Development of Parametric Steam Explosion Code for Severe Accident Analysis

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1. Introduction

- FCI and SE, which occur in the event of severe accident, are important phenomena for the progress and termination of the accident and the integrity of the plant containment building.
- Steam explosions can be hypothesized to occur at any time during the aftermath of a severe accident.
- Steam explosion Code for Associated Risk (SCAR) module is being developed as part of the SAFARI project.
- SCAR module is developed based on a non-equilibrium model, similar with UWFCI. [1]
- This tool estimates explosion pressures and impulses at every possible mixing condition throughout the coolability transient.

2. Methodology

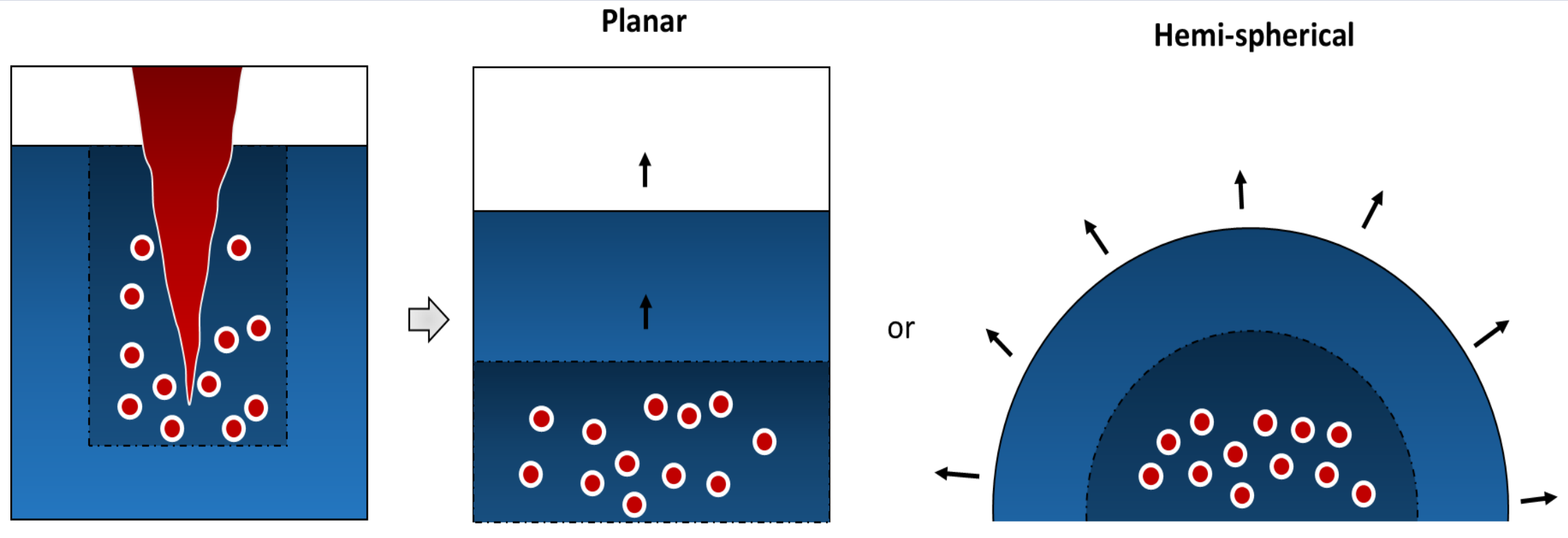


Fig 1. Constraint options [2]

Governing Equations

- Mass conservation
- $\frac{dm_f}{dt} = -\dot{m}_{fr}$
- $\frac{dm_{fr}}{dt} = \dot{m}_{fr}$
- $\frac{dm_c}{dt} = -\dot{m}_g + \dot{m}_s$
- $\frac{dm_g}{dt} = \dot{m}_g$
- $\frac{dm_s}{dt} = -\dot{m}_s$

