A Parametric Concept Model of Ex-Vessel Steam Explosion in the SAFARI Project

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1. Introduction

In the absence of adequate cooling under severe accident conditions, fuel may melt and breach the reactor vessel. In some reactors, ex-vessel cooling is adopted as part of the severe accident management strategy. Here, a molten fuel jet interacts with the water in the cavity and fragments along its path to the bottom of the reactor cavity. In the event of an internal or external trigger, the fragmented fuel may undergo fine fragmentation, leading to rapid vaporization. This phenomenon, known as a steam explosion, can substantially increase system pressures and may compromise the integrity of the containment. Therefore, steam explosions are regarded as one of the most important severe accident issues in nuclear power plants. Steam explosions can occur at any time during the aftermath of a severe accident. The risk associated with a steam explosion depends on the established mixing conditions prior to the trigger, such as fuel fragment temperature, size distribution, coolant temperature, void fraction, and so on. Hence, it is essential to estimate the risk of a steam explosion at every time step during the coolability transient to reliably assess the safety of the system.

To evaluate the risk of a steam explosion under severe accident conditions, the Steam Explosion Code for Associated Risk (SCAR) module is being developed as part of the SAFARI project, alongside SIMBA, a coolability model providing mixing parameters. SCAR estimates explosion pressures and impulses for every potential mixing condition throughout the coolability transient. Designed to be computationally inexpensive, SCAR is suitable for integration with system codes. Unlike mechanistic codes such as TEXAS and MC3D, SCAR adopts a cost-effective lumped modeling approach while still accounting for necessary complexities, including the semi-mechanistic fine fragmentation process and system geometry information.

This report explores the details of the module, elaborating on its distinct features, the underlying models that drive its functionality, and the assumptions.

2. Module concept of SCAR

The SCAR module is developed based on a non-equilibrium model, similar with UWFCI [2], where the liquid and coolant are allowed to exist at different temperatures.

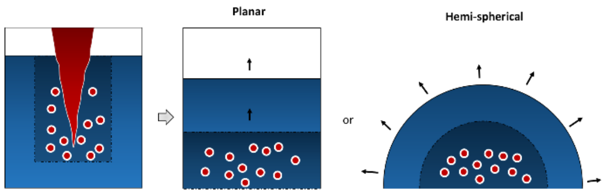

Fig. 1. Constraint options

In the SCAR module, the liquid zone is divided into two zones: the mixing coolant zone and the slug zone. The mixing coolant zone is the area where coolant reacts with fuel jet. While slug zone is the area where coolant and fuel do not react. Therefore, SCAR module can analyze the two constraint options of FCI phenomenon.

2.1 Governing Equations

Thirteen main governing equations are integrated over time using the fourth-order Runge-Kutta method. The SCAR module is a Python-based code. The details of the governing equations are as follows:

Mass Conservation

$$\frac{dm_f}{dt} = -\dot{m}_{fr} \tag{1}$$

$$\frac{dm_{fr}}{dt} = \dot{m}_{fr} \tag{2}$$

$$\frac{dm_c}{dt} = -\dot{m}_g + \dot{m}_s \tag{3}$$

$$\frac{dm_g}{dt} = \dot{m}_g \tag{4}$$

$$\frac{dm_s}{dt} = -\dot{m}_s \tag{5}$$

Energy Conservation

$$\frac{dE_f}{dt} = -Q_{fg} + \dot{m}_{fr} V_f P - \dot{m}_{fr} h_{fn} \tag{6}$$

$$\frac{dE_{fr}}{dt} = -Q_{frg} - \dot{m}_{fr} V_f P + \dot{m}_{fr} h_{fn} \tag{7}$$

$$\frac{dE_c}{dt} = Q_{fc} + Q_{frc} - \dot{m}_g c_{pc}(T_c - T_{ref}) + P\dot{V}_c - \dot{m}_s c_{pc}(T_s - T_{ref}) \tag{8}$$

$$\frac{dE_g}{dt} = Q_{fg} + Q_{frg} - Q_{fc} - Q_{frc} + \dot{m}_g c_{pc}(T_c - T_{ref}) - P\dot{V}_g \tag{9}$$

$$\frac{dE_s}{dt} = -\dot{m}_s c_{pc}(T_c - T_{ref}) + P\dot{V}_s \tag{10}$$

where m_f is mass of fuel, m_{fr} is mass of fuel fragment, m_c is mass of coolant, m_g is mass of gas, m_s is mass of slug. T_{ref} is $273.15K$.

