SEVERE ACCIDENT PHENOMENA
part 1: In-vessel

IAEA Workshop on Severe Accident Management Guidelines

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presented by

Randall Gauntt

(Sandia National Laboratories)

IAEA

International Atomic Energy Agency

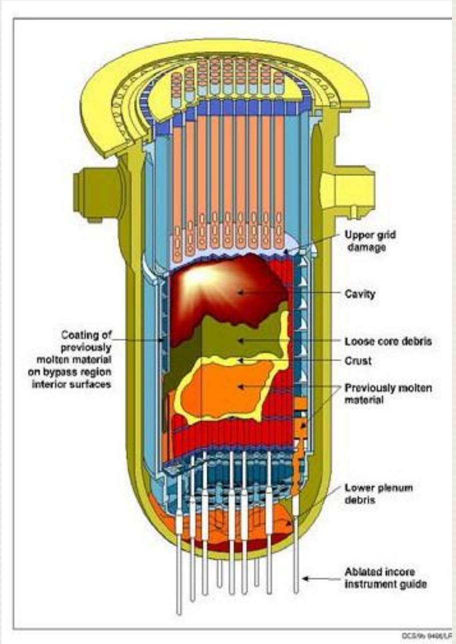
Outline

- **Severe accident phenomena part 1 : In-vessel**
  - ➢ **Introduction**
  - ➢ **Experimental basis**
  - ➢ **Role of fission products and decay heat**
  - ➢ **Early phase core degradation**
  - ➢ **Late phase core degradation**
  - ➢ **Lower head failure**
  - ➢ **Fission product release**
  - ➢ **Reflood phenomena**
  - ➢ **Research priorities/Conclusion**
  - ➢ **Acknowledgements and References**

Introduction

Severe accidents in nuclear power plants encompass a very wide range of interacting phenomena:

- **Thermal hydraulic behaviour in the vessel and primary circuit;**
- **Degradation of the reactor core, including oxidation of fuel rod cladding, melt formation, relocation of material to the lower head, melt pool behaviour, lower head failure, ex-vessel corium recovery, molten core-concrete interactions;**
- **Release of fission products from the fuel, structural material release, transport and deposition in the primary circuit, their behaviour in the containment (especially now with special emphasis on iodine and ruthenium), aerosol behaviour;**
- **Thermal hydraulics in the containment, hydrogen behaviour, molten fuel-coolant interactions, direct containment heating.**



