Current status of MELCOR 2.2 for fusion safety analyses

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ABSTRACT

MELCOR is an integral code developed by Sandia National Laboratories (SNL) for the US Nuclear Regulatory Commission (USNRC) to perform severe accident analyses of Light Water Reactors (LWR). More recently, MELCOR capabilities are being extended also to analyze non-LWR fission technologies. Within the European MELCOR User Group (EMUG), organized in the framework of USNRC Cooperative Severe Accident Research Program (CSARP), an activity on the evaluation of the applicability of MELCOR 2.2 for fusion safety analyses has been launched and it has been coordinated by ENEA. The aim of the activity was to identify the physical models to be possibly implemented in MELCOR 2.2 necessary for fusion safety analyses, and to check if those models are already available in MELCOR 1.8.6 for fusion version, developed by Idaho National Laboratory (INL). From this activity, a list of modeling needs emerged from the safety analyses of fusion-related installations have been identified and described. Then, the importance of the various needs, intended as the priority for model implementation in the MELCOR 2.2 code, has been evaluated according to the technical expert judgement of the authors. In the present paper, the identified modeling needs are discussed. The ultimate goal would be to propose to have a single integrated MELCOR 2.2 code release capable to cover both fission and fusion applications.

Abbreviations: ACP, Activated Corrosion Product; BB, Breeding Blanket; CSARP, Cooperative Severe Accident Research Program; CF, Control Function; CVH, Control Volume Hydrodynamic; DCLL, Dual Coolant Lithium Lead; DTT, Divertor Tokamak Test; EDF, External Data Files; EMUG, European MELCOR User Group; EOS, Equation of State; FLIBE, LIF+BeF_2 molten salt; FOM, Figure Of Merit; HCLL, Helium-Cooled Lithium Lead; HCPB, Helium-Cooled Pebble Bed; HITEC, $KNO_3 + NaNO_2 + NaNO_3$ molten salt; HTC, Heat Transfer Coefficient; IFMIF-DONES, International Fusion Material Irradiation Facility-DEMO-Oriented NEutron Source; IHTS, Intermediate Heat Transport System; INL, Idaho National Laboratory; ITER, International Thermonuclear Experimental Reactor; LOCA, Loss of Coolant Accident; LOVA, Loss of Vacuum Accident; MDH, Magnetohydrodynamic; MELCOR, Methods of Estimation of Leakages and Consequences of Releases; NCG, Non-Condensable Gas; PFC, Plasma Facing Components; PIRT, Phenomena Identification and Ranking Tables; SNAP, Symbolic Nuclear Analysis Package; SNL, Sandia National Laboratories; TMAP, Tritium Migration Analysis Progam; USNRC, United States Nuclear Regulatory Commission; VV, Vacuum Vessel; VVPSS, Vacuum Vessel Pressure Suppressor System; WCLL, Water-Cooled Lead Lithium.

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1. Introduction

Several organizations worldwide are conducting research on the safety of nuclear fusion installations. MELCOR fusion version is being adopted as one of the reference codes to carry out deterministic safety analyses of fusion installations and related facilities.

Initially, MELCOR was developed by Sandia National Laboratories (SNL) for the United States Nuclear Regulatory Commission (USNRC) for the safety analyses of Light Water Reactors (LWR) [1]. MELCOR is a fully integrated code able to simulate the thermal-hydraulic phenomena in steady-state and incidental/accidental conditions, as well as core degradation and aerosol/vapor transport up to the outer environment during severe accident. The code capabilities have been extended to analyze non-LWR fission technologies, for the past two decades by SNL. The newest current avaliable version is MELCOR 2.2.

The Idaho National Laboratories (INL) made fusion reactor specific modifications to MELCOR 1.8.2 (developed and validated through pedigree analysis for the use in International Thermonuclear Experimental Reactor (ITER) Safety Preliminary Report) and later these modifications were introduced into MELCOR 1.8.6 [2,3]. Currently, MELCOR fusion is applied for safety analyses of fusion reactors and fusion-related facilities, such as ITER [4], DEMO [5,6], more recently the IFMIF-DONES (International Fusion Material Irradiation Facility-DEMO—Oriented Neutron Source) accelerator neutron source [7–10], and it will be adopted for the Divertor Tokamak Test (DTT) facility [11].