- Energy conservation
- $\frac{dE_f}{dt} = -Q_{fg} + \dot{m}_{fr} V_f P - \dot{m}_{fr} h_{fn}$
- $\frac{dE_{fr}}{dt} = -Q_{frg} - \dot{m}_{fr} V_f P + \dot{m}_{fr} h_{fn}$
- $\frac{dE_c}{dt} = Q_{fc} + Q_{frc} - \dot{m}_g c_{pc}(T_c - T_{ref}) + P\dot{V}_c + \dot{m}_s c_{pc}(T_s - T_{ref})$
- $\frac{dE_g}{dt} = Q_{fg} + Q_{frg} - Q_{fc} - Q_{frc} + \dot{m}_g c_{pc}(T_c - T_{ref}) - P\dot{V}_g$
- $\frac{dE_s}{dt} = -\dot{m}_s c_{pc}(T_s - T_{ref}) + P\dot{V}_s$

Fragmentation model

- Choice of the fine-fragmentation model is based on the model used in TEXAS-V. [3]

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

- It is simpler and introduces a cut off for the fine-fragmentation process based on void fraction($f(\alpha)$) and fragmentation time scale($g(\tau_{fr})$).

Fragmentation time scale (τ_{fr})

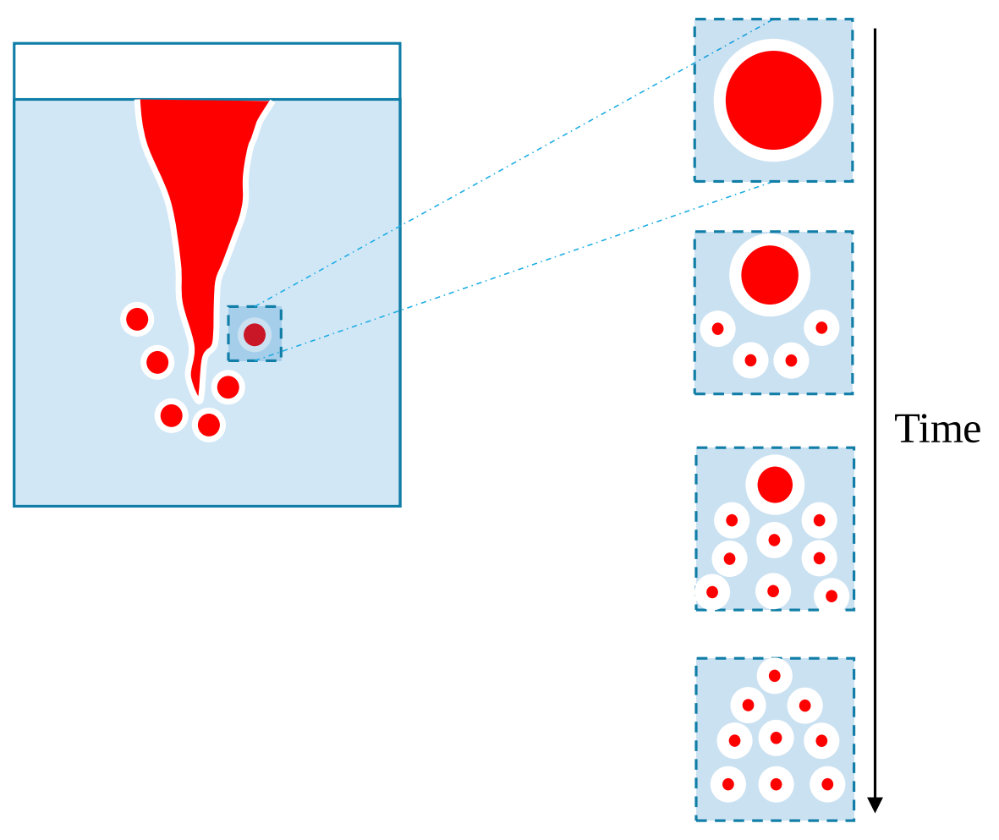
1. Slug breach concept

- 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.