TMI-2 final state

This presentation summarises the main in-vessel phenomena involved

Stages of Reactor Accidents

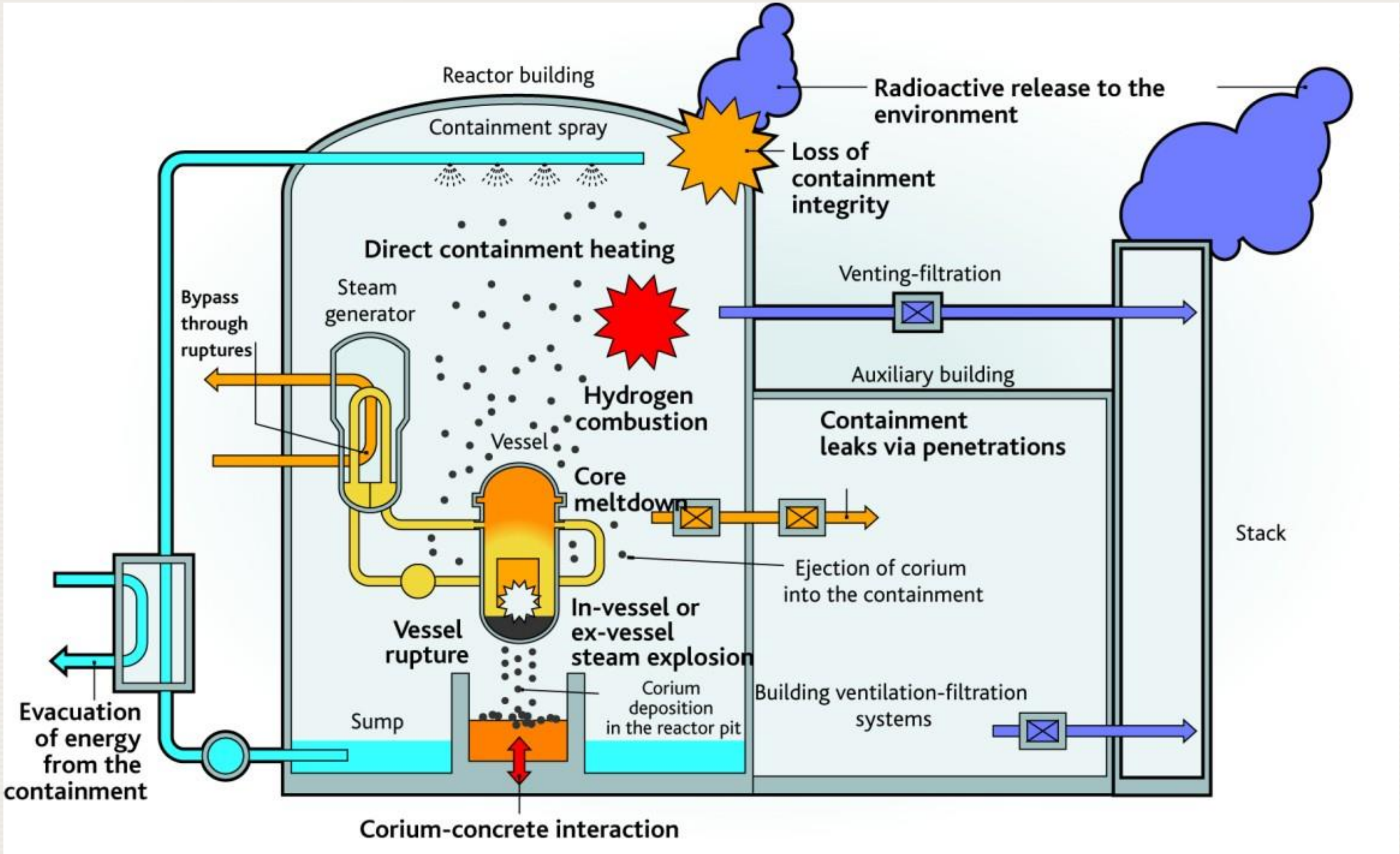
1. boildown of coolant and fuel heatup
2. clad balloon and rupture
3. clad oxidation and temp. transient

} **DBA & SA**

4. clad melting and fuel liquefaction
5. candling and accumulation of core debris
6. relocation of debris from core region
7. debris interactions with vessel