The development of a common MELCOR version release, including specific models for fusion safety analyses, would allow the use of all the state-of-art features implemented in the code and the capabilities of SNAP (Symbolic Nuclear Analysis Package) [12] for the development of input-decks, post processing of the data, and uncertainty analysis. Moreover, MELCOR 2.2 includes several developments in code performance, aerosol transport and interacting phenomena, quenching or radiation modeling among others, that improved its usability and accuracy as shown in validation exercises [13,14]. However, the current released version of the code, (MELCOR 2.2.9X), still has not yet implemented some models required to carry out analyses of some specific phenomena occurring in fusion facilities.

At the European MELCOR User Group (EMUG), held in 2018 in Zagreb (Croatia), organized in the framework of USNRC Cooperative Severe Accident Research Program (CSARP), a session was dedicated to “GEN IV and Fusion Applications”. Afterwards, an activity has been launched and it has been coordinated by ENEA to identify the models necessary for fusion safety analyses possibly to be implemented in MELCOR 2.2, based on the feedback provided by several MELCOR users.

The present paper describes the code modeling needs to address fusion safety issues, ranking their priority for implementation according to the technical background and priorities suggested by the participant organizations involved in fusion activities. In addition, it is described whether the models are already implemented in MELCOR 1.8.6 for fusion version [2], developed by INL, or if the physical phenomena of interest can be simulated through specific methodologies.

It should be underlined that experimental data are required to formulate models and validate the computational tools. The availability of adequate experimental data (and the related scaling issue [15,16]) or the need for new experiments is not addressed in the present paper. This contribution is intended as a first step toward the identification and ranking of the modeling needs for fusion applications, while the availability of data and the needs for new experiments should be investigated in future works.

2. Modeling needs to address fusion facilities safety issues

The models identified to be implemented in MELCOR 2.2 for addressing fusion safety issues are listed in Table 1. In the table, the priority for model implementation has been evaluated as:

- High (H): modeling need fundamental to simulate the system with the actual thermalfluid-dynamic conditions in the different part of the plant (e.g. availability of the correct working fluid in each subsystem at the correct thermodynamic conditions);
- Medium (M): modeling need that impacts a safety related Figure Of Merit (FOM) (e.g. tritium transport for the estimation of the source term);
- Low (L): modeling need useful for a code simulation but with a minor or negligible impact on safety related FOM (e.g. magnetic pump behavior in accidental conditions).

The ranking has been performed according to the technical expert judgement of the authors. This approach based on expert judgement is quite common in the nuclear sector and it has been extensively applied to develop Phenomena Identification and Ranking Tables (PIRT) for safety analysis in nuclear fission applications. Some examples of PIRT developed according to the judgement of an expert panel are provided in [17–23]. In particular, a three-level ranking scale is often used in PIRTs, as in the present paper.

The following subsections provide additional details regarding each code modeling need, including their present availability in the MELCOR fusion version.

2.1. Modeling need N. 1: Inclusion of additional working fluids with multiphase capabilities

In magnetic fusion technology, several materials can be used: the molten salt FLIBE ($Li_2 BeF_4$) [24], metallic lithium, LiPb, solid ceramic lithium compound, etc. Different Breeding Blanket (BB) concepts adopting various materials as coolant and breeder are under discussion (e.g. H_2O/LiPb [25], He/LiPb [26] in case of DEMO design, etc.). Molten salts [27] with lower melting point, e.g. HITEC and Solar salt, are also used as Intermediate Heat Transport Circuit (IHTS) or energy storage fluid.

In order to analyze the complexity of the thermohydraulic behavior of fusion facilities during their normal operation and accident conditions, the use of different multiphase fluids should be implemented in the code. For example, in the cryostat of the ITER facility there are two different fluids (Helium and Nitrogen) that work as coolants. In particular, this system is composed by three liquid Helium refrigerators that

Table 1
List of identified code modeling needs.