2.2 Steam Explosion Module

2.2.1 Fragmentation model

The SCAR module offers five choices for the fine-fragmentation process: one parametric model, two semi-mechanistic thermal fragmentation models, and two semi-mechanistic hydrodynamic fragmentation models. The details of these models are discussed in the following:

First, Oh's parametric fine-fragmentation parametric model [3]: The parametric model proposed by Oh calculates the rate of mass fragmentation using an exponential decay function. This rate is proportional to the difference between the initial mass of the mixed fuel(m_{fi}) and the product of the mass of a single fine-fragmented fuel(m_{frs}) and the number of mixed fragmented fuels(N_{mix}).

$$\frac{dm_{fr}}{dt} = -\frac{m_{fi} - m_{frs}N_{mix}}{\tau_{fr}} e^{-\frac{t}{\tau_{fr}}} \quad (11)$$

Second, Kim's thermal fine-fragmentation model [4]: Kim's model proposes that film destabilization leads to the formation of small liquid jets due to Rayleigh-Taylor instabilities. These jets can penetrate the melt drop before vaporization, resulting in the ejection of a superficial part of the drop. It depends on the trigger pressure and the velocity of the fragmentation(v_{frag}) calculated based on Rayleigh-Taylor instability.

$$\frac{dm_{fr}}{dt} = -\rho_f N_{mix} \pi C_0 {D_f}^2 v_{frag} \quad (12)$$

Third, Tang's thermal fine-fragmentation model [5]: Tang's model is also based on Kim's thermal fine-fragmentation concept. It is simpler and introduces a cut off for the fine-fragmentation process based on void fraction($f(\alpha)$) and fragmentation time scale($g(\tau_{fr})$). When the void fraction exceeds 30%, $f(\alpha)$ ensures the process halts. Similarly When the transient time exceeds the fragmentation time scale, $g(\tau_{fr})$ ensures the process halts.

$$\frac{dm_{fr}}{dt} = -6C_{fr} m_f \sqrt{\frac{\Delta P_{fr}}{\rho_c {R_f}^2}} f(\alpha) g(\tau_{fr}) \quad (13)$$

Fourth, MC3D hydrodynamic fine-fragmentation model [6]: MC3D model is based on the relative velocity between the fuel, coolant and the hydrodynamic fine-fragmentation constant($\boldsymbol{C_{fr\_hydro}}$). SCAR module uses the shock wave velocity in the mixing medium as a substitute since the velocities of the fuel and coolant are not explicitly solved.

$$\frac{dm_{fr}}{dt} = 6C_{fr\_hydro} m_f \sqrt{\frac{\rho_c}{\rho_f}} \Delta v D_f \quad (14)$$

Fifth, ESPROSE hydrodynamic fine-fragmentation model: ESPROSE hydrodynamic fine-fragmentation model is similar to the MC3D model, calculates the fragmentation time scale based on the Bond number(B_o). In this formulation, fine-fragmentation constant is incorporated into the calculation of the fragmentation time scale.

$$\frac{dm_{fr}}{dt} = -\frac{\pi {D_f}^2 \Delta v \sqrt{\rho_f \rho_m}}{6t_{fr\_star}} \quad (15)$$

2.2.2 Fragmentation Time Scale

First, the Slug breach concept: Instability analysis considers the growth of waves associated with the entire spectrum of possible wavelengths of the Taylor instability to identify the fastest wavelength growth rate during the explosion expansion. When the fastest-growing wave exceeds the slug's thickness, the explosion is considered to have ceased (as shown in Figure 4), similar to the findings in the work by Oh et al. [2].

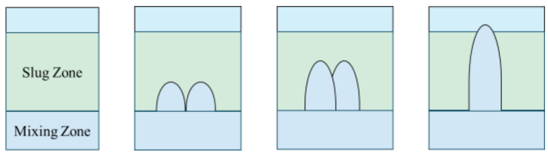

Fig. 2. Slug breach concept

Second, the Acoustic constraint concept: After the shock wave reaches the free surface, which is the end of the slug area, the fragmentation stops when it reaches the point where the shock occurred again.