2. Acoustic constraint concept

- After the shock wave reaches the free surface, which is the end of the slug area, fragmentation stops when it reaches the point where the shock occurred again.

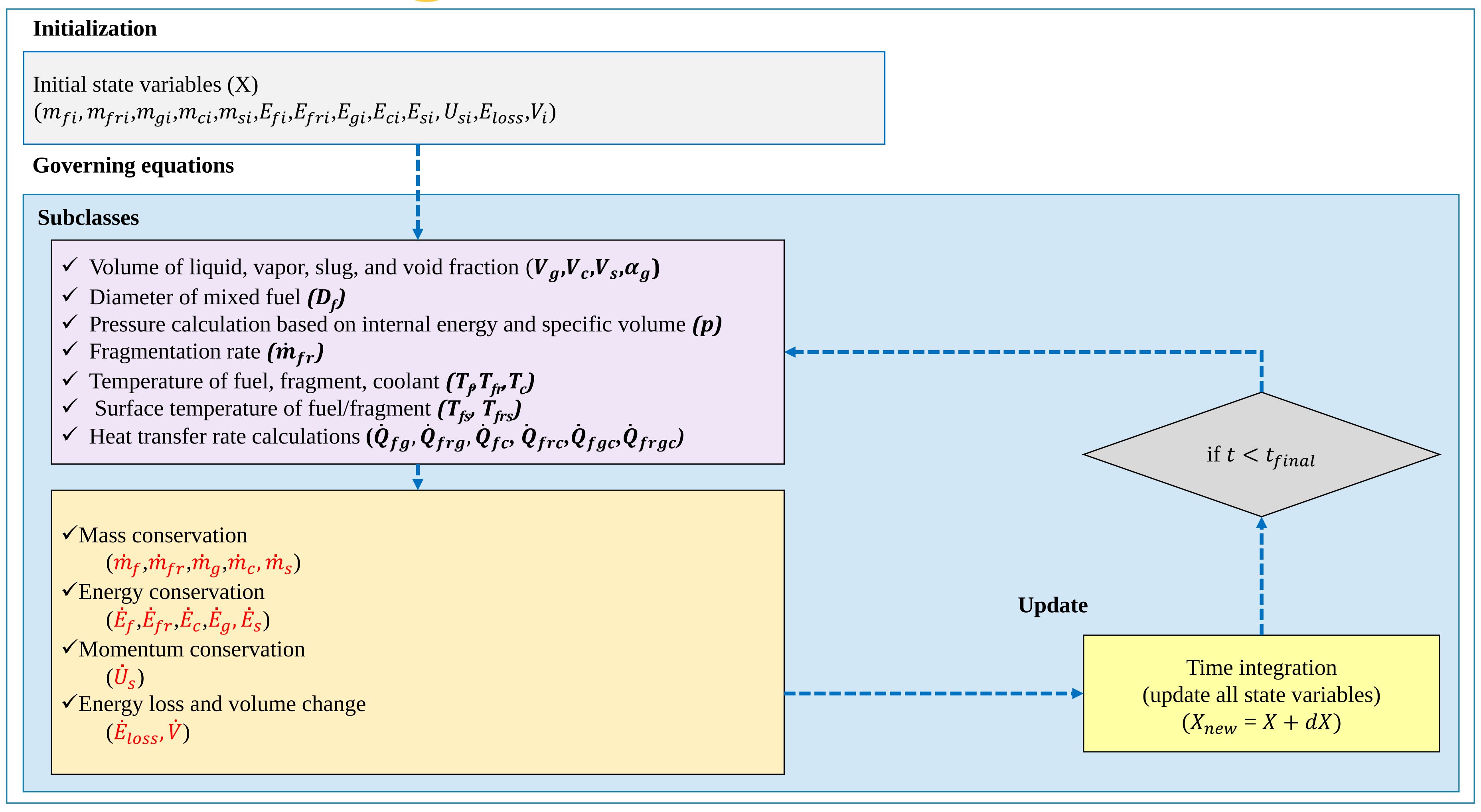
3. Fragmentation diameter concept



- Fragment breaks up into fine fragments with a constant fine-fragment diameter(D_{fr})
- Fine-fragmentation process ceases when the fragment diameter(D_f) becomes equal to the fine-fragment diameter(D_{fr})

