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# Modeling and analysis of molten fuel vaporization and expansion for a sodium fast reactor severe accident

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## HIGHLIGHTS

- Evaluation tool for the expansion phase of a SFR Core-Disruptive Accident.
- Comparison of adiabatic and non-adiabatic expansions due to sodium entrainment.
- Tool comparison to the EXCOBULLE tests and to PFBR safety studies.
- Parametric studies on a SFR-like geometry to assess the released energy variability.

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## ABSTRACT

The safety assessment of Sodium-cooled Fast Reactors (SFR) requires to account for hypothetical severe accidents involving the melting down of the core materials. This paper deals with the modeling of a fuel vaporization transient that might occur in a SFR in case of severe accident. After a nuclear power excursion, some fuel might be molten and vaporized. In this case, the expansion of fuel vapor might generate a mechanical stress on the reactor vessel and structures. Assessing the vessel integrity is of major importance for the reactor design. A fuel vaporization and expansion modeling, which has been simplified using a Dimensional Analysis, is presented. The modeling is implemented in a tool, called DETONa, able to perform fast calculations, of the order of one minute. The vaporized fuel's thermal exchange with the reactor liquid coolant leading to a possible coolant vaporization is simulated by DETONa. The coolant is assumed to be entrained into the fuel vapor. A droplet entrainment model based on Rayleigh-Taylor instabilities associated to their diameter's limitation using Weber stability criterion is proposed. The modeling is validated on experimental results and on code-to-code comparisons. Parametric calculations are conducted on a reactor case. The impact of the initial molten fuel mass, its initial temperature, critical Weber number and radiative heat transfer are investigated. The non-adiabatic modeling and the adiabatic modeling yield results different by 40% in certain cases. DETONa is shown to be sensitive to the fuel initial temperature, the heat transfer coefficient and the Rayleigh-Taylor wavelength, involving variations that can range to 18%.

## 1. Introduction

A Sodium-cooled Fast Reactor (SFR) of Generation IV (Fig. 1) is under development in France. The reactor safety analyses have to account for severe accidents, involving the melting down of the reactor's core.

However, despite the past R&D progress and outcomes, severe accidents modeling still deals with various physical processes associated to remaining uncertainties, like heat transfer, fragmentation, neutronic and thermal hydraulic interactions, or fluid-structure interactions. Assessing uncertainties and evaluating safety margins with parametric studies are the main purpose of fast-running tools development. Such an assessment relies on the combination of these fast-running tools (Marie et al., 2013, 2016a,b; Droin et al., 2015, 2017; Herbreteau et al., 2016) with statistical analysis techniques (Marrel et al., 2015).

This paper deals with the modeling of the expansion phase of an energetic Core Disruptive Accident (CDA) that precedes a potential radiological release, and its associated tool development. CDAs were among the first accidents studied for SFRs safety. The term

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## Nomenclature

*Roman symbols*

| | |
|---|---|
| $A$ [m$^2$] | area |
| $Bi$ [–] | biot number |
| $c_p$ [J kg$^{-1}$ K$^{-1}$] | specific heat capacity at constant pressure |
| $d$ [m] | diameter |
| d [–] | differential operator |
| $Eu$ [–] | Euler number |
| $Fr$ [–] | Froude number |
| $g$ [m s$^{-2}$] | gravity acceleration |
| $H$ [J] | enthalpy |
| $h$ [J kg$^{-1}$] | specific enthalpy |
| $Ja$ [–] | Jakob number |
| $K$ [J] | kinetic energy |
| $k$ [W m$^{-1}$ K$^{-1}$] | thermal conductivity |
| $L$ [m] | characteristic length |
| $m$ [kg] | mass |
| $Nu$ [–] | Nusselt number |
| $n$ [–] | jets or droplets number |
| $Pe$ [–] | Peclet number |
| $Pr$ [–] | Prandtl number |
| $p$ [Pa] | pressure |
| $Q$ [J] | heat transfer |
| $R$ [m] | radius |
| $\dot{R}$ [m s$^{-1}$] | radius time-derivative |
| $\ddot{R}$ [m s$^{-2}$] | radius second time-derivative |
| $Re$ [–] | Reynolds number |
| $T$ [K] | temperature |
| $t$ [s] | time |
| $V$ [m$^3$] | volume |
| $v$ [m s$^{-1}$] | velocity |
| $W$ [J] | work |
| $We$ [–] | Weber number |
| $x$ [–] | vapor quality |

