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Lithium fire protection design approach in IFMIF-DONES facility

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ABSTRACT

Several experimental facilities, mainly focused on nuclear fusion applications, propose lithium as main coolant and/or tritium breeder material, limiter or divertor for its advantageous properties. Lithium fire hazard represents a critical risk for the production of an important population of reactive, corrosive and toxic aerosols, and for the potential mobilization, transport and release of radioactive species, initially retained in the molten metal, as in experimental facilities like the IFMIF-DONES accelerator neutron source. Consequently, a specific methodology should be developed for managing possible lithium fire scenarios that could occur during the lifetime of these unique facilities. Applying the Defense-in-Depth principle to minimize the fire risk in the particular case of the IFMIF-DONES plant, this work describes a set of passive and active measures for lithium fire prevention, detection and mitigation in compliance with main international and national standards on fire protection. According to the present safety analyses, active measures, including the use of fixed extinguishing systems employing chemical agents, do not seem to be entirely reliable in case of large lithium fires, for which more preferable passive fire protection measures are also being considered to be implemented in the final design of IFMIF-DONES, such as room inertization, catch pans and drain systems, constituting together a main line of defense to safely manage potential lithium fire scenarios.

1. Introduction

The use of liquid metals for nuclear applications has increased during the last decades. In particular, lithium, in its elemental form, as oxides or alloys, is often recognized as one of the most promising candidates for the final coolant and/or breeder selection in several fusion facilities for its advantageous physical, chemical and nuclear properties.

Due to its high chemical reactivity with several media and potential flammability, its safe use and handling shall be always guaranteed in normal operation and, especially, under potential accidental scenarios. Specific concern should be put in developing a reliable fire protection methodology to minimize the risk of lithium fires, especially in those facilities using considerable quantities of this alkali metal. In the fusion field, some concepts of future machine prototypes and other experimental facilities use lead-lithium in the blankets around the plasma, lithium oxides, salts or pure lithium as an alternative first wall coating, divertor or limiter, breeder and/or coolant, which all imply significant quantities of this alkali metal [1–13].

From the past experience of similar facilities housing lithium circuits, it has been observed that the risk of lithium leaks, mainly due to failure of components initially confining the molten metal, cannot be ignored, since it can potentially lead to fire scenarios if the spilled lithium gets in contact with air or water, as occurred at the Lithium Processing Test Loop (LPTL) at Argonne National Laboratory in 1979 [14], and at the

Abbreviations: AC, Access Cell; ACP, Activation Corrosion Products; CSN, Spanish Nuclear Safety Council; DiD, Defense-in-Depth; ELS, Experimental Lithium System; EM, Electromagnetic; ELTL, EVEDA Li Test Loop; EVEDA, Engineering Validation and Engineering Design Activities; FPS, Fire Protection System; HEPA, High Efficiency Particulate Air; HRS, Heat Removal System; HVAC, Heating and Ventilation Air Conditioning; IAEA, International Atomic Energy Agency; ICC, International Code Council; ICS, Impurity Control System; IFC, International Fire Code; IFMIF-DONES, International Fusion Materials Irradiation Facility - DEMO-Oriented Neutron Source; LIMITS, Liquid Metal Integrated Test System; LLC, Lithium Loop Cell; LPTL, Lithium Processing Test Loop; LS, Lithium Systems; NFPA, National Fire Protection Association; PLO, Primary Loop; RAS, Reference Accident Scenarios; SSC, Structures, Systems and Components; TC, Test Cell; TS, Target System; WPENS, Early Neutron Source Work Package.

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Table 1
Main thermophysical properties of lithium at different temperatures.

Lithium properties	At melting point of 180.54°C	At 350°C (maximum design temperature of lithium components in IFMIF-DONES PLO)	At boiling point of 1335-1347°C (at 1 atm)	Ref. (in order)
Density (kgm^{-3})	516	500	401	[20]
Enthalpy (Jkg^{-1})	1.140×10^{6}	1.326×10^{6}	5.972×10^{6}	[20,21,20]
Latent heat of fusion (Jkg^{-1})	4.55×10^{5}	-	-	[20]
Latent heat of vaporization (Jkg^{-1})	-	-	21.20×10^{6}	[22]
Heat capacity ($Jkg^{-1}K^{-1}$)	4379	4250	3000	[22]
Thermal conductivity ($Wm^{-1}K^{-1}$)	44.0	49.8	64.7	[20]
Viscosity ($Ns^{-1}m^{-2}$)	0.645×10^{-3}	0.490×10^{-3}	0.140×10^{-3}	[20]
Vapor pressure (Pa)	1.771×10^{-8}	1.184×10^{-3}	1.013×10^{5}	[20]
Surface tension (N/m)	0.396	0.375	0.240	[20]

Liquid Metal Integrated Test System (LIMITS), a lithium loop located at the Plasma Materials Test Facility at Sandia National Laboratories, in 2011 [15,16].

A particular case is the IFMIF-DONES high power accelerator facility for irradiation of material samples under similar conditions expected in future fusion reactors, which will handle approximately 14 cubic meters of liquid lithium (in the main loop) as a flowing target for deuterons to generate high neutron fluxes [17]. In most of these applications, including IFMIF-DONES, the life and toxic chemical hazards of lithium fires and its compounds coexists with the radiological source term potentially mobilized upon fire conditions.

This work aims at illustrating a set of fire protection strategies applicable to lithium facilities handling large volumes of this alkali metal, and, in particular, to the IFMIF-DONES facility, based on main international and national standards, scientific literature review, and recent outcomes from safety activities carried out in the frame of the Early Neutron Source Work Package (WPENS) of the EUROfusion Consortium [18,19].