Fig 2. Fragmentation diameter concept [2]

Code flow chart



Initialization

Initial state variables (X)
$(m_{fi}, m_{fri}, m_{gi}, m_{ci}, m_{si}, E_{fi}, E_{fri}, E_{gi}, E_{ci}, E_{si}, U_{si}, E_{loss}, V_i)$

Governing equations

Subclasses

- ✓ Volume of liquid, vapor, slug, and void fraction **(V_g, V_c, V_s, α_g)**
- ✓ Diameter of mixed fuel **(D_f)**
- ✓ Pressure calculation based on internal energy and specific volume **(p)**
- ✓ Fragmentation rate **($\dot{m}_{fr}$)**
- ✓ Temperature of fuel, fragment, coolant **(T_f, T_{fr}, T_c)**
- ✓ Surface temperature of fuel/fragment **(T_{fs}, T_{frs})**
- ✓ Heat transfer rate calculations **($\dot{Q}_{fg}, \dot{Q}_{frg}, \dot{Q}_{fc}, \dot{Q}_{frc}, \dot{Q}_{fgc}, \dot{Q}_{frgc}$)**

- ✓Mass conservation
  ($\dot{m}_f, \dot{m}_{fr}, \dot{m}_g, \dot{m}_c, \dot{m}_s$)
- ✓Energy conservation
  ($\dot{E}_f, \dot{E}_{fr}, \dot{E}_c, \dot{E}_g, \dot{E}_s$)
- ✓Momentum conservation
  ($\dot{U}_s$)
- ✓Energy loss and volume change
  ($\dot{E}_{loss}, \dot{V}$)

Update

Time integration
(update all state variables)
($X_{new} = X + dX$)