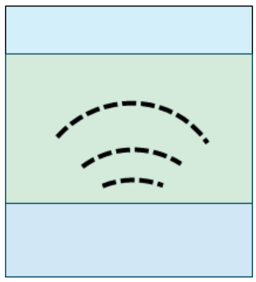

Fig. 3. Acoustic constraint concept

Third, when a fragmented fuel undergoes breakup, resulting in fine-fragmentation, the diameter of each fine-fragment(D_{fr}) is assumed to be constant. This assumption aligns with those made in codes such as UWFCI [2] and TEXAS [8].

Regardless of the chosen fine-fragmentation model, it is assumed that the fine-fragmentation process ceases when the diameter of the fragment(D_f)equals the fine-fragment diameter(D_{fr}). This assumption is based on the understanding that once a fragment has been reduced to the size of a fine fragment, further fragmentation into smaller sizes is not feasible.

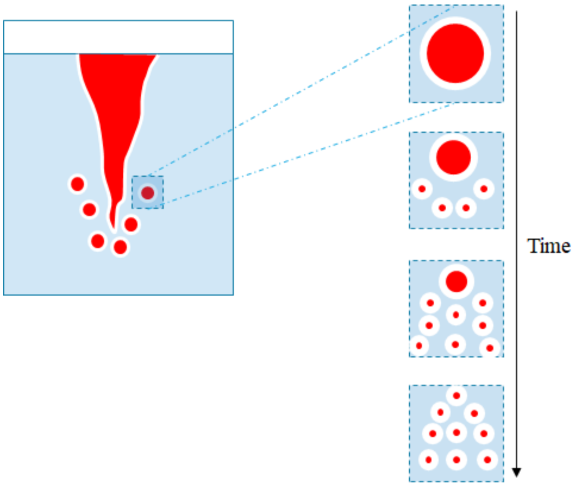

Fig. 4. Fragmentation diameter concept

2.2.3 Equation of State

We solve the governing equations for energy and mass of vapor, as well as the volume of the mixing zone. By utilizing these equations, we can obtain specific internal energy (u_g) and specific volume (v_g). The SCAR module then calculates pressure(P) and temperature(T_g) based on these values by using IAPWS steam table.

2.3 Calculation Procedure

Initially, the user initializes and specifies the parameters to be used in the calculations. Next at each time step, the fragmentation model, which is configured with a predetermined fragmentation ratio, computes fragmentation time and various parameters by utilizing steam tables to calculate the volume of gas, internal energy, including mass of fuel, diameter of jet, and temperature through solving heat transfer equations. Following this, the governing equations are updated and solved over time. These calculations end when the fragmentation time is reached.

3. Preliminary Validation for SCAR module

3.1 Preliminary Validation Strategy

The SCAR model necessitates specific tuning of its coefficients, particularly for the fine-fragmentation process, given that constants from other codes like TEXAS may not directly apply. To address this, a rigorous three-phase verification and validation strategy has been proposed. In summary, the three phases are as follows: Phase 1 incorporates TEXAS mixing data to assess performance of SCAR module; Phase 2 utilizes SIMBA mixing predictions to fine-tune SCAR's coefficients; and Phase 3 entails a direct comparison between SCAR and TEXAS to evaluate SCAR's accuracy and reliability in real reactor scenarios. A detailed description of the verification and validation strategy is provided in report [1].

The SCAR module was employed to predict the steam explosion pressure and impulse involved in KROTOS experiments. KROTOS experiments are part of the widely used experimental databases for studying corium-water interaction conducted at the Joint Research Center (Ispra, Italy) [12]. In this validation effort, the thermal fine-fragmentation model by Corradini et al. [11] was utilized to model the fine-fragmentation process. The choice of the fine-fragmentation model is based on the model used in TEXAS-V. The fine-fragmentation rate is given as follows:

$$\frac{dm_{fr}}{dt} = -6C_{fr}m_f\sqrt{\frac{\Delta P_{fr}}{\rho_c {R_f}^2}}f(\alpha)g(\tau_{fr}) \qquad (16)$$

where C_{fr} represents the fine-fragmentation coefficient, ΔP_{fr} denotes the threshold pressure, $f(\alpha)$ ensures that the fine-fragmentation process ceases at void fractions higher than 0.5, and $g(\tau_{fr})$ ensures that the process stops if the time exceeds the global fine-fragmentation time scale.

3.2 KROTOS Experiment

The aim of the KROTOS test facility is to provide experimental data on FCI phenomena during severe accidents in nuclear power plants. The experiments simulate the interaction between molten core materials and the reactor's coolant, which may occur during a severe accident. One of the most renowned experimental programs for studying corium-water interaction was conducted at the KROTOS facility in the Joint Research Center (Ispra, Italy) [12]. The experimental setup is depicted in Figure 7.

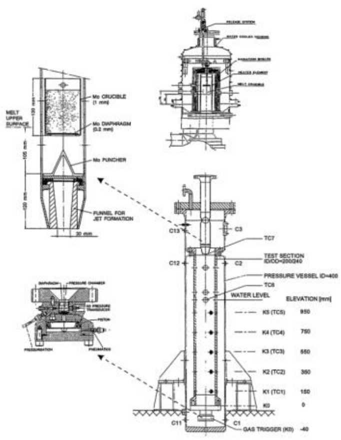

Fig. 5. KROTOS experiment facility

We selected the KROTOS 44 experiment for several reasons. First, it exhibited a strong explosion: During the KROTOS K44 test, a powerful explosion with a peak pressure of about 68 MPa occurred. This significant release of energy aids in modeling and understanding worst-case scenarios in nuclear safety. Second, it involved a one-dimensional explosion: The KROTOS K44 test was designed to produce an explosion in a single direction, simplifying the experimental conditions and facilitating data analysis. By focusing on a one-dimensional explosion, the steam explosion physics can be evaluated without the complexity introduced by multi-dimensional effects. Third, pressure and melt penetration were monitored by the test section: The experimental setup of the KROTOS K44 test allowed for meticulous monitoring of key parameters such as pressure and the penetration of the melt. The design of the test section enabled detailed data collection regarding the explosion and the progression of the melt, which is critical for validation studies. Fourth, melt penetration to the bottom of the test tube at the time of triggering: In the KROTOS K44 test, the melt, representing the reactor core material, deeply penetrated into the coolant before the triggering event. This condition closely resembles a realistic scenario of a severe nuclear accident, making it an ideal condition for validating the ability of the SCAR model to accurately predict the behavior of a full FCI phenomena.

3.3 Initial condition of KROTOS 44 experiment

The steam explosion in the KROTOS 44 test is being simulated by SCAR module. As mentioned in introduction, SCAR module requires input table.

KROTOS	K44
Composition	Al_2O_3
Mass, kg	1.5
Temperature, K	2673
Release diameter, mm	30
Free fall in gas, m	0.44
Height, m	1.105
Temperature, K	363
Subcooling, K	10
Pressure, MPa	0.1
Temperature, K	328

Table. 1. KROTOS 44 Initial condition

As part of Phase I, for the present analysis, the necessary parameters for mixing are acquired by executing the TEXAS-V code till the moment of triggering.

3.4 Sensitivity Analysis

Fig. 6 shows the changes of maximum impulse with different fragmentation constants(C_{fr}). C_{fr} is varied from 0.0001 to 0.004. It can be observed that the maximum impulse increase with an increase in the fragmentation constant. Moreover, when C_{fr} is 0.0011, the value of maximum impulse predicted by the code is close to the experimental result.

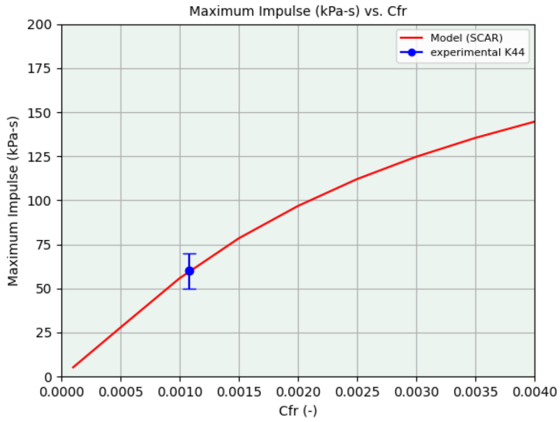

Fig. 6. Predicted maximum impulse vs C_{fr}

4. Conclusions

The development and preliminary validation of the SCAR module within the SAFARI project signify a significant advancement in assessing the risk of steam explosions in nuclear reactors. Through a phased validation approach encompassing performance evaluation, parameter fine-tuning, and code-to-code comparisons, promising results have emerged, notably from preliminary validation against KROTOS experiments. Sensitivity analysis has offered valuable insights into the module's behavior, indicating areas for further refinement. While additional validation and fine-tuning are required, the SCAR module exhibits strong potential as a dependable tool for estimating pressure and impulse in steam explosions, thus enhancing safety protocols in nuclear reactor operations.

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