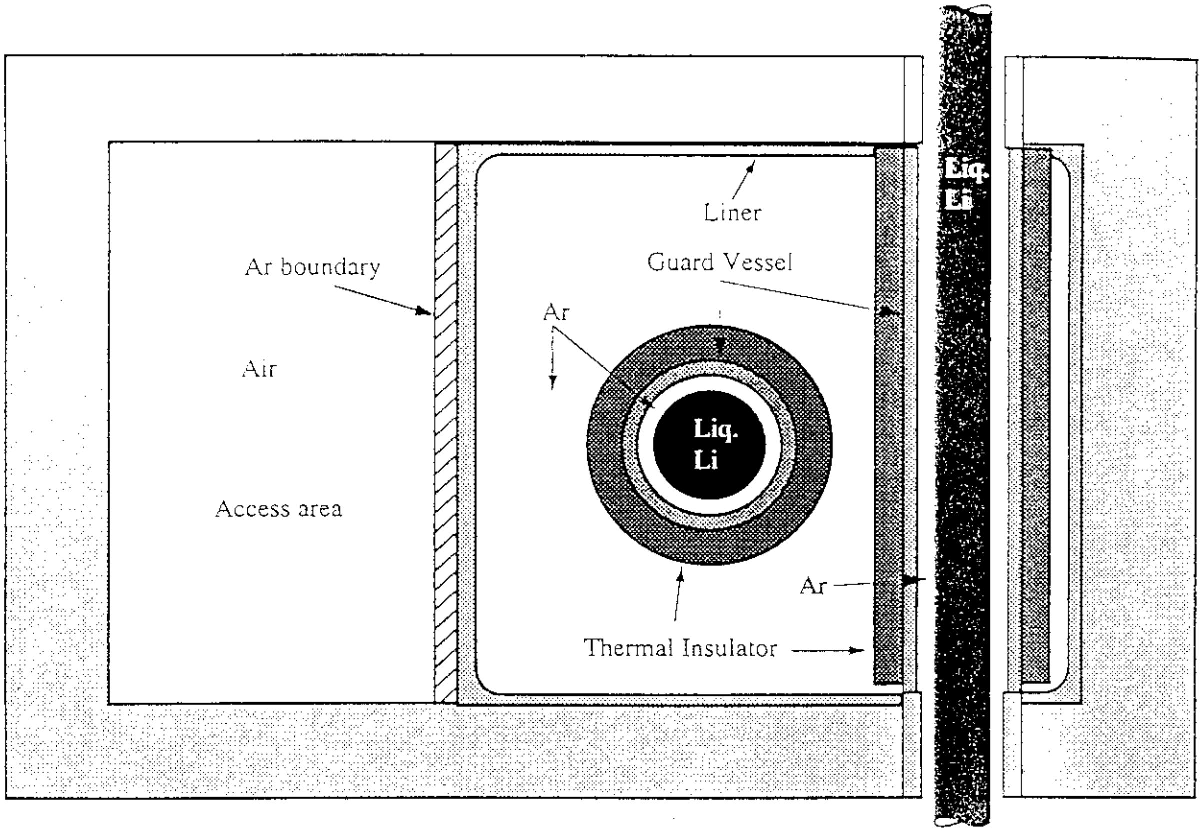


Fig.1 Multiple confinement of lithium system.

