FROM RESEARCH TO INDUSTRY

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USE OF THE DUNE ENVIRONMENT FOR THE DEVELOPMENT OF A VAPOR EXPLOSION CALCULATION TOOL

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CONTEXT : GENERATION IV REACTOR SAFETY

- **Generation IV international forum** → specifications:
  - improve safety → Among other things, take into account, **from the very conception of the reactor**, the possible occurrence of a severe accident
  - improve nuclear non-proliferation
  - minimize the waste production (nuclear fuel recycling)
  - optimize the use of natural ressources
  - decrease the reactor building and operating costs

Severe accident sequence = Series of events leading to the ruin of the reactor core

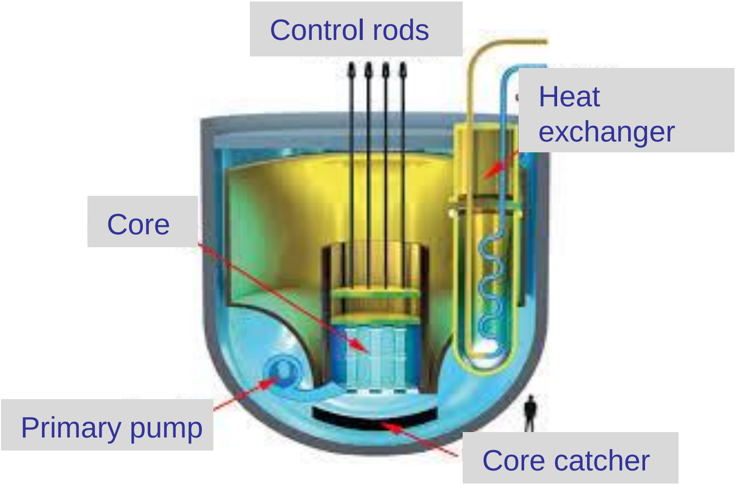
- **CEA (+ partners) → conception of a Sodium-cooled Fast neutron Reactor (SFR)**

  designed to match the Gen IV forum specifications

- Severe accident study → **Core degradation**
  - Local heat-up (various initiators considered)
  - Material melting → corium (molten core) formation (~3000°C)
  - Corium relocation into the reactor lower plenum
  - Corium jet in contact with « cold » sodium (FCI)

    → violent interaction (vapor explosion) that may threaten the reactor structures

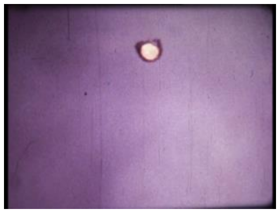
    → fine corium debris generation, sedimentation on the core catcher : cooling? recriticality?



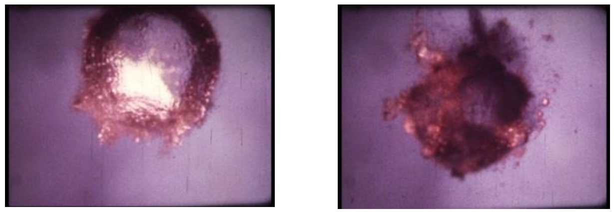
⇨To be evaluated for the reactor conception

VAPOR EXPLOSION

- Example of vapor explosion : molten material representing corium injected into water



Molten oxide droplet surrounded by a vapor film



Vapor film destabilisation, droplet explosion

L.S. Nelson experiments, SANDIA ~1980
1-10g droplets of molten alloy injected in water

- **SFR** accident scenarios → hot **liquid corium** (~3000°C) flow into more volatile cold **liquid sodium** (~500°C)

Process similar to corium-water interaction (deeply studied for water-cooled reactors):
- heavy corium fragmentation
- coolant heating and vaporisation
- vapor explosion

… but different:
- sodium thermal behaviour
- interaction time scale
- debris size

Corium-sodium interaction

Physics not entirely understood→ knowledge needs to be improved:

- dedicated experimental programs

↓ Data for closure laws model development and validation

↑ Storage of knowledge

- development of a detailed computer code

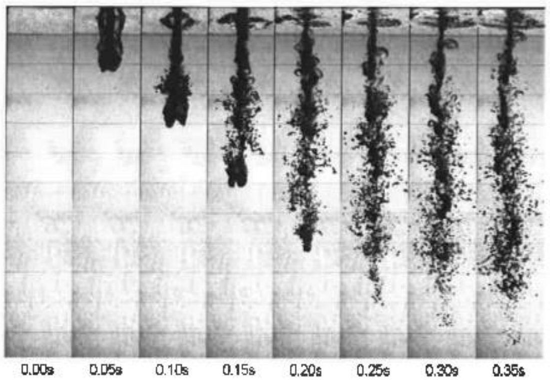
COMPUTER CODE DEVELOPMENT

Corium-sodium interaction → development of a new computer code

We need to be abble to:
- locate the corium in the system at each time-step and have access to its physical state
- follow the vapor production and the pressure build-up within the system
- calculate the pressure wave expansion

