R&D AT CEA IN SUPPORT OF SAFETY

Michel DURIN, Thierry FORGERON & Patrick DUMAZ

CEA, Nuclear Energy Division

(DEN/DISN)

A content closely related to the main physical phenomena involved during Pressurized Water Reactor accidents

1, External hazards: earthquakes

2, Design basis accidents: Loss Of Coolant Accident (LOCA) and Reactivity-Initiated Accident (RIA)

3, Severe accidents:
- Hydrogen generation and distribution, hydrogen risk management
- Behavior of the molten corium issued from core degradation
- “Source term”: radioactive materials release, transport & deposition

Remarks: Presentation of the main Nuclear Energy Division (DEN) programs only
All these programs done in the frame of various collaborations
I. External hazard: the seismic risk

R&D main issues:
- **Tests** for qualifying structures and equipment at reference seismic levels:
  - Materials behavior laws
  - Definition of damaging criteria
- **Models** for justifying any structure under dynamic loading

Seismic behavior of a nuclear building mockup on the Azalée vibrating table (of the TAMARIS platform)
I. External hazard: the seismic risk

Outcomes:
- Quantification of real design margins by testing up to failure (with high load levels beyond design level)
- Account of the spatial incoherence of seismic motions
- Knowledge integration into codes (CAST3M) and standards

Future orientations:
Strengthening experimental tools:
the EXtension TAMaris project

- Testing mockups closer to scale 1
- Large-scale motions & accelerations
- Testing of multi-supported structures
II. Design basis accidents

Two very important accidents deeply investigated

The **Loss Of Coolant Accident (LOCA)**, especially the **Large Break (LB-LOCA)**
and the **Reactivity-Initiated Accident (RIA)**

In the context of UOX fuel optimization
and MOX fuel use ("parité MOX")

⇒ Questions about safety criteria evolution and real safety margins

CEA involved in
- System thermal-hydraulics, a key scientific field
  The successful CATHARE story
  (and now NEPTUNE simulation platform)
- The fuel behavior in these demanding accidental conditions
II. Design basis accidents: LOCA

1. Loss Of Coolant Accident (LOCA): by a primary circuit break
   => Fast primary coolant vaporization and core voiding
   Main issue: core coolability during and after the transient

   Acceptance criteria to insure coolability
   • Clad temperature < 1204°C (2200°F)
   • Local oxidation rate < 17% of clad thickness
   • Enough residual ductility after reflooding
   + Limited quantity of generated hydrogen
A set of experimental facilities to study fuel behavior with extensive separate effects tests on: Zy-4, M5... As received, pre-hydrided, pre-oxidized, irradiated ...
+ some fundamental studies

II. Design basis accidents: LOCA

- Clad ballooning and burst
- High temperature oxidation
- Quench resistance
- Post quench mechanical behavior
Cladding mechanical behavior:

Viscoplastic deformations and rupture ⇒ temperature ramps under internal pressure (EDGAR facility, one or several rods)

Cladding creep-ballooning strongly depends on the $\alpha \rightarrow \beta$ Zr phase transformation

<table>
<thead>
<tr>
<th>Strain at Rupture %</th>
<th>Ductility</th>
<th>Stress at Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rupture Temperature (°C)</td>
<td>Thermal Ramp Tests</td>
<td>Burst Stress (MPa)</td>
</tr>
</tbody>
</table>

- $\alpha$
- $\alpha + \beta$
- $\beta$
Zirconium oxidation kinetics at high temperature

For short (LOCA prototypical) oxidation times and for most of Zirconium alloys, HT oxidation kinetics is more or less parabolic (de ∝ dt/e)

Quenching, Post-Quenching mechanical testing

Extensive metallurgical analysis ➔
Relationship between phases thicknesses & oxygen/hydrogen profiles 
and the post-quenching properties

+ Effects of cooling scenario, of pre-hydriding 
& pretransient oxides …

& effect of steam pressure (high P in small break LOCA)
Outcomes:

- 3D modeling of the clad ballooning and rupture is a necessary evolution to have more precise simulations
  Taking into account metallurgical evolutions and thermo-mechanical interactions between rods

- LOCA criteria defined in 1972 by the US NRC for non-irradiated Zy-4
  On going serious examination in the US, BU reduction?
  Questioning results about fragmentation and dispersion of fuel (recent tests at Studsvick) In the frame of intensive studies worldwide: ANL, ORNL, Studsvick, Halden, JAEA, KAERI, KIT, PSI ...

In France a « GP critères APRP » planned in 2013-2014, In the frame of significant national effort by IRSN, EDF-MAI and AREVA
II. Design basis accidents: RIA

2. Reactivity Initiated Accidents (RIA): by control rods ejection
   ⇒ Fast power and temperature transient of fuel rods
   Main issue: limit rod fracture and avoid fuel materials dispersion into the primary reactor coolant

   RIA criteria (also defined more than 30 years ago) limiting the energy deposition in the fuel pellet during the transient:
   230 cal/g for fresh fuel, 200 cal/g for irradiated fuel

Accident first stage (few tens of ms)
- Prompt neutron effects, huge power increase
- “Adiabatic” fuel heating, strong PCMI (Pellet Cladding Mechanical Interaction)
- Power decrease due to the fuel temperature rise (Doppler effect)

Second stage (few s)
- Thermal and thermal-hydraulics evolutions (the DNB issue: Departure from Nucleate Boiling)
II. Design basis accidents: RIA

A global approach that combined integral MTR experiments, separate effects tests, codes development and validation,

**Integral testing:** the Cabri International Project (CIP) conducted by IRSN with close collaborations of EDF & CEA

- First tests performed in 1993-2000 in the sodium loop: REP-Na program

- New tests planned ~2014, in a new water loop:

  ➤ CABRI reactor renovation and water loop implementation

  ➤ 10 CIP tests planned (Zr4 & advanced cladding, UO$_2$ & MOX)

DNB and post DNB phases essential
Separate effect tests of the cladding mechanical behavior:
⇒ Fast transient mechanical properties in PROMETRA, anisotropic constitutive equations at high strain rates & material failure criteria about 500 reference experiments widely published for fresh and irradiated Zr4 & M5:
Axial tensile, hoop tensile and closed-end tube internal pressurization

Fast Joule heating system

HOOP TENSILE TEST, 1 s-1

AXIAL TENSILE TEST, 5 s-1
II. Design basis accidents: RIA

3D modeling of phenomena, PCMI
With **Alcyone** of the Pleiades fuel simulation platform
A better understanding of basic phenomena

Pellet cladding contact on the mid plane

Deformations during power ramps

Gas swelling in the RIM

**Outcomes:**
Basic R&D have led to detailed model development
Like for LOCA, a “GP RIA” is planned in the coming years
III. Severe Accidents

Following loss of coolant and extended core uncovering:

- **In-vessel core degradation:**
  - Fuel degradation, Hydrogen generation
  - Debris and corium formations (corium = molten fuel with molten structural materials)
  - In-vessel progression
  - Vessel failure

- **Out-of-vessel corium progression**
  - Corium-concrete interaction
  - Corium-water interaction

During accident, Fission Products (FP) and other radioactive materials release, transport & deposition

➤ The source term issue and the further consequences for the environment and for humans
During core degradation, cladding oxidation by steam starting at \( \approx 800^\circ C \), very high oxidation above 1500°C ⇒ Hydrogen release into the primary circuit and transport up to the containment. In Fukushima, several Hydrogen explosions suspected.

Steam/hydrogen/air mixture in the containment, above 4%, hydrogen combustion could occur.

To limit the explosion risk, catalytic hydrogen recombiners installed in PWR containment.

Shapiro diagram
Priority given to:
- Prevent hydrogen combustion ➔ Predictive models of $H_2$ distribution and $H_2$ removing by recombiners
  ⇒ Experiments in mock-up at different scales, 100 m$^3$ for the CEA MISTRA facility
  ⇒ Simulations with the CAST3M platform

- $H_2$ combustion understanding, Deflagration to detonation transition
  Various experiments to validate CAST3M models
III. Severe Accidents: hydrogen

- **Explosions effects:** Experimental and computational approach of the fluid-structure interactions on steel and concrete structures
  
  The EUROPLEXUS code development

- **Innovating tools for mitigation and detection:**
  - Monitoring of the containment atmosphere composition
  - New types of fuel cladding materials (Accident Tolerant Fuel)

  ![Fuel clad made of SiC/SiC composite](image)

- **Outcomes**
  - Mechanisms of stratification occurrence and destabilization well identified in MISTRA testing
  - Scaling still a key issue to well simulate the reactor case
Main issues:
- in-vessel corium progression & vessel failure
  ⟷ Avoid High P failure, Direct Containment Heating (DCH) risk
- Corium Water interactions in the vessel & in the reactor pit
  ⟷ Steam explosion risk and possible containment integrity loss
- Molten Corium-Concrete interactions (MCCI)
  ⟷ risk of a base-mat breakthrough

PLINIUS, an experimental platform to support the R&D
In VULCANO, 40 kg of realistic corium (UO$_2$, ZrO$_2$) can be melted
- EPR core-catcher studies,
  corium spreading with and without water
- Corium-concrete interactions
- Study of mitigation devices for Gen2/Gen3 reactors
  but also for Gen4 SFR (ASTRID core-catcher)
III. Severe Accidents: corium behavior

MCCI, corium progression rate, concrete erosion
VULCANO tests and modeling of the kinetics of axial and radial concrete ablation
⇒ Calculation of the time required for base-mat melt-through