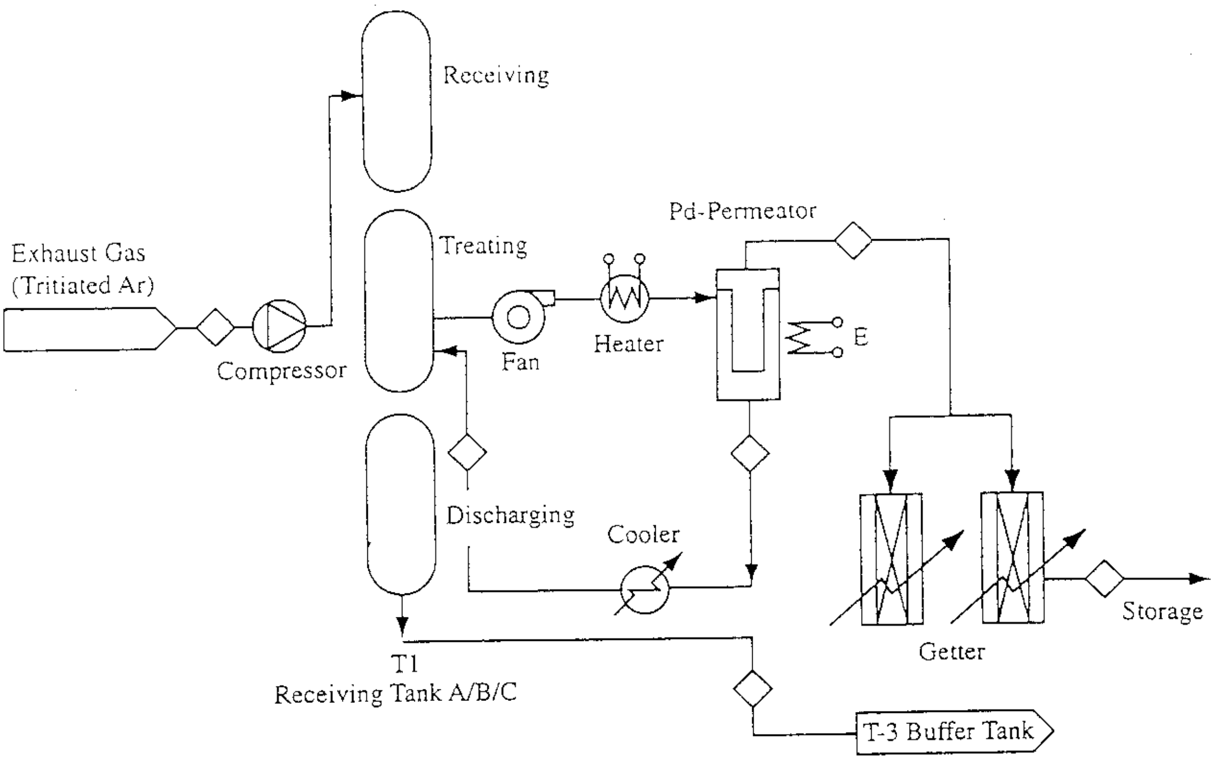
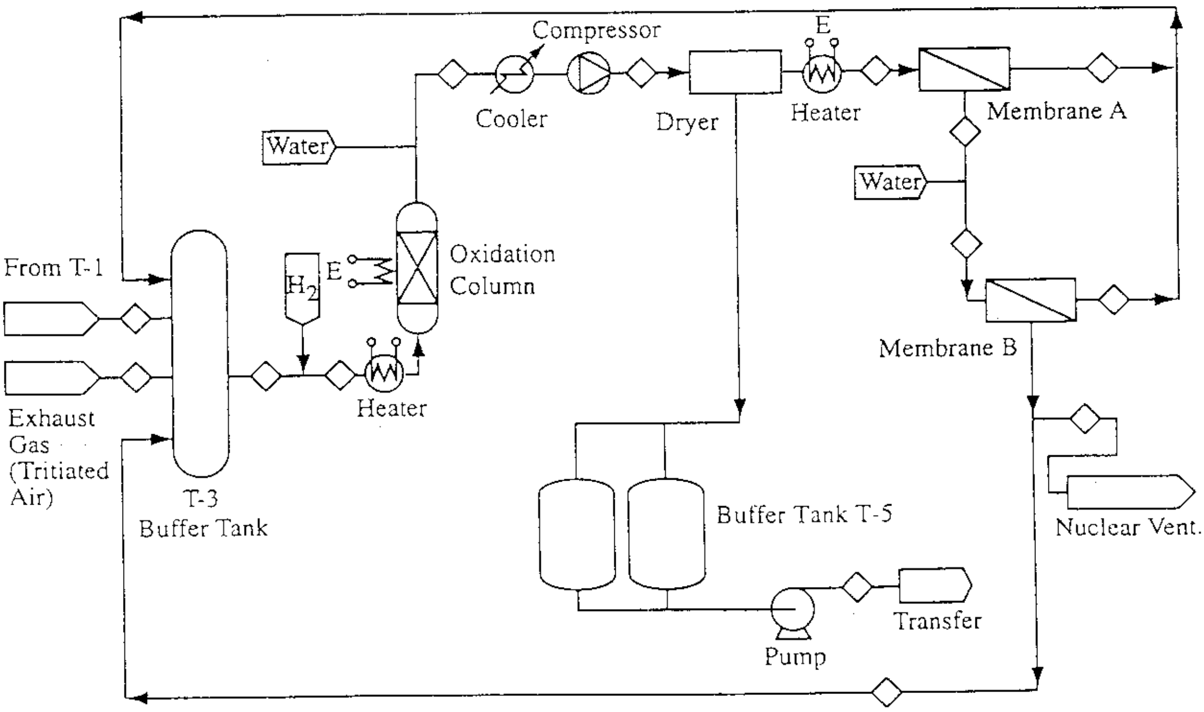


Fig.2 Flow diagram of the exhaust detritiation sytem. (a) Front end processing by permeation,



(b) Detritiation based on hollow-fiber membrane.