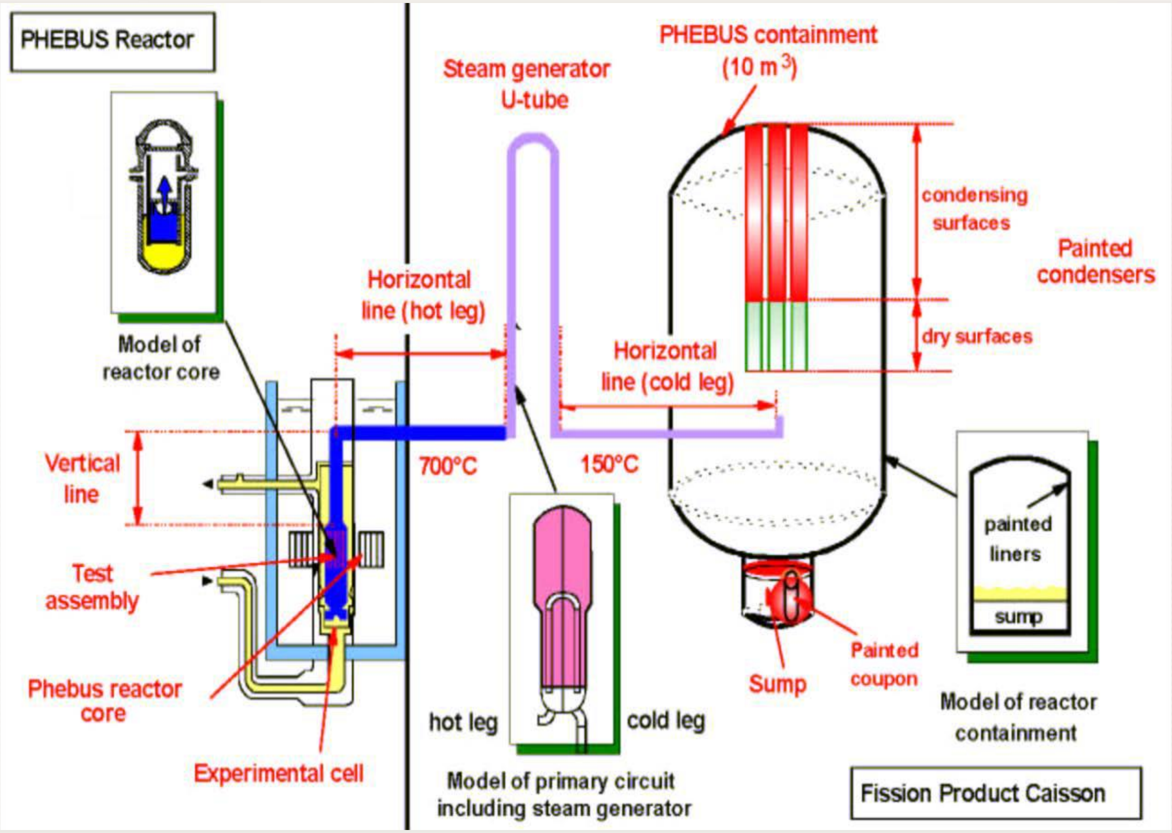
} **SA**

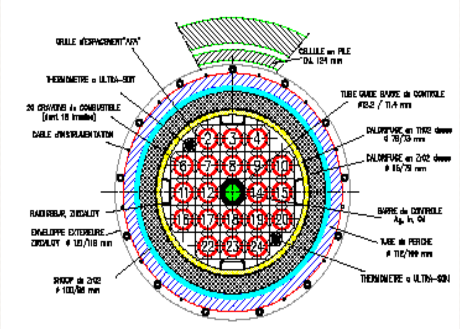
Phenomena in a typical core melt accident



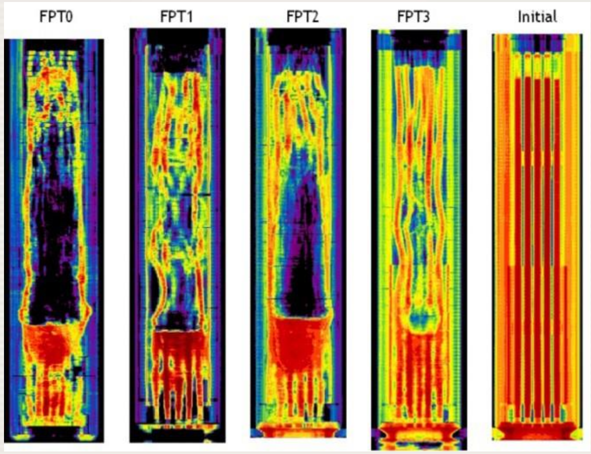
Core degradation – experimental basis (2/2)

The Phébus FP integral experiments feature many of the phenomena listed above (fission product and structural material release, transport and deposition in the circuit, containment phenomena) such data are widely used for validation of SA modelling codes