N°	Code modeling needs	Priority*
1	Inclusion of additional working fluids with multiphase capabilities	H
2	Implementation of the possibility to use different fluids simultaneously in the same code input	H
3	Introduction of models for chemical reactions of selected working fluids	M
4	Introduction of model for steam and air oxidation of the PFC	M
5	Improvement of models for aerosol behavior: transport, deposition and resuspension	M
6	Implementation of specific heat transfer correlations for simulating Helium and other working fluids in the geometry of interest	M
7	Standard Scrubber model in FL Package for Helium	L
8	Inclusion of dissolved Non Condensable Gas (NCG) species (including hydrogen isotope species) within working fluids	M
9	Implementation of magnetic pump modeling for design and transient features (e.g. coast-down, etc.)	L
10	Inclusion of Magnetohydrodynamics (MHD) effects on heat transfer correlations and pressure drop evaluation	L
11	Extension of the water properties below the triple point	M
12	Implementation of model for air and Helium condensation onto cryogenic structures	M
13	Extension of the working range of materials to cryogenic conditions	H

*Low (L), Medium (M), High (H).

operate in parallel to supply Helium and provide the required cooling power for coils and magnets. Likewise, an air separator produces liquid Nitrogen (LN_2) for the liquid Helium refrigerators [28].

It should be underlined that, to update the library of working fluids, it would be necessary to:

- extend the Equation Of State's (EOS) pressure field to low pressures (<300 Pa);
- include the possibility for users to add libraries for other fluids.

Examples of additional working fluids with multiphase capabilities which could be useful for fusion safety analysis are:

- Air,
- Lithium,
- LiPb,
- FLIBE (LIF+BeF2) breeder material,
- Helium,
- KNO3 + NaNO2 + NaNO3 molten salt (HITEC),
- Solar salt intermediate circuit fluid, heat storage.

Table 2 shows the priority for code implementation of different working fluids according to the technical expert judgement of the authors.

Some additional working fluids are already implemented in MELCOR fusion, in particular:

- MELCOR 1.8.2 allows Helium and air as a working fluid [29];
- MELCOR 1.8.5 allows Helium, Hydrogen, FLiBe, Lithium, Nitrogen, LiPb, etc. [30];
- MELCOR 1.8.6 allows Helium, LiPb [31] and, being a development of MELCOR 1.8.5, it allows also Hydrogen, FLiBe, Lithium, Nitrogen.

2.2. *Modeling need N. 2: Implementation of the possibility to use different fluids simultaneously in the same code input*

Implementation of the possibility to use different fluids in different circuits simultaneously during the same code calculation, such as:

- Lithium/H_2O,
- PbLi/H_2O,
- PbLi/He,
- He/H_2O,
- CO_2/FLiNaK,
- FLiBe/FLiNak,
- Pb/H_2O.

Some of the above mentioned working fluids have been already implemented in MELCOR1.8.6 for fusion, e.g. H_2O, LiPb, He, etc.; however, only one working fluid can be considered in a single input deck. It is important to adopt fusion relevant working fluids in MELCOR 2.2 for performing safety analyses of fusion installations and reproduce the fluid behavior and possibly interactions in mixture, especially in accident scenarios. In case of failure of the first wall or structural material in the breeding zone of the BB or divertor PFC, exothermic reaction may occur if the coolant (e.g. water) gets in contact with the PFC (e.g. tungsten/beryllium), breeding material (e.g. Lithium/LiPb) or neutron multiplier material (e.g. LiPb/beryllium). The reaction type will depend on the selected BB and divertor concepts.

Table 2
Priority for code implementation for different fluids.

Fluid	Priority*
FLIBE	L
Air	M
Helium	H
HITEC	H
Lithium	H
LiPb	H
Solar salt	H

* Low (L), Medium (M), High (H).