Physics to model

- Mass exchanges
  - corium fragmentation (jet → coarse particles → fine particles) + coalescence (agglomeration)
  - corium solidification
  - sodium bubble fragmentation + coalescence
  - sodium vaporisation/ condensation



Matsubo, 2008 :
molten U-alloy78 injected into water

- Heat exchanges
  - internal conduction within the sodium bulk
  - convection / conduction / radiation between corium and sodium for the different flow regimes
- Momentum exchanges
  - phase and wall frictions, virtual mass, solid pressure

*Software for COrium-Na interaction Evaluation

- Development of the **SCONE*** software

Main features:
Fast transient phenomenon: ~ms → ~s
Multi-materials : sodium and corium
Multi-phases : liquid sodium and vapor, continuous and dispersed corium

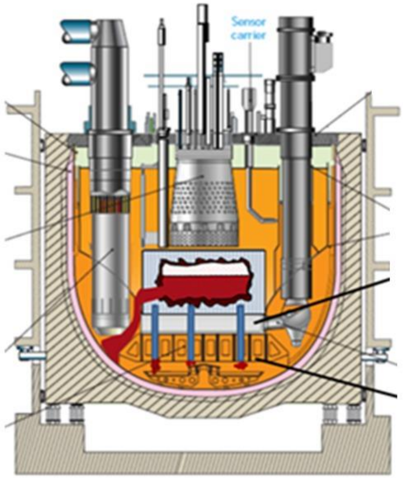
- First elements of reflexion:

  - Mass, momentum and energy conservation equations written for each phase (phase volume fractions)
    - liquid sodium → Eulerian field
    - sodium vapor → Eulerian field
    - dispersed corium → Lagrangian or Eulerian with a multifluid description… under investigation
    - continuous corium → Eulerian with an interface tracking method … under investigation

  - Numerical scheme based on the ICE** scheme → structured meshing = first step
    → will evolve towards unstructred meshings to represent complex geometries

  - Space discretisation
    Mass and energy balance equations discretised using the finite-volume method
    Momentum equations discretised using the finite-difference method

  - Time discretisation : first order Euler scheme



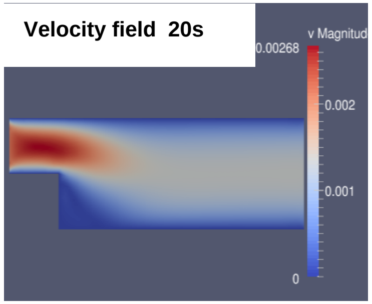
**Implicit Continuous-fluid Eulerian method
Harlow, 1968

DUNE AND US (1/2)

- We have chosen to reduce the effort on numerics by using an open source platform (under LGPL or LGPL-like licence)
  - ⇨ pre-selection of available tools acording to criteria established by our team
  - ⇨ study 2 of them in more details
    - → Only DUNE remains: more tests to perform

- Step by step approach:
  - The first tests started in 2014, we followed the version evolutions (from 2.3.0 to 2.4)
  - We had a look at the DuMu^x module → too application-dependent for our needs
  - The US-NRC water/steam tables were implemented (~ defining a new material)
  - The dedicated DUNE-FCI module was created
  - We played with the PDElab:

    - we modified the cgstokes test case:
      - Non-stationary term added (→ time loop, definition of the initial state)
      - Gravity added
      - New boundary class to distinguish velocity and pressure boundary conditions (driving force: pressure gradient)



DUNE AND US (2/2)

- we tried to implement our **ICE-based scheme**
  - P, T, e and ρ located at the mesh centers
  - Normal velocities at the mesh faces → delicate with PDELab, too finite-element oriented

    ⇨ We decided to rely on the basic components of DUNE (DUNE-GRID) to build our own library for our ICE scheme (an interface such as PDElab will be needed)

Work underway

Implementation of our ICE scheme with DUNE-GRID for a very simple case:

- model the system with the Euler equations
- discretize the equations using our ICE-based scheme
- already think about the data structure → convenient access to data to code the physics and use the future code

What keeps us busy these days: attach the normal velocities at the mesh faces

↳ establish the connectivity between the cell face global numbering and the cell numbering in DUNE-GRID

On going…

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