In Section 2, main lithium characteristics and implicit hazards existing in experimental facilities using liquid lithium are briefly presented. In Section 3, the lithium fire protection approach in IFMIF-DONES is extensively analyzed. In particular, in Subsection 3.1, the methodology, used by the Lithium Fire Hazard Analysis applied to IFMIF-DONES, is summarized describing those systems, rooms and accidental scenarios that could be potentially affected by lithium fires. In Subsections 3.2, 3.3. and 3.4, different passive and active measures on lithium fire protection are described, including those whose actual implementation in the final design of the facility is still under discussion. Final conclusions are outlined in Section 4, while Appendix A collects the main outcomes from the review carried out on experimental facilities housing lithium loops which show some affinities with IFMIF-DONES.

2. Lithium characteristics and risks

Lithium is the least reactive of the alkali metals. It has a relatively low melting point, high boiling point, low vapor pressure, high heat capacity and thermal conductivity, low density and viscosity. Table 1 collects main thermophysical properties of lithium at different temperatures of interest, including the maximum design temperature of lithium components expected in the Primary Loop (PLO) of the IFMIF-DONES plant.

Liquid lithium shall be handled carefully, since it can produce exothermic reactions with many substances, including air, water and concrete, and its reaction products (e.g. LiOH, Li_2O, Li_2O_2, Li_3N, Li_2CO_3, LiH) are generally water-reactive, corrosive and harmful for the respiratory system [9,23-27]. Generally, lithium poses additional physical hazards being unstable, combustible (in liquid form), flammable and pyrophoric (in the form of finely divided particles, powder or dust in air). Pure lithium is also considered a toxic and corrosive material which reacts with body moisture (when in contact with human skin) causing thermal and caustic burns [28]. Furthermore, it has been demonstrated experimentally from lithium fire pool tests that the production of lithium aerosols accounts for up to a 10% of the total available lithium [25,26]; therefore, there is a hazard of significant dispersion of reaction products if not depleted. Considering the toxicity of lithium and its compounds, occupational exposure limits (i.e., inhalable fractions) applicable to facilities like IFMIF-DONES were identified and collected in Table 2.

In addition, the reaction between lithium and water can generate a considerable quantity of hydrogen gas [26,32–39], potentially leading to unpredictable explosions if hydrogen flammability conditions are reached.

In experimental facilities like IFMIF-DONES, the toxic chemical risk, represented by lithium and its compounds, often coexists with the

Table 2
Occupational exposure limits for several lithium compounds.

Lithium compounds	TLV-TWA[a] (mg/m^3)	TLV-STEL[b] (mg/m^3)	TLV-C[c] (mg/m^3)	IDLH[d] (mg/m^3)	Ref. (in order)
Li (elem.)	n/a	0.2	n/a	n/a	[28]
Li_2O	n/a	0.091*	n/a	n/a	[29]
LiOH	n/a	0.091*	n/a	n/a	[29]
$LiOH.H_2O$	n/a	0.2	n/a	n/a	[28]
Li_3N	n/a	30*	n/a	n/a	[29]
Li_2CO_3	n/a	0.2	n/a	n/a	[25]
LiH	0.025	0.02/0.02	0.05	0.5	[30,28/31,28,30]

[a]TLV-TWA = Threshold Limit Value - Time-Weighted Averaged
[b]TLV-STEL = Threshold Limit Value - Short-Term Exposure Limit
[c]TLV-C = Threshold Limit Value - Ceiling value
[d]IDLH = Immediately Dangerous to Life or Health concentration
*These values refer to Protective Action Criteria 1 (PAC-1) to be considered for the public in one-time, off-normal exposure events [29]. PAC-1 refer to the maximum airborne concentrations of chemicals below which public could experience mild, transient health effects (evaluated for 60-min exposures). In this table, PAC-1 have been considered as TLV-STEL in the absence of formal occupational exposure limits for Li_2O, LiOH and Li_3N.

radiological hazard. In the particular case of IFMIF-DONES facility, the lithium-deuterons interaction will firstly produce tritium (T) and beryllium-7 (Be-7) [40], while secondary neutrons (also produced in the nuclear reaction) will add contributions to both. Also, some corrosion products dissolved in the liquid lithium will be activated in smaller amounts [41]. The majority of T will be dissolved and retained in the liquid metal (due to the high solubility of hydrogen species in the lithium at IFMIF-DONES temperatures), while some very limited amounts will permeate in the form of free gas molecules [42]. Other radiological material as Be-7, additionally present in the lithium stream, will be transported throughout the loops and could potentially deposit in several points (e.g., pipes, heat exchanger) during the normal operation of the facility depending on local lithium temperature and solubility. However, appropriate thermodynamics conditions along the loop are chosen to promote maximum depositions in dedicated cold traps for Be-7 [43] and activation corrosion products (ACP). In addition, dedicated yttrium traps are designed to take the dissolved T [44]. Nevertheless, there will be a remaining radiological content dominated by T which could be mobilized upon fire (i.e., by thermal desorption) representing a radiological hazard for workers and the public. The mobilization of Be-7 and ACP is expected to be of second order according to the present analyses.