*Subscripts*

| | |
|---|---|
| $Ar$ [–] | argon |
| $b$ [–] | bubble |
| $d$ [–] | droplet |
| exp [–] | expansion |
| $f$ [–] | fuel |
| $j$ [–] | jets or droplets family number |
| jets [–] | jets |
| $Na$ [–] | sodium |
| $RT$ [–] | Rayleigh-Taylor |
| $vap$ [–] | vaporization |

*Superscripts*

| | |
|---|---|
| $C$ [–] | critical or cutoff |
| $conv$ [–] | convection |
| eff [–] | effective |
| $l$ [–] | liquid |
| $lv$ [–] | liquid-vapor phase change |
| $l+v$ [–] | two-phase liquid-vapor mixture |
| $M$ [–] | most unstable |
| $mix$ [–] | mixing |
| $rad$ [–] | radiative |
| $sat$ [–] | saturation |
| $tot$ [–] | total |
| $v$ [–] | vapor |
| $vap$ [–] | vaporized |

*Greek symbols*

| | |
|---|---|
| $\Delta$ [–] | variation |
| $\delta$ [–] | infinitesimal variation |
| $\varepsilon$ [–] | radiative emissivity |
| $\gamma$ [–] | specific heat capacities ratio |
| $\kappa$ [W m$^{-2}$ K$^{-1}$] | heat transfer coefficient |
| $\lambda$ [m] | wavelength |
| $\eta$ [Pa s] | dynamic viscosity |
| $\vec{\nabla}$ [m$^{-1}$] | gradient operator |
| $\rho$ [kg m$^{-3}$] | density |
| $\nu$ [W m$^2$ K$^{-4}$] | Stefan-Boltzmann constant |
| $\sigma$ [J m$^{-2}$] | surface tension |

*energetic* means that the accident leads to a release of mechanical energy that might damage the primary vessel. CDAs lead to the generation of large thermal energies, high enough to heat nuclear fuel far over its saturation temperature, triggering its fast vaporization. This can be achieved when the core of a reactor collapses, leading to a power excursion induced by fissile materials compaction. The mechanical energy release due to materials dispersal after a nuclear excursion caused by the collapse of a SFR core was firstly studied by Bethe and Tait (1956). Even if the Bethe-Tait accident is not always exactly studied as it stood in 1956, the energetic expansion stage is today classical in SFR safety assessments. The most commonly used models for the energetic part of the accident assume that the fuel vaporization creates a high-pressure fuel vapor *bubble*, which can be several meters large (Epstein et al., 2001). This bubble's expansion loads the primary vessel. CDAs may also involve fast vaporization and expansion of the sodium coolant or of steel components, which may also generate a mechanical loading. Yet, these transients occur for milder power excursions, that are not powerful enough to vaporize quickly large masses of nuclear fuel. These cases are not treated in this paper, which is devoted to the fuel vaporization that might occur after an intense power excursion.[1] It is less probable, but has to be modeled also.

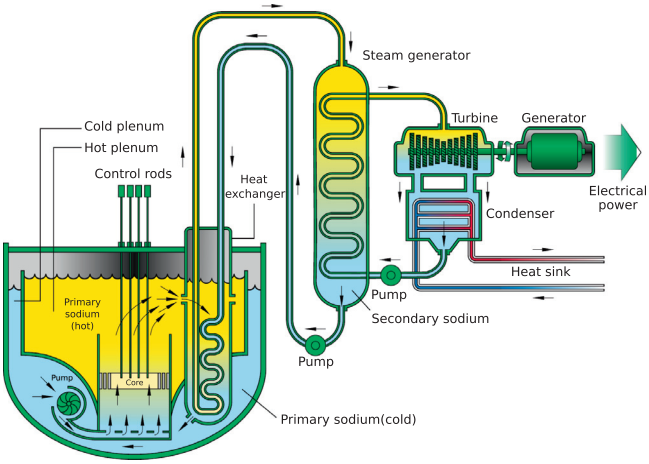

**Fig. 1.** Sodium fast reactor concept.

While the fuel vaporization-expansion transient has been widely studied, especially in the adiabatic fuel vapor expansion case, a lack of knowledge remains on some parts of the accident. The thermal exchange between very hot fuel vapor and colder

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[1] Similarly, fission gas release may generate mechanical loading. This is not treated now, but it is planned to consider it by adding a pressure source term.