if $t < t_{final}$

3. Validation

KROTOS Experiment

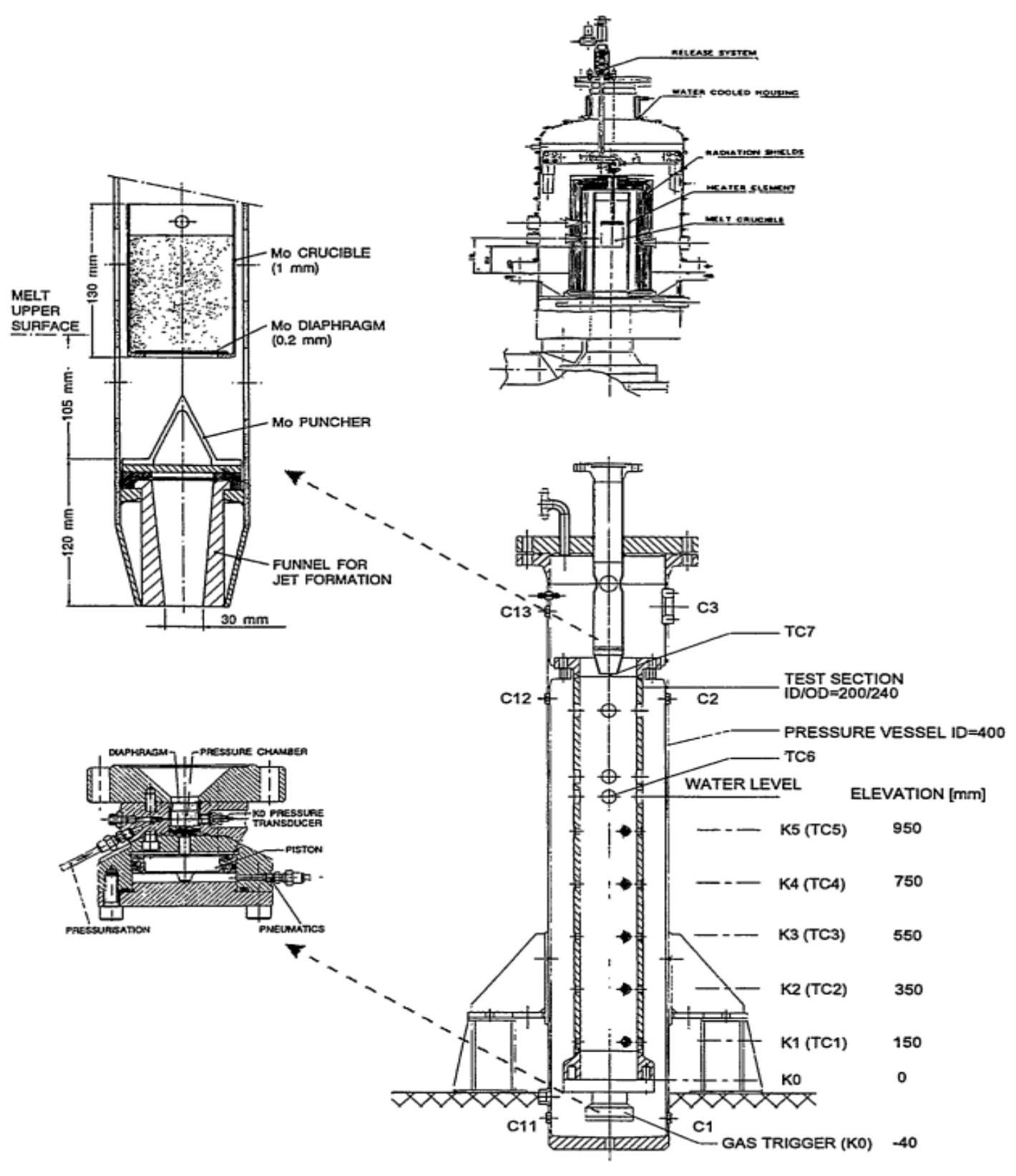


Fig 3. KROTOS experiment facility [4]

KROTOS	K44
Composition	Al_2O_3
Mass, kg	1.5
Temperature, K	2673
Release diameter, m	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 [4]

Why KROTOS K44 test?

- **1. Strong explosion:** A powerful explosion with a peak pressure of about 68 MPa occurred.
- **2. One-dimensional explosion:** The K44 test was designed to produce an explosion in a single direction → Can be evaluated without the complexity introduced by multi-dimensional effects.
- **3. Pressure and melt penetration were monitored by the test section:** The experimental setup of the K44 test allowed for meticulous monitoring of key parameters such as pressure and the penetration of the melt.
- **4. Melt penetration to the bottom of the test tube at the time of triggering:** This condition making it an ideal condition for validating the ability of the SCAR model to accurately predict the behavior of a full FCI phenomena.