3. Fire protection approach in IFMIF-DONES facility

IFMIF-DONES will be built in Spain and classified as a first-category radioactive facility following the directive of the Spanish Nuclear Safety Council (CSN). Fire protection approach in IFMIF-DONES is firstly planned in response to top-level Spanish regulations in which an explicit assessment must be provided [45]. Generally, three main safety elements of fire protection can be identified as follows [45–47]: a control program for combustible materials and ignition sources, a specific fire hazard assessment, and the identification of postulated scenarios with fire risk evaluated at several areas of the facility.

3.1. Lithium Fire Hazard Analysis

A Lithium Fire Hazard Analysis is being carried out in the frame of the WPENS project considering the current design of the IFMIF-DONES plant. This analysis aims at avoiding or limiting potential radioactive and chemical releases resulting from a lithium fire scenario inside the facility. Its ultimate objective is to evaluate and to demonstrate that the risk of lithium fires would be acceptable in order to protect the workers, the public and the environment.

The methodology of this analysis is based on the Defense-in-Depth (DiD) principle for fire risk which is systematically applied in IFMIF-DONES. This principle includes a set of safety measures covering fire prevention, detection and mitigation layers [18]. The DiD principle focuses on the following objectives:

1) To avoid or limit the occurrence of those conditions potentially leading to a fire scenario;
2) To develop a fire detection network suitable for each class of fire;
3) To identify mitigation/reduction measures aimed at limiting or preventing fire propagation, ensuring the integrity of safety class Structures, Systems and Components (SSCs), defining an adequate suppression system, and providing safe procedures for personnel evacuation.

Main international standards can be directly applied or adapted:

- "Fire Protection in Nuclear Power Plants" (IAEA-TECDOC-1944), edited by the International Atomic Energy Agency (IAEA) [45];
- Standards edited by the National Fire Protection Association (NFPA), including the "Standard for Combustible Metals" (NFPA 484) [46];
- "International Fire Code" (IFC), edited by the International Code Council (ICC) [47].

In addition, specific guidelines applicable to lithium leakages and fires were developed in a preliminary stage to assess the topics of fire protection and liquid metal handling related to IFMIF-DONES within the framework of past WPENS activities [48,49]. These same guidelines were not further developed and not intended to provide a comprehensive list of design and functional requirements for lithium systems.

During the normal operation of IFMIF-DONES, liquid lithium will flow inside the Lithium Systems (LS), which include the Target System (TS), the Heat Removal System (HRS) and the Impurity Control System (ICS), as shown in Fig. 1 [17]. LS are required to provide the lithium jet target for generating high energy neutrons, to extract the power deposited in the lithium stream by the deuteron beam, and to remove lithium impurities. The rooms, housing LS and other lithium components, for which the lithium fire-related risk is being evaluated, are the

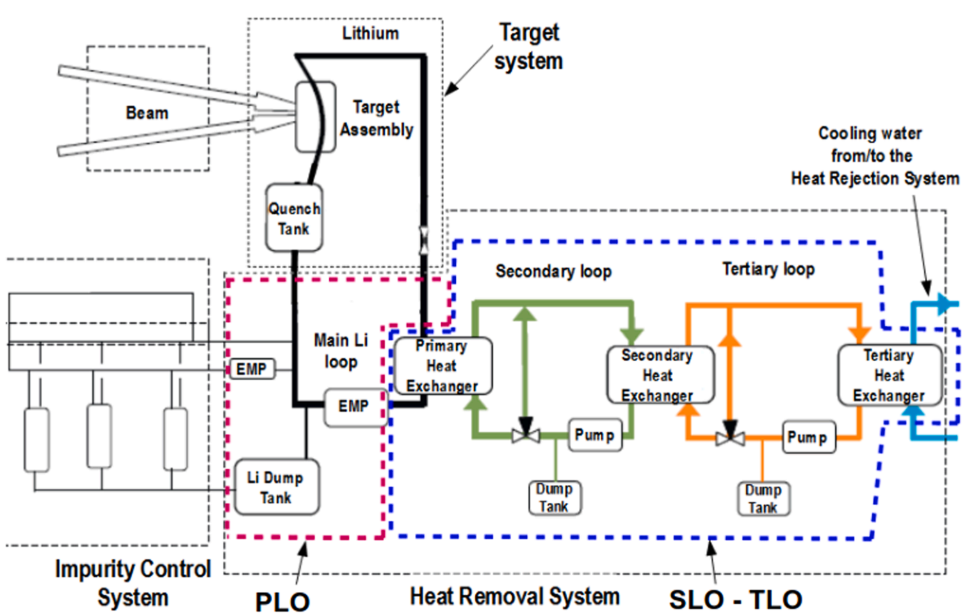

Fig. 1. Schematic diagram of the IFMIF-DONES Lithium Systems [50].

following: Lithium Trap Cell (R009-1, R009-2), Lithium Loop Cell (R016), Lithium Sampling Cell (R017) and Test Cell (R130). IFMIF-DONES safety analyses have identified the following postulated scenarios or Reference Accident Scenarios (RAS) involving lithium fires (still under analysis) [19]:

- LS1-1. Lithium fire event in LLC area during operation;
- LS1-2. Lithium fire event in ICS area (R009-1, R009-2, R017);
- LS1-3. Lithium fire event in TC area;
- LS1-4. Lithium fire event in TC/AC (Access Cell) area during maintenance.

The worst RAS in terms of spilled lithium inventory and potential consequent fire magnitude are those lithium fire scenarios which could involve the LS physical degradation inside the LLC (R016) and TC (R130) rooms. In this sense, safety analyses have identified that the worst lithium leak would be the consequence of a double guillotine break at the electromagnetic pump outlet (in correspondence of the lowest elevation point of the PLO, as shown in Fig. 1) inside the LLC room. For the TC room, two breaks are, instead, postulated: a first break in correspondence of the inlet channel entering the Target Assembly, and a second one affecting the outlet channel of the Quench Tank.