Bundle X-section



Bundle final states

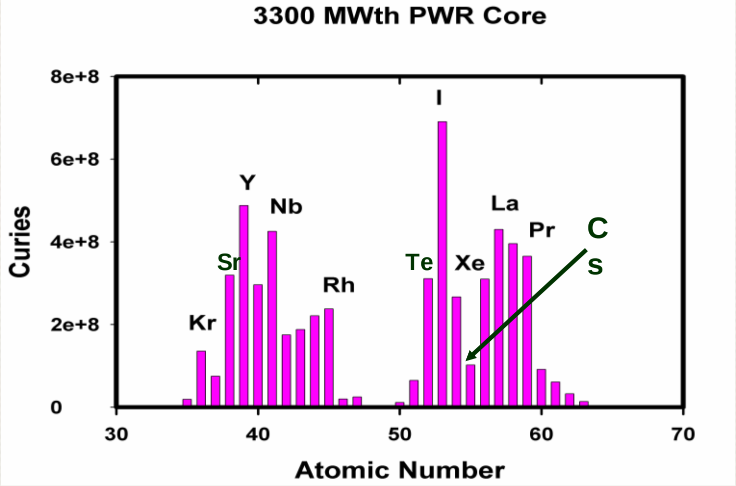
Inventory and role of fission products

Initial inventory of fission products (FP):

- **2000 kg in a French PWR 900 MWe (Xe 300 kg, Kr 22 kg, Cs 160 kg, I 13 kg, Mo 180 kg, Ru 140 kg, Zr 200 kg, Ba 80 kg etc.):**
- **Corresponds mainly to the mass of stable isotopes: example of total iodine mass of 13 kg, incl. 0,8 kg of radioactive iodine.**

Wide range of half-lives

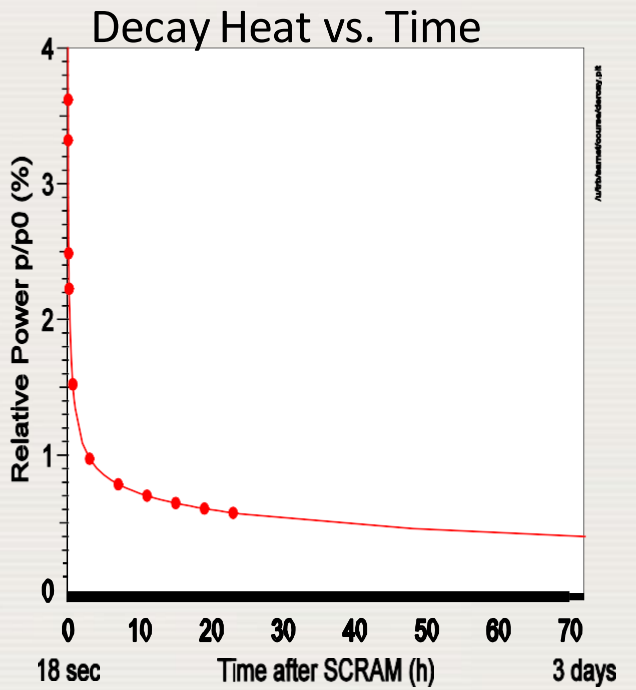
- **^{133}Xe: 5 days, ^{85}Kr: 10 years, ^{137}Cs: 30 years, ^{131}I: 8 days, ^{129}I: 1.7x10^{7} years.**



The role of decay heat

The decay heat drives at least the initial stages of the degradation in loss-of-coolant accidents, causing evaporation of water; it reduces with time

Time after SCRAM	18s	1h	10h	3d
Decay heat (%) relative to full power	4.0	1.3	0.7	0.4
Adiabatic heat-up rate of core (K/s)	4.0	1.3	0.7	0.4
Evaporation of water at p = 7 Mpa (kg/s)	100	32	17	10



PWR with P_{el} = 1300 MW; $P_{thermal}$ = 3750 MW; M_{UO2} = 107 t
Specific heat capacity cpUO2 = 350 Ws/kg/K, Specific power (100%) P = 35 MW/kg
Evaporation enthalpy h(1 MPa) = 2; h(7 MPa) = 1.5; h(18 MPa) = 0.75 MWs/kg,