Codes like TRACE [32] and RELAP5–3D [33] integrate the possibility of modeling circuits running with different fluids in separate systems of a common input deck. This code capability is useful, for example, for safety analyses applied to different BB concepts for DEMO. The multi fluid approach is also important considering its possible application to the IHTS with molten salt as working fluid. In particular, codes like TRACE are used for the evaluation of Generation IV reactors [34] and the experimental facilities [35] which analyze the heat transfer and flow regimes. Moreover, TRACE 5 patch 7 [36] can handle Helium, liquid sodium, Air, Lead, Lead-Bismuth, Water, Heavy Water, Nitrogen, FLiBe, FLiNaK, KFZrF4 and NaFZrF4 salts. The fluids properties are integrated in the code and, at the occurrence, it is possible to use specific fluid tables. Some fluids present some limitation in the adopted table. For example, TRACE does not allow the modeling of freezing or evaporating phenomena applied to salts. Such limit has an important influence especially in some specific scenarios such as start-up or Design Extended Conditions.

A methodology, suggested by INL in [37] with MELCOR 1.8.6 for fusion, to overcome this code limitation, present in MELCOR 1.8.6 for fusion, consists of defining two different inputs (one for each different working fluids) and parallelizing [38] the calculations (to simulate, for example, blowdowns).

The coupling of the two working fluids is implemented in MELCOR 1.8.6 for fusion by means of an external script. This script shares some relevant information at the same time step with the two input decks. An exercise, using this methodology, was performed by the Sapienza University of Rome [39] to analyze an in-box LOCA of the WCLL blanket concept. Two different input decks were created: the first one to simulate a water circuit and the second one to simulate the LiPb system (Fig. 1). In addition to the MELCOR inputs, a Python script was developed with the aim of coupling the two simulations and obtain more reliable data. Even adopting this procedure for the analysis, intrinsic code limitations of MELCOR multicomponent capabilities remain since several simplifications have been made to be able to perform the simulation.

2.3. *Modeling need N. 3: Introduciton of models for chemical reactions of selected working fluids*

In a safety analysis involving BB or other experimental installations, it is important to model chemical reactions between working fluids, such as those between Lithium (and/or LiPb) with water, air and concrete [40,41].

Chemical reactions, e.g. involving lithium and water, can also

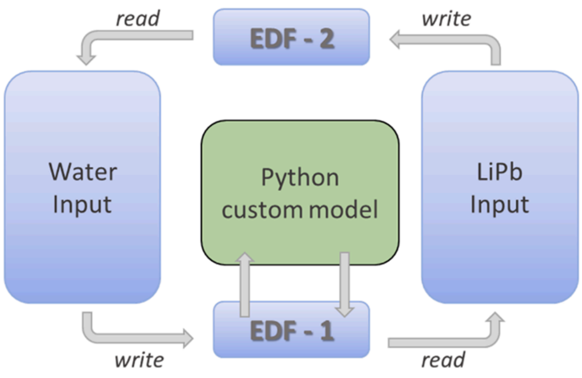

Fig. 1. Scheme of the Python script [39].

generate H_2 and other gasses/aerosols (e.g. NH_3, LiOH). For example, in the case of a Vacuum Vessel (VV) LOCA scenario involving water and LiPb some oxidations, Hydrogen and other gasses/aerosols production can occur. The physical hazard due to the energy and hydrogen release from exothermic reactions with consequent possible overpressure, deflagration or explosion events could also be worsened by the potential mobilization and release of an important population of toxic and corrosive aerosols. Moreover, in fusion facilities like IFMIF-DONES, the radiological source term (represented by T, Be7 and activation products), initially retained by the flowing liquid lithium in closed loops or in dedicated traps, could be mobilized upon lithium fire conditions.

Few chemical reactions are implemented in MELCOR v1.8.6 for fusion, in particular a Lithium-air reaction model is implemented in the code to simulate the reactions of lithium with nitrogen and oxygen [40, 42]. In addition, with the same version, it is possible to simulate specific Lithium reaction products, i.e. Li_2O, Li_3N, through the standard MELCOR RN Package as two independent aerosol classes. A model for the Lithium – H_2O reaction has not been implemented in the code yet [43].

2.4. *Modeling need N. 4: Introducion of model for steam and air oxidation of the PFC*

In order to model PFC oxidation, it is necessary to distinguish between models for steam and air oxidation of the PFC.