In order to safely manage these accidental scenarios and to implement a robust DiD strategy in the final design of IFMIF-DONES facility, a set of measures relevant to lithium fire prevention, detection and mitigation, supported by scientific contributions and always in accordance with the aforementioned national and international standards on lithium fire protection, is described in Subsections 3.2, 3.3 and 3.4.

3.2. Prevention measures

Prevention measures are designed to reduce as low as possible the occurrence of those conditions that can lead to a fire if lithium confinement conditions are lost. Generally, lithium handling, processing and storage shall be performed in compliance with the requirements collected by NFPA 484 (chapter 16) and IFC (chapter 50). Some of these requirements describe design features and material selections aimed at reducing the chemical reaction risks for solid and molten lithium, while others address safety aspects regarding lithium storage and use inside a facility.

3.2.1. Lithium leak prevention measures

The first prevention measure, contemplated by the DiD strategy, aims at confining lithium at process level, i.e., inside pipes and other equipment in direct contact with the liquid metal, which represent the first confinement barrier. In this context, the SSCs, fulfilling specific safety functions in a nuclear facility, shall be designed and protected to minimize their loss of functionality [45,51]. Specific mechanical standards (e.g., ASME, RCC-MRx, ANSI B31.1) are being applied to the lithium circuits and components to enhance the global robustness of the IFMIF-DONES design.

Design considerations can be directly applied to minimize the probability of occurrence of lithium leakages in a certain system. Therefore, it is recommended to reduce, or try to limit as possible, the lithium inventory for each system (e.g., a closed loop). While not possible when considering the IFMIF-DONES PLO, the recommendation could be extended for online purification circuits and other auxiliary sections. Additionally, it is important to evaluate the material compatibility with flowing lithium and its characteristics (e.g., roughness, thickness) when choosing the type of material (e.g., SS316L, SS304) for lithium handling components (e.g., tanks, pipes, sealed flanges, welds) [41,52-57].

Furthermore, stand-by (or emergency) power and preventive maintenance shall be provided especially to those systems and equipment required to safely manage a lithium fire scenario (e.g., HVAC if applicable, isolation valves, atmosphere purification systems, monitoring systems, etc.) in accordance with section 1203 of [47].

3.2.2. Lithium fire prevention measures

When the first confinement barrier fails and a leakage occurs inside the room housing the damaged lithium system, limiting, or avoiding if possible, the concentration of air constituents and relative humidity in the room atmosphere, as well as the presence of water, is crucial. From past literature reviews [26,27], a relevant discrepancy has been noted concerning the ignition temperature of lithium in air between 180°C and 640°C, which could be remarkably affected by several variable factors (e.g., metal impurities, presence of oxides and nitrides on the metal surface, composition and humidity of the reactant atmosphere, metal reaction surface). During the normal operation of IFMIF-DONES, the majority of the lithium inventory is found inside the PLO at a maximum temperature of approximately 320°C (the maximum design temperature of lithium components is presently assumed as 350°C). Under this context, a set of experimental activities is being prepared at the National Fusion Laboratory of CIEMAT with the purpose to study lithium behavior and ignition conditions in support of IFMIF-DONES licensing process [58].

Presently, in IFMIF-DONES plant, a main line of defense during design basis accidents consists of maintaining a high purity inert gas atmosphere (helium or argon) inside those rooms housing lithium systems (i.e., LLC, TC) as a passive prevention measure against lithium ignition upon spills. In this sense, the use of gas sensors for monitoring oxygen, nitrogen and hydrogen concentrations in inert gas atmospheres and temperature sensors will be implemented in the final design of IFMIF-DONES [48,59], as well as ancillary systems for room atmosphere purification.

A large lithium leakage can transfer a considerable amount of heat to the room atmosphere and to the surrounding structures in contact with the molten metal, potentially leading to room overpressures. Therefore, the use of structural materials to promote heat removal capacity [60] is in discussion as explained below. On the other hand, as a countermeasure of radioactive contaminated rooms in order to avoid spreading, inerted rooms will be in negative gauge pressure, which provides some additional margin to overpressure events.

As an additional feature, room floors and walls will be covered with stainless steel liners in order to avoid the lithium reaction with concrete (which can occur also under inert gas atmosphere) [24,32].

Provision of certain passive design features could be credited as preventive measures. Therefore, promotion of a fast cooling upon spill and to confine lithium leakages are under analysis in IFMIF-DONES, since both strategies could also reduce the probability of reaching lithium ignition. In this sense, IFMIF-DONES designers are considering two main approaches (somewhat contradictory, then needing optimization):

- To promote the lithium cooling by designing floors with a specific slope to obtain dispersion, or showing a relatively massive steel structure acting as heat sink, while using grids or fins to increase the effective heat transfer area (this strategy aims for a rapid solidification);
- To drive and confine the leaked lithium by means of catch pans, boxes, pits, floor lining compartmentalization and draining pipes to enclosures, as discussed below.

A specific lithium recovery system is being preliminarily designed for IFMIF-DONES, since it could enhance the safety of the installation from the fire prevention and limitation points of view [61,62]. This system consists of draining pipes communicating the segmented catch pans located on the steel-lined floor with a lithium recovery tank for confining and collecting potential lithium leakages [63]. A dedicated heating system could be needed to avoid lithium solidification on all the components of the lithium recovery system (e.g., catch pans, collecting pipes, recovery tank).