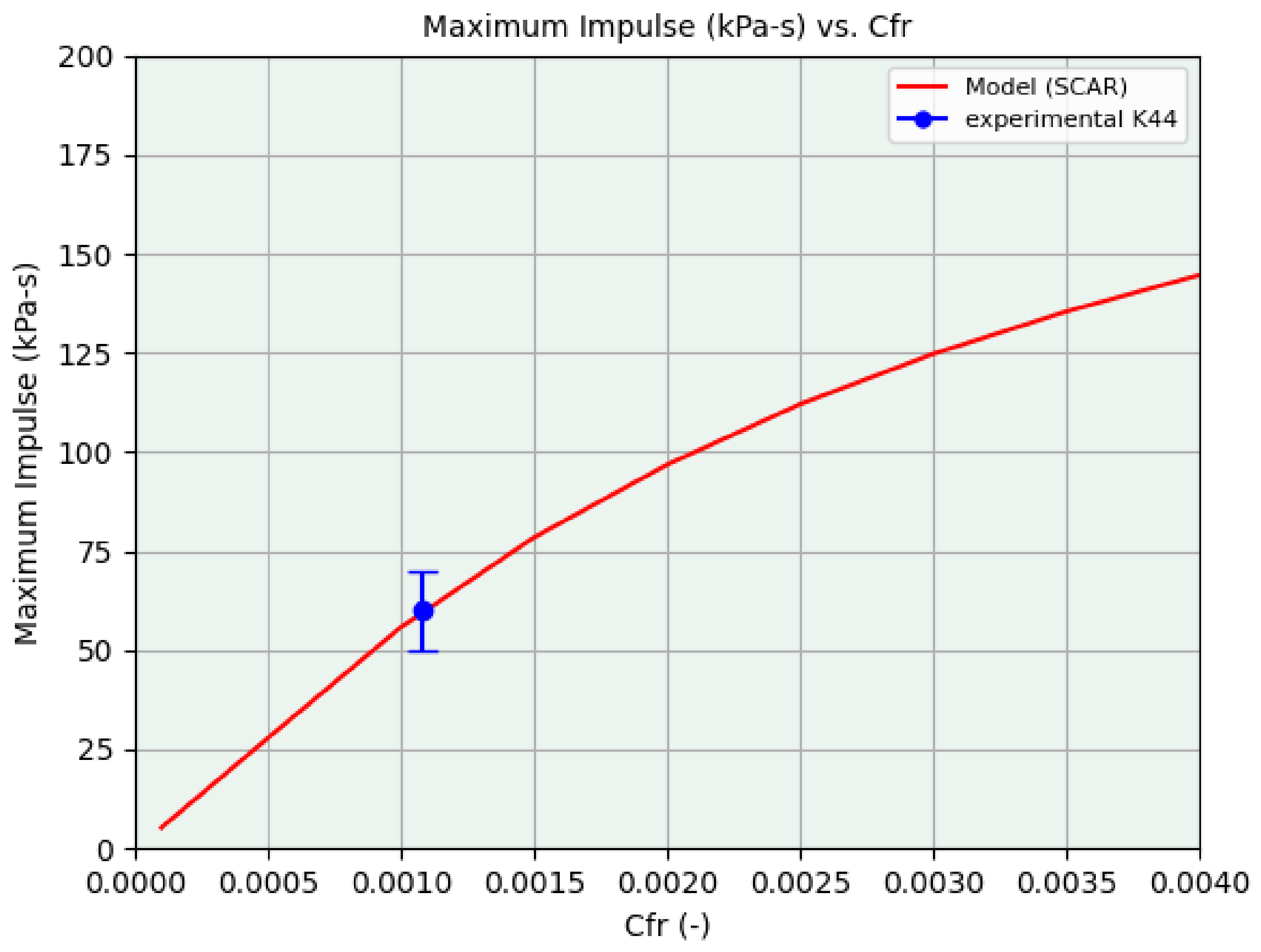


Fig 4. Predicted maximum impulse vs C_{fr} [2]

KROTOS 44 C_{fr} Sensitivity Analysis

- When C_{fr} increases, maximum pressure and impulse increase.
- When $C_{fr} = 0.0011$, It is close to experimental result.
- The dependency of C_{fr} decreases as the C_{fr} increases. The reason is that the Void fraction limit (0.3) is reached faster.

4. Conclusions

- The SCAR module offers a computational tool to estimate the pressure and impulse generated during such a steam explosion.
- SCAR module has been designed to be computationally inexpensive and is suitable for coupling with system codes.
- Preliminary validation efforts using the KROTOS 44 experiments have shown promising results.
- The results of the Sensitivity Analysis indicate that the SCAR module requires further validation and fine-tuning, yet it holds the potential to be a reliable tool for assessing the risk of steam explosions in nuclear reactors.

Acknowledgement

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