Regarding steam oxidation, this phenomenon may be caused by a blowdown transient. The consequences of this scenario are highly dependent on the nature of the specific material: e.g. Beryllium produces a strongly exothermic reaction, Tungsten a soft exothermic reaction, and Carbon an endothermic reaction. A LOCA transient in the VV will generate hydrogen, and, if a simultaneous Loss of Vacuum Accident (LOVA) occurs, there will be risk of a hydrogen explosion due to presence of oxygen in the VV atmosphere. This could lead to the mobilization of radioactive dust and release of tritium and Activated Corrosion Products (ACPs). A possible approach to simulate this phenomenon is to create a source term of Hydrogen and a sink term of steam in the Control Volume Hydrodynamic node (CVH) that encompasses the PFC heat structure. The hydrogen production reaction rate constant can be calculated by taking into account specific Control Functions (CF) and the temperature of the heat structure component. The amount of oxide generated and the Hydrogen source will depend on a CF; it will be correlated on the reaction rate constant and the already reacted mass. In MELCOR v1.8.2 and 1.8.6 for fusion, it is possible to model the oxidation of PFC material in the presence of steam [30].

In relation to air oxidation of the PFC, due to a LOVA, air can enter in the VV and can interact with the material composing the PFC, (e.g., Beryllium, Tungsten and Carbon). This interaction determines materials oxidation and energy production. As for the steam oxidation, this phenomenon could lead to the release of radioactive materials to the environment. A possible approach to simulate this phenomenon is analogous to what has been already mentioned in relation to steam oxidation of PFC. In MELCOR v1.8.2 and 1.8.6 for fusion, it is possible to model the oxidation of PFC material in the presence of air [44].

2.5. *Modeling need N. 5: Improvement of models for aerosol behavior: transport, deposition and resuspension*

The prediction of aerosols behavior in an accidental scenario is fundamental for the estimation of the radiological consequences and for the safety evaluation of nuclear fusion installations [45]. During the last years, several updates to MELCOR fusion (v1.8.2/v1.8.5) have been done in order to cover different aspects regarding the aerosol behavior.

For example, the aerosol deposition model was updated (in MELCOR fusion v1.8.2) by adding different carrier gasses (e.g., air, steam, helium, gas mixtures, etc.) [29].

In addition, the erosion of the PFCs generates dust that can be mobilized again due to resuspension during the transient progression of an accident scenario (LOCA and LOVA). This phenomenon is relevant for safety sinceit can influence the release of radioactive products. Specific models should be developed to provide a better reproduction of resuspension phenomena occurring at low pressure (order of few kPa) and at higher pressure (order of >100 kPa). Improvements were done in MELCOR fusion (v1.8.5) on aerosol resuspension modeling [46]. Two models have been implemented:

- Vainshtein resuspension model;
- Reeks and Hall ➔ Rock 'n Roll resuspension model.

In addition, the structural materials and the dust generated through the erosion of the PFCs might have a remnant magnetization after sitting in a magnetic field for some time. This phenomenon should be considered for aerosol deposition and resuspension. Currently, no model is implemented in MELCOR fusion to cover this issue.

MELCOR 2.2 already implements resuspension models [47] (they call the phenomenon "lift-off" instead of "resuspension"), although the suitability of the available models in fusion applications has not been tested yet. An attempt to introduce a resuspension model in MELCOR 1.8.6 using CFs was also done in the past showing promising results [48].

Finally, in a transient progression involving BB technologies, it is important to model aerosol transport in different working fluids. For example, in the case of the VV LOCA involving water and LiPb, resuspension of dust and lithium-lead vapors and droplets can occur. This is relevant for safety because it can determine the release of radioactive products. MELCOR 2.2 should include the modeling of these phenomena depending on the thermal-hydraulics boundary conditions simulated during the scenario in order to cover the transport of the dust and ACPs in presence of more than one working fluid. Currently no model is implemented in MELCOR fusion to address aerosol transport in different working fluids.

2.6. *Modeling need N. 6: Implementation of specific heat transfer correlations for simulating Helium and other working fluids in the geometry of interest*

Since Dittus-Boelter correlation applied in MELCOR for forced convection cannot be accurate enough in some conditions and geometry, other correlations (e.g. Gnielinski correlation [33,49]), can be implemented in the code to improve the accuracy of the calculated results. For example the correlation from Seban-Shimazaki can be implemented in MELCOR 2.2 to model the heat transfer process between liquid lithium and solid structures. This particular correlation was originally conceived for a fully developed turbulent flow in a tubular geometry considering a constant wall temperature [50]. However, the applicability of such correlations outside the standard pressure range (e.g. below the atmosphere pressure) has to be verified. In order to obviate the problem, the users should have the possibility to modify certain correlations through sensitivity coefficients as allowed in other codes, e.g. in [51].

An approach to overcome the missing correlation would be to determine the Heat Transfer Coefficient (HTC) of a heat structure with CF based on properties such as temperature, density, viscosity, characteristic length, etc., which define specific non-dimensional numbers.

It is necessary to extend the correlations for HTC in MELCOR fusion due to different coolants and flow behaviors expected in normal operation and accident scenarios.

2.7. *Modeling need N. 7: Standard scrubber model in Fl package for Helium*

Pool scrubbing has already been developed for simulating steam/water-containing aerosol. The model is present in MELCOR 1.8.6 for Fusion [52] (FL package -→ FLnnn02 – Flow path junction switches IBUBF 1). Such a model could be used for simulating the activated product's wash phenomenon and tritium combination with water inside the suppression pool into the Vacuum Vessel Pressure Suppressor System (VVPSS). It would be interesting to benchmark its accuracy if Helium is used.

In addition to scrubbing phenomena into the suppression pool, it should be also consider the development of a model to simulate the interaction of high enthalpy helium with water. Implementing this model could improve the evaluation of scrubbing effects, considering the helium flow dynamics in the pool and its thermal interaction with water.

The phenomena related to the injection of helium in water strongly depend on the geometry of the suppression system and helium flow conditions. A gaseous flow in critical conditions, horizontally injected into a water pool, involves the onset of different hydrodynamic aspects at the gas-liquid interface. In particular, in these conditions, the interaction between these two fluids will result in the growth of a helium expansion cone, negatively impacting the scrubbing process. Substantial changes in the flow regime of the blown fluid have been experimentally investigated, passing from low to high discharge rates [53]. In particular, a "bubbling regime" can be established for low gas flow rates [54], and this could enhance the activated product's wash phenomenon.

The implementation in MELCOR of this model could be helpful from both safety and design perspectives since the primary functions of VVPSS are to trap radioactive materials and avoid overpressurization in the VV, maintaining the integrity of the primary confinement barrier in cases of in-vessel LOCA.

2.8. *Modeling need N. 8: Inclusion of dissolved non condensable gas (NCG)species (including hydrogen isotope species)within working fluids*

Tritium is a relevant radioisotope and represents a critical safety issue in fusion-related facilities. Tritium exists in a dissolved state within metallic working fluids (e.g., LiPb in blankets, Li in innovative divertors or in IFMIF-DONES circuits) and cannot be properly modeled by a specific NCG or aerosol in the current MELCOR 2.2 version. In general, tritium can form different species or compounds, as tritiated lithium hydrides, which can be transported within a working fluid and, successively, released by thermodiffusion in response to vapor pressure curves and solubility values. For example, a spill of liquid LiPb in a given control volume would not automatically lead to a release of tritium according to the current models implemented in the code.

In the most recent version of MELCOR fusion (v1.8.6), this issue can be partially addressed by simulating tritium, as hydrogen (H2) or deuterium (D2), by means of the NCG package. Similarly, tritium as T2 could be modelled by creating a new NCG class which implies defining the respective coefficients and properties of the gas to be included in the MELCOR library.

A second and more conservative approach from the safety point of view is to assume that the radiological source term represented by elemental tritium gas, initially retained by the working fluid, will be immediately oxidized and released to the atmosphere of a control volume as tritiated water or HTO (which is known to be more radiotoxic than elemental tritium).

A transport model for HTO was originally implemented in the conservation of mass equations solved for the RN package (from the modified v1.8.2 used for ITER safety analyses) to account for HTO convection between CVs and between pool and atmosphere of a given volume [44]. This model relies on the assumption that tritiated water behaves in the same way both in vapor and liquid phase and it is only applicable to volumes having water as working fluid. To bypass this latter limitation and using the HTO model to simulate tritium also with other working fluids, e.g., Li, PbLi, tritiated water can be simulated as an independent aerosol class by defining specific user control functions within the RN package.

An additional important mechanism in fusion safety is tritium permeation through the circuit pipes. More recently, MELCOR fusion is being further developed to be coupled with the Tritium Migration Analysis Progam (TMAP) code [55,56]. TMAP was developed to dynamically analyze the transport of hydrogen species (e.g. H_2, D_2, T_2, DT, HT) through structures, between structures and adjoining enclosures, and among enclosures. The future MELCOR-TMAP code will also integrate the possibility of using multiple working fluids, such as H_2O, PbLi, Sn, SbLi, FLiBe, Li, Na, cryogenic He, N_2 and O_2, in the same code input. This task would be highly welcome, especially if consolidated in a future MELCOR version 2.2.x, but it seems that the task is not yet completed and a coupled MELCOR-TMAP code is not yet ready for release [57].

2.9. *Modeling need N. 9: Implementation of magnetic pump modeling for design and transient features (e.g. coast-down, etc.)*

Since electromagnetic pumps are often proposed in fusion liquid metal circuits (coil designs or permanent magnet designs), numerical models which take into account related effects, like coast-down after a trip, can help to properly simulate and investigate transient sequences, especially those involving accident scenarios such as LOFAs. In addition, the possibility to choose between different electromagnetic pump configurations, e.g., in series, in parallel, (feature not yet implemented in the code) would allow the user to explore alternative solutions for design and safety purposes.

This proposal aims at an extension of the available general model for pumps, which could be further detailed towards a more realistic but complex behavior.

In the MELCOR fusion code (v1.8.6), two simplified models are currently implemented to simulate the behavior of a generic pump, both relying on the definition of a user control function which defines the relationship between the pressure head developed by the pump and the volumetric flow rate through it [52]. The first model gives the user a great flexibility in defining the pump pressure head, but, at the same time, it may introduce a user effect for the final computed results due to the lack of a formal modeling representation of a particular pump curve operation. The second model specifies a parabolic relationship between the pressure head and the volumetric flow, and its use is limited only to those cases where the approximation of a constant-speed coolant pump can be accepted.

Over the last years, some tentative efforts have been reported [58], but a more formal built-in and consolidated modeling would be welcome in a future MELCOR code version.

2.10. *Modeling need N. 10: inclusion of magnetohydrodynamics (MHD) effects on heat transfer correlations and pressure drop evaluation*

Magnetic fields are captured by means of the Hartmann number of a particular fluid of interest and they can significantly affect heat transfer processes and pressure drops. This phenomenon is very important for the normal operation and, obviously, is able to impact the transient until the magnets switch off. In particular, the pressure drop is expected to have more impact in this phase with a laminarization of the motion and different distributions of the mass flow rate.

Currently no models are implemented in the standard version of MELCOR fusion to cover this phenomenon and the impact on distributed (normally named 2D) and concentrated (3D) pressure drops and heat transfer. A MELCOR fusion model able to simulate the MHD pressure drops behavior is mentioned in [43], but is not available for all users.

A first implementation was done in ATHENA, taking into account 2D pressure drops in simple geometry and maintained in RELAP5–3D [59]. A detailed model for the pressure drops (2D and 3D) evaluation was developed in an updated version for the fusion reactors of RELAP5/-Mod3.3 [60]. Recently, also the first evaluation of the heat transfer modification was implemented [61].

A more detailed review of the MHD effects implementation in system TH codes is available in [62].

2.11. Modeling need N. 11: Extension of the water properties below the triple point

Simulation of cryogenic temperatures could be useful for safety analysis considering specific phenomena such as water freezing in the cryostat of a fusion reactor during an accident scenario. As an example, if a leak of water into cryostat is sufficiently small, the pressure increase will not be large enough and the conditions of the transient will happen below the triple point of water. Specific modifications are present in MELCOR fusion (v1.8.2) covering three areas: EOS, transport properties, and ice film buildup on heat structure [29]. A freezing film model is also available in MELCOR fusion (v1.8.2), although it has not been implemented in more recent versions of the code, i.e. 1.8.5, 1.8.6 [29,42].

2.12. Modeling need N. 12: implementation of model for air and Helium condensation onto cryogenic structures

Safety analyses of the cryostat, which represents the secondary confinement barrier for in-vessel components of a fusion reactor, require the implementation in the code of models to simulate condensation and ice formation of air or Helium, which may enter in the cryostat due to a break on the walls of the cryostat and a LOCA in a superconductor cooling circuit, respectively. In this view, the implementation of the thermo-physical properties of air and helium at cryogenic temperature plays a key role in investigating condensation phenomena that could influence the plant behavior during the selected transients progression.

Regarding air condensation, some modifications to the air condensation model are present in MELCOR fusion (v1.8.2) [30,63]. This model is no longer available in more recent versions of MELCOR fusion, i.e. v1.8.5, v1.8.6. With regard to Helium condensation, the model has been implmemented in MELCOR fusion (v 1.8.2) [29].

2.13. Modeling need N. 13: Extenstion of the working range of materials to cryogenic conditions

Magnet systems present overpressure risks due to superconductor quench events, leading to rapid boiling of helium or nitrogen cryogen. Cryostat safety can be compromised by massive helium or nitrogen ingress during a quench event. Additionally, since MELCOR for fusion handles cryogenic cooling, it is necessary to extend the range of material properties of the cryogenic fluids and the construction materials accordingly. These models are implemented in MELCOR fusion (v 1.8.5 and 1.8.6).

Currently, MELCOR 2.2 does not allow for extrapolation of material properties below 273.15 K for the mayority of the in-built materials which impede any calculation below this range. An approach to overcome the material properties extrapolation problem could be to work solely with user-defined materials, which in turn would impair traceabiilty and validation of results.

3. Conclusions

Several organizations worldwide are actively involved in the research on safety analysis of nuclear fusion installations. In addition, several activities are in progress to design new experimental facilities, such as IFMIF-DONES in Spain and DTT in Italy. In the present paper, the main models required to be implemented in MELCOR 2.2 to address fusion safety issues have been identified and ranked according to the technical expert judgement of several MELCOR users. These models have been described, and their current implementation status in MELCOR fusion version has been highlighted.

In particular, the implementation of additional different working fluids and the possibility to use different fluids in different circuits should be further developed to perform more consistent safety analyses of fusion installations. In fact, the design of these plants is based on the use of different BB concepts using different materials for the breeder and coolant. Linked to that, the introduction of models for chemical reactions for different working fluids has been underlined. A refined modeling of steam oxidation and air oxidation of the PFCs is needed to study the risk of hydrogen explosion and material oxidation. The aerosol resuspension model to be implemented is highlighted considering also the possibility to introduce models for aerosols transport in multifluid. Implementation of specific heat transfer correlations for simulating new working fluids and the introduction of a standard scrubber model in FL for Helium could improve the accuracy of results. The possibility to implement NCG as working fluids could permit to develop further studies focused on Tritium transport. Implementation of magnetic pump modeling and MHD effects on heat transfer could be helpful.

Considering the cryogenic conditions present in fusion plants, the extension of water properties below the triple point is required to consider the water freezing phenomenon in the cryostat. In relation to the cryostat, the modeling of air and helium condensation in cryogenic structures should also be implemented in the code. Also related to the cryogenic conditions, allowance of low temperature operations, cryogenic working fluids and the extension of material properties to cryogenic range could permit to analyze transients scenarios involving magnet systems with possible overpressure due to superconductor quench events.

In conclusion, the development of a future common MELCOR version including fusion features is strongly recommended by the authors. This future version would allow to use all the state-of-art features already implemented in MELCOR 2.2 and would made the future code advances automatically available for the MELCOR fusion community. In addition, this would allow the use of SNAP by fusion users, which could be important to support the development of fusion safety analyses. This paper, based on the feedback of MELCOR code users in fusion application, represents a first contribution to identify the code modeling needs, which would be necessary to be implemented also in other deterministic codes (e.g. thermal-hydraulic system codes) to address specific fusion safety issues.

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.

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