Convenient emergency draining procedures shall be planned carefully depending on the specific evolution of the accident scenario initiated by the lithium leakage. In fact, if a lithium fire cannot be avoided, the lithium draining operation, performed by the lithium recovery system, might potentially propagate and extend the fire to other systems and rooms of the facility. The definition of these procedures is still under development in IFMIF-DONES, particularly in what concerns the demonstration of a safety-credited action.

The fire protection preventive measures for the worker are completed with the important layer of administrative procedures. Hence, during maintenance operations, when the liquid lithium is drained into a dump tank and is isolated under inert conditions, the risk of lithium ignition is negligible. It could be produced only due to possible existing remnants of lithium inside pipes and other components, or when the inertization is accidentally lost in the same tank. Therefore, the following measures, applicable to facilities like IFMIF-DONES, in order to prevent and mitigate a lithium fire, and to avoid injuries to workers, would be:

- To wear appropriate personal protective equipment;
- To install portable manual fire extinguishers inside the rooms of concern;
- To provide the corresponding emergency protocols and procedures for worker evacuation and fire management.

3.3. Detection measures

A lithium leak can proceed from a rupture affecting different parts of a lithium system (e.g., pump, valve, filter, tank). The physical degradation and consequent rupture of a lithium component could be the product of several failure causes [64], e.g., thermo-mechanical stresses, incorrect assembling/installation, vibrations, fatigue, material defects, liquid metal embrittlement [16,65], erosion/corrosion, earthquake, impact of heavy loads.

3.3.1. Lithium leak and fire detection measures

When the failure is produced, an early detection of lithium leakages and fires is essential for a prompt response in applying corrective actions in order to manage the accident scenario. In this regard, redundancy and reliability to operate are important characteristics for an automatic lithium leak and fire detection system. In IFMIF-DONES facility, this system should include the following main elements [61,66]:

- Lithium leak detectors for all pipes, catch pans, dump tanks and welds (placed in the surfaces below the thermal insulation);
- Lithium leak detectors on valve stems;
- Smoke and flame detectors placed on room floors used for early detection of lithium fires;
- An integrated monitoring system able to generate alarm and warning signals, equipped with multiple surveillance cameras.

In addition, it is expected to equip tanks, containing lithium, with redundant liquid level meters of different technologies [61].

Furthermore, the use of inert gases (e.g., argon), as described in the previous section, could pose a critical safety risk for workers in case of gas leakages. One major hazard is, in fact, represented by the accumulation of inert gas followed by air displacement in the operator room resulting in oxygen deficiency threats. To minimize the risk of anoxia, a detection system with gas sensors, continuously measuring the oxygen concentration in the room, and an adequate ventilation shall be provided. Visible and/or audible warnings shall be produced in case of deviations in the oxygen content of the room atmosphere.

In addition, detectors of negative pressure in inerted rooms can also identify a potential inlet of air, i.e., a failure in the dynamic confinement.

Generally, deviations from normal operation parameters of lithium systems should be continuously monitored in order to promptly detect a lithium leak (e.g., anomalous reduction of pressure and lithium flow rate in a closed loop).

3.4. Mitigation measures

Two complementary strategies for mitigating the propagation and consequences of a lithium fire consist of reducing the concentration of reactants at the gas-liquid metal interface and cooling down the liquid metal until it reaches temperatures below the ignition [67].

3.4.1. Inert gas flooding

As explained in Subsection 3.2.2, inert gas will be used in prevention measures. Additionally, the use of inert gas flooding into enclosures (assuming they are initially filled with air if primary inertization is lost) could apparently be effective in displacing air constituents away from the liquid metal surface, thus, decreasing the reaction rate of the lithium chemical interactions [68,69]. Furthermore, a dedicated inert gas flooding system could provide two advantageous effects by keeping hydrogen (case of lithium-water reaction product with very low probability event by design conditions according to the present safety analyses) under its low flammability limit, and by promoting the cooling of both the room atmosphere and liquid metal leak. The main disadvantage of this mitigation measure is that large volumes of inert gas might be required to actively substitute the air atmosphere of an enclosure if a large structural rupture occurs. Therefore, the use of inert gas flooding as a mitigation measure is not considered as a design baseline in IFMIF-DONES at the present stage.

3.4.2. Passive fire mitigation and limitation measures

Generally, spatial separation and fire rated compartmentalization (including fire barriers) are considered effective passive fire protection means to implement in the final design of a facility [45,70]. Room isolation (achieved by means of redundant valves or fire dampers) represents another reliable measure applicable to rooms, which have an adequate gas-tightness and robustness, since it can lead to the self-extinguishment of lithium fires.

The use of structural materials with high heat removal capacity and thermal conductivity in final spill receptors, as described in Subsection 3.2.2, can substantially promote the cooling of the liquid metal and reduce pressure and thermal loads on structures and enclosures, especially during a fire when high temperature gradients can be easily reached.

Additionally, other passive devices, i.e., catch pans, boxes, or drain and sump extinguishing systems, tested in the frame of experimental activities related to fire protection with sodium, sodium-potassium and lithium, could potentially contribute positively to metal fire prevention and mitigation by [67,71-75]:

- Containing the metal leak in a limited area, avoiding its full spreading on the room floor surface and minimizing the metal surface that could be exposed to reactants;
- Restricting the access of reactants (i.e., O_2, N_2, CO_2) towards the burning metal surface reducing the metal combustion rate and smothering the lithium reactions in progress (using, for instance, a metal cover plate with orifices or trays);
- Preventing the metal reaction with concrete (the use of thermal insulation can prevent the steam release from underneath the heated pan in direct contact with concrete, though it can reduce heat losses from the liquid metal to the surroundings);
- Promoting the metal leak drain and cooling through the bottom and sides of the steel pan or box (or through the steel lined walls of the sump);
- Making more effective the use of chemical agents in extinguishing fires in confined zones;

Table 3
Major components and bulk density for the preferred lithium fire extinguishers.

Fire extinguisher	Major components	Bulk density (kg/m^3)	Ref.
Lith-X	Graphite (93%) Magnesium Aluminum Silicate (4-6%) Magnesium stearate (1-3%)	900	[81,82]
Copper powder	Copper (>98.75%)	2000	[83]
Natrex-L	Sodium chloride	800-850	[77]
MITEX	Carbon	500-700	
GRAPHEX-CK23	Graphitic sulphate	500-600	
Salt ternary eutectic (TEC powder)	Barium chloride (25%) Sodium chloride (35%) Potassium chloride (40%)	1000-1040	[23,84]
Extover®	Silica	400±60	[80]

- Limiting the production and mobilization of aerosols (for instance, by means of small orifices to allow liquid lithium to enter, and aerosols not to escape);
- Facilitating the cleaning up and maintenance procedures after the occurrence of the accident scenarios involving lithium leaks and fires.

The implementation of the previously described measures is presently being studied by IFMIF-DONES designers.

3.4.3. Fire extinguishing systems using chemical agents

An additional line of defense based on dedicated fire extinguishing systems is also under analysis. Extinguishing agents for metal fires suppression and temperature decrease must be chosen very carefully. Generally, many conventional extinguishing media such as water, foams, CO_2, ABC powder, halons, sand and many oxide powders have been reported to even increase metal fires, cause explosions, or, at least, sparks and metal sputtering [46]. Some of the preferred chemicals to be used in the case of lithium fires are Class D fire extinguishing chemical agents such as Natrex-L [76,77], Lith-X and copper powder [46,78]. Also, other promising carbon-based agents for lithium fires suppression (i.e., MITEX and GRAPHEX) were experimentally tested and selected during the IFMIF-EVEDA phase [77,79]. More recently, a new environmentally friendly and multifunctional Class D extinguishing agent suitable for metal fires consists of small porous spheres made of glass [80]. Table 3 collects the main components and bulk densities of the preferred Class D fire extinguishers to be applied to lithium fires. In addition, the following characteristics are recommended for the final selection of a specific lithium fire extinguishing agent:

- To be able to quench lithium reactions quickly and to have good heat absorbing capacity and high thermal conductivity;
- To be non-corrosive, non-toxic and non-hygroscopic (at the temperature range of interest);
- To be easy to store and reasonably economic;
- To avoid secondary exothermic reactions with molten lithium and re-ignition on the metal surface;
- To avoid (or limit as possible) the generation and mobilization of additional aerosols and particles, which can significantly reduce visibility indoors;
- To have a bulk density lower or, at least, very similar compared to that of lithium to avoid the sinking of the specific fire extinguishing agent below the liquid lithium surface and to improve its efficacy using a minor quantity of the agent;
- To avoid complexity during the cleaning up and disposal procedures of the final mixed residues (i.e., used fire extinguishing agent, final lithium reaction products and other compounds) after the fire extinction.

To contribute to the final selection of the chemical agent to be used in IFMIF-DONES, a comparative study on these selected Class D fire extinguishers is presently being carried out, as part of the recent safety activities of the WPENS project. It consists of identifying and evaluating selected relevant parameters, such as the average ratio of weight of chemical agent to weigh of lithium (required to suppress the metal fire), advantageous thermophysical properties of the agent (high heat capacity and thermal conductivity), the production of possible secondary exothermic reactions and of additional airborne particles during a fire, modes of application, storage, cleaning up and disposability, availability and cost.

Application of extinguishing agents can be performed by manual operation methods (i.e., by shovel, gas-propelled, portable, wheeled extinguishers, or stationary units) and/or by using automatic fixed pipe distribution systems. Both methods of application have their own advantages and disadvantages.

Manual methods allow a direct application of the chemical agents to the area surrounding the fire and, generally, involve the minimum amount of agent to extinguish it. However, these methods are limited to occupied rooms and are generally used for relatively small fires. Also, they require trained firefighters and access to the area potentially affected by the fire.

On the contrary, fixed pipe distribution systems can minimize the exposure of firefighters to metal fire consequences (e.g., aerosols, heat, caustic burns) and can be used for extinguishing large metal fires. Nevertheless, they are often more expensive and less effective methods for metal fire extinguishment compared to manual methods, since they require a higher amount of the chemical agent to effectively suppress the fire (up to an order of magnitude higher than the same quantity needed with a portable extinguisher). In addition, several problems related to fixed fire extinguishing systems were identified in the past [67], such as the lack of proof testing under realistic accident conditions, possible corrosive effects of the chemical agents on structures and components (it is known that most fire extinguishing powders used for metal fires can potentially cause corrosion, carburization or nitriding of stainless steel), possible plugging of delivery pipes and nozzles, possible incomplete coverage of the burning metal surface due to structures, obstacles, thermal convection currents, jet action of the compressed gas. Nevertheless, all these effects could be acceptable if a large lithium fire event is demonstrated to have a very low probability of occurrence. In general, these systems might be considered the best method of fire control when there is a limited access to the hazard area.

Due to the complexity of the IFMIF-DONES design, the preferred method of application of the fire extinguisher, i.e., manual or by means of a fixed pipe distribution system, shall be evaluated on a case-by-case basis. Other factors can contribute to the final choice of one or more methods, such as space availability in the room of concern, reliability of the selected fire extinguishing technology, integration with other systems (e.g., remote handling, electrical cables), room classification, etc. Implementation of such automatic and/or manual, active and/or passive lithium fire extinguishing systems, as parts of the final design of the Fire Protection System (FPS) of IFMIF-DONES facility, is currently under analysis. The challenge for IFMIF-DONES design would be to develop a

Table 4
Main fire protection measures presently considered and those under discussion for their implementation in the final design of the IFMIF-DONES facility.

Prevention measures
1. Specific mechanical standards (e.g., ASME, RCC-MRx, ANSI B31.1) shall be applied to the design and fabrication of lithium components and circuits
2. Stand-by (or emergency) power and preventive maintenance shall be provided especially to those systems and equipment required to safely manage a lithium fire scenario
3. Inert gas atmosphere shall be provided and maintained in those rooms housing lithium systems
4. Use of gas sensors for monitoring oxygen, nitrogen and hydrogen concentrations in inert gas atmospheres
5. Use of structural materials with high heat removal capacity (under discussion)
6. Inerted rooms will be in negative gauge pressure to avoid potential radioactive releases and to provide additional margin to overpressure events
7. Use of stainless steel liners in those rooms housing lithium systems to avoid lithium-concrete reactions
8. Designing floors with a specific slope, with relatively massive steel structure, with grids or fins to promote lithium cooling (under discussion)
9. Use of metal catch pans, boxes, floor compartments and draining pipes to a lithium recovery system (under discussion)
Detection measures
10. Use of lithium leak detectors for all pipes, catch pans, tanks and welds
11. Use of smoke and flame detectors on room floors
12. Integrated monitoring system for alarm and warning signals with multiple surveillance cameras
13. Use of redundant and different liquid level meters in tanks containing molten lithium
14. Use of detectors of negative pressure in inerted rooms to identify potential air in-leakages
15. Monitoring of deviations from normal operation parameters of lithium systems (e.g., pressure, lithium flow rate, lithium level inside tanks, etc.)
Mitigation measures
16. Inert gas flooding into enclosures (not considered at the present stage)
17. Spatial separation and fire-rated compartmentalization, including fire barriers
18. Room isolation by means of redundant valves or fire dampers
19. Use of passive devices and systems (e.g., metal catch pans or boxes, drain and sump systems) for lithium fire prevention, limitation and mitigation (under discussion)
20. Use of dedicated Class D fire extinguishing systems using chemical agents, including manual extinguishers and automatic fixed pipe distribution systems (under discussion)
21. Use of ventilation systems equipped with aerosol filtration and retention technologies (under discussion)
22. Use of aqueous scrubbers and fibrous demisters for additional aerosol retention (not considered at the present stage)

safety-credited passive extinguishing system (preferable to an automatic active one) inside a complex room (e.g., LLC) with limited access during the normal operation of the facility.

3.4.4. Aerosol control and retention technologies

A final line of defense is related to the control of potential particles produced during a fire. The Heating and Ventilation Air Conditioning (HVAC) system includes aerosol filtration systems with High Efficiency Particulate Air (HEPA) filters as a primary radioactive and chemical toxicity mitigation system. However, these systems should not interfere with the extinguishment of the lithium fire taking place by promoting convection currents which could hasten the combustion rate of the burning lithium.

Also, in the past, different methods of aerosol containment were further explored, such as sand and gravel filters or submerged gravel scrubbers [82]. A combination of aqueous scrubbers and subsequent fibrous demisters (to remove smaller sized aerosols) was reported to provide a passive, compact and very efficient solution for lithium aerosols retention (> 99%) [85]. This type of solutions for aerosols/smoke filtration is at discussion level and it has not been considered yet in the final design of the IFMIF-DONES facility.

A list of the main fire protection measures, described in the previous Subsections and which are presently being considered or under discussion for their implementation in IFMIF-DONES final design, is outlined in Table 4.

4. Conclusions

Lithium chemical reactivity and potential flammability are critical aspects for a safe handling of this alkali metal in IFMIF-DONES and other experimental facilities, especially in case of accident scenarios involving large lithium leaks.

A reliable fire protection methodology is being developed and implemented in design phase with the purpose to reduce as low as possible the risk for lithium leaks and fires, and to minimize or, whether possible, to avoid potential consequences, such as the mobilization of toxic aerosols and radionuclides with consequent further harms to people (i.e., workers and the public) and the environment. A Defense-in-Depth strategy has been adopted to define a comprehensive set of passive and active measures for preventing, detecting and mitigating lithium leakages and fires. While some design aspects are still under discussion, it is expected to fix them at short term for completion of detailed engineering of the facility.

An optimal solution for a robust and reliable Fire Protection System in IFMIF-DONES would be a combination of passive safety elements (e.g., metal catch pans or boxes, lithium recovery and draining systems) and active systems (both manual and automatic) for extinguishing potential lithium fires that might occur over the lifetime of the facility.

CRediT authorship contribution statement

Gianluca D'Ovidio: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Francisco Martín-Fuertes:** Conceptualization, Investigation, Writing – review & editing. **Juan Carlos Marugán:** Conceptualization, Investigation, Writing – review & editing. **Santiago Bermejo:** Conceptualization, Investigation, Writing – review & editing. **Francesco Saverio Nitti:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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Appendix A. Experiences with liquid lithium loops in international experimental facilities

In this appendix, main outcomes from a brief review carried out on selected international (medium- and large-scale) experimental facilities housing lithium loops have been collected in Table A.1 in order to identify:

- Main operational parameters of each facility, i.e., I = lithium inventory (l, m^3), F = flow rate (l/s) or velocity (m/s), T = temperature (°C), accumulated operating time (h);

Table A.1
Main outcomes from the brief review conducted on selected international facilities housing lithium loops.

Facility	Operational parameters	Li leak and fire accidents	Main safety-related systems and measures for lithium fire protection
LiFus 6 loop, ENEA, Brasimone, Italy [2]	I < 20 l	No accident nor injury ever occurred (only one very small Li leakage from joints of the Li sampler)	Li leak sensors and cables on pipes, valves, connections
	F = 0.5 l/s		Stainless steel safety box equipped with nitrogen gas supply system and with dedicated basin on the floor for Li leak containment
	T = 350°C 8000 h		Compartmentalization of the Li loop Smoke detectors with autonomous control panel Manual fire extinguishers (CO_2, Lith-X) and automatic fire extinguishing system (Argon flooding) Fire dampers and door for the main hall Motorized and remotely controlled video cameras
EVEDA Li Test Loop (ELTL), Oarai Research & Development Institute, JAEA, Oarai, Japan [5,61]	I = 5 m^3	Damages to the loop due to the Tōhoku earthquake (Japan, March 11th, 2011)	Li leak detectors on all pipes and components of the loop
	F = 50 l/s T = 250°C 1560 h	No Li leaks ever occurred	Smoke detectors for floors and cooler ducts Li level meters in Li tanks Installation of multiple surveillance cameras Confinement vessel (air-tight steel container) housing the Li target pressurized with argon during the loop operation Steel plates on the compartmentalized floor with drain lines for Li leaks (with an emergency lithium leakage tank) Portable fire extinguishers (Natrex-L) Physical separation between the laboratory area and the control room Central management of the alarm and warning signals by the control room
Liquid Li circulation facility, Osaka University, Japan [86–88]	I = 0.42 m^3 (main loop) F = 13 l/s T = 300°C (In operation from 2002)	No Li leaks ever occurred	Li leak detectors on valves Stainless steel floor lining to prevent Li-concrete reaction Emergency Li drain system (with dump tank) in case of emergency shut down Automatic argon gas injection system (equipped with an electromagnetic valve) for fire self-extinguishment inside the underground pit Manual metal fire extinguishers
Lithium Processing Test Loop (LPTL), ANL, Argonne, USA [14]	I = 0.19 m^3	Small Li leakage into valve bonnet due to high residual stress and corrosion/erosion	Electrical shorting-type leak detectors on all tanks, pipes, valves, connections (except on the center portion of the EM pump where the large leakage occurred)
	F = 0.25 l/s	Large Li leak (~37.9 kg) from the electromagnetic (EM) pump channel (crack in the rectangular section of the EM pump channel due to residual stress) with fire (October 5th, 1979)	Photoelectric smoke detectors
	T = 500°C > 9500 h (main loop) (started its operation in December 1977)		Induction-type level probe in Li reservoir Li flow indicator-controller Automatic and manual Li draining system to dump tank Carbon steel catch pan (with elevated grating) covering the floor underneath the loop Manual fire extinguishers (sand, Lith-X, Metal-X, Lith-3 were used for extinguishing the fire of 1979) Filtered exhaust system (scrubber) for heat and smoke removal

(continued on next page)

Table A.1 (*continued*)

Facility	Operational parameters	Li leak and fire accidents	Main safety-related systems and measures for lithium fire protection
Liquid Metal Integrated Test System (LIMITS), Plasma Materials Test Facility (PMTF), SNL, Albuquerque, USA [16,89,15]	I < 70 l	Li leak from the lithium preheater with fire due thermal stress and liquid metal embrittlement	Pressure transducer and flow meter for Li flow monitoring
	F = 10 m/s	Li leak from copper gasket dissolution and Li contact with insulation causing fire due to incompatibility between molten lithium and copper	Li level meter in the furnace
	(in the test section)		Thermocouples for temperature monitoring in the chambers and piping
	T = 200 - 220°C (first operated with lithium in March 2003)		Portable fire extinguishers (Lith-Ex)
Experimental Lithium System (ELS), HEDL, Richland (WA), USA [90]	I = 3.8 m^3	No large Li leaks ever occurred	Lithium components (dump tank, surge tank, EM pump, Li target prototype, etc.) contained in separated and closed modules (or pits), entirely covered with carbon steel liners
	F = 380 l/s	Small Li spill resulted from an elastomer seal failure during Li filling procedure	Mild steel catch pans with perforated carbon steel cover plates and dedicated fire suppression system (local argon injection with fixed argon supply lines) located in all modules
	T = 430°C >16000 h (March 1980 - January 1984)	Occasional small Li leaks from valve connectors	Li level sensors for surge and dump tanks Temperature and smoke detectors Large and small Li fire extinguishers based on carbon microspheres Emergency ventilation system with Venturi air scrubber system, moisture separator and HEPA filters Portable oxygen monitors for inspection of the two modules to avoid accidental oxygen deficiency (anoxia)

- Potential lithium leak and fire accidents occurred during their operation (and, if possible, their associated failure causes);
- Main safety-related systems and measures involved in lithium fire protection (actually implemented in their final design).

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