Ongoing EDF, IRSN, GDF-SUEZ and CEA program
Testing of different types of concretes and corium compositions
Outcomes:
- Improving concrete erosion kinetics models, extrapolation to the reactor case according to corium composition
- Better knowledge of corium cooling mechanisms, study of possible means to limit its progression
KROTOS facility to study corium water interactions

-5 kg of corium at 2800°C ⇒ realistic corium jet

Measurements with high speed X-ray radiography
⇒ Better understanding of jet fragmentation and steam explosion phenomena

Corium jet at 3000°K: characterization of the corium/steam/water pre-mixing
(LINATRON X-ray apparatus)
III. Severe Accidents: corium behavior

Pre-mixing & fragmentation phases before explosion

SERENA-2 program (OECD program) just completed
Complementary testing in KROTOS and in TROI (KAERI facility)
Quantitative data (thanks to the Linatron apparatus) on void fraction and jet fragmentation ➔ the MC3D code development with IRSN

Steam explosion still a very difficult phenomenon to predict well, R&D will be pursued
III. Severe Accidents: corium behavior

Mitigation strategies for existing or new reactors

1. Through degraded core reflooding (TMI2)
   - Flow and relocation of oxide/metal corium
   - Debris and corium pool cooling

2. Through outer cooling of the reactor vessel by reactor pit flooding
   (the AP600/AP1000 approach)
   - Cooling capabilities (CHF limitations, natural circulation flow)

Study of combining internal reflooding and reactor pit flooding,
reduce of vessel failure risk

A quite important issue: the “focusing effect”

$\Phi_{\text{max}} : 1 \text{ à } 1,3 \text{ MW/m}^2$
CALO mock-up:
Reactor pit hydraulics with **realistic geometries**
Boiling simulated with
**Air/liquid water flow**

- Échelle 1 en hauteur pour reproduire le thermosiphon
- Tranche de cuve
- Mise en place de parois simulant le calorifuge
- Injection d’air pour simuler l’ébullition
  - *En fond de cuve (flux en provenance du bain)*
- Circulation d’eau
  - *Uniquement par le haut (aspersion enceinte)*
  - *Par boucle de récirculation (injection dédiée pdc)*
Fission Products phenomena to consider after fuel failure & melting:

FPs release from the solid fuel:
Noble gases (krypton, xenon) & Volatile FPs (iodine, cesium, tellurium …), then a fraction of less volatile FPs (barium, ruthenium, strontium …) & actinides

FPs transport in the primary coolant system:
Deposition before transfer to the containment, Primary circuit bypass In case of vessel failure

FPs containment behavior
Additional depositions in the containment, Environment releases due to containment leakage or filtered containment venting

Additional release of low volatile FPs:
Through air inflow to the vessel, Through corium-concrete interactions or possible FP re-suspensions
III. Severe Accidents: source term

Approach in the frame of the ISTP (International Source Term Project, IRSN, EDF, CEA and other OECD partners)

Analytical programs: (France)-(USA)-(Canada) (Japan)

Experimental data base on FPs release & transport

Mechanistic model development: (IRSN)

Integration into scenario codes: (IRSN/GRS) (Sandia/US)

Source Term Assessment Probabilistic Safety Analyses (level 2)

Integral tests: (France)

CEA contribution with the VERDON experiments (follow-up of VERCORS)

Crisis preparation
VERDON Facility
+ Osiris irradiation
& Saclay-Cadarache transportation

4 tests underway (2011-2013) to study:
- Air flow conditions (Ru oxides releases)
- FP releases from MOX fuel

Outcomes:
- Good knowledge of UO₂ fuel release
- Improved modeling required for MOX & releases and transport during air ingress
- The iodine chemistry in circuits and within the containment still questionable
The severe accident R&D is a long and difficult road:
- Complex & coupled phenomena
- difficult modeling and validation

and very expensive experiments (nuclear installations use)

➔ Necessity to share the R&D and to create a R&D community to obtain technical & scientific consensus
  in order to develop appropriate and accepted severe accident mitigation and accident management measures

➔ CEA studies in support to industrial needs
  - Past studies for the EPR core catcher
  - On going studies for existing plants: Risk/Benefit of preventing flooding of the reactor cavity
    Benefit: corium IVR, Base-mat breakthrough risk reduction
    Risk: Steam explosion in case IVR failure
Conclusions

CEA provides its skills and expertise to public authorities and nuclear industries, Its R&D contributes to enhance reactors safety

High Quality R&D at CEA implies a close integration between large scale, small/separate effect tests and an ambitious development of multi-scale, multi-physics simulation tools

A research conducted in close collaborations and partnerships
- at the national level with IRSN, as well as with industrial partners and also with academic partners
- in international frameworks (OECD/NEA, Europe)

Significant advances obtained in the predictive simulations of challenging phenomena encountered in accidents