F. Fichot, IRSN, SARNET course, Pisa, January 2011

Early phase of core degradation

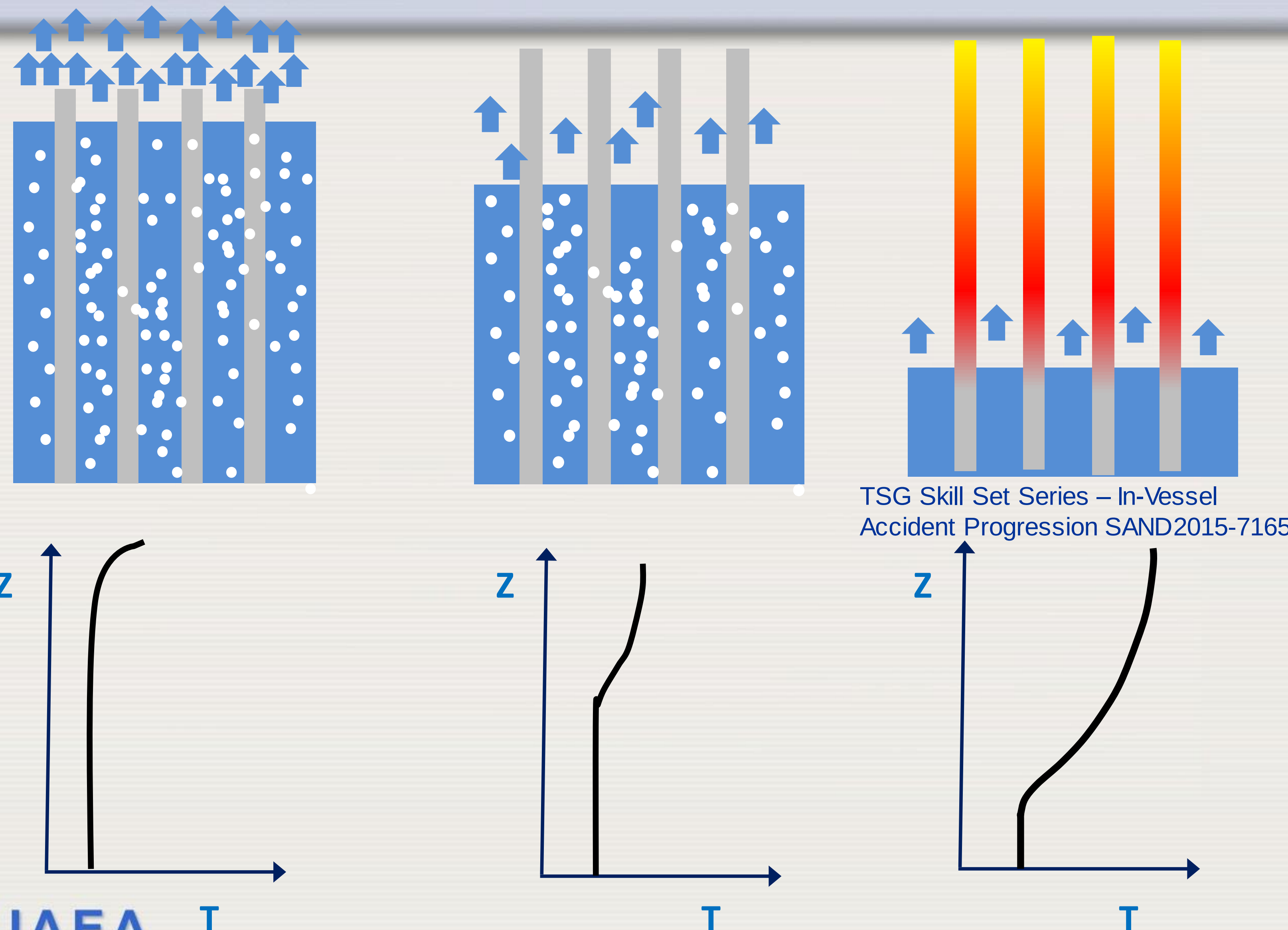
Depending on the core initial state and the accident scenario, core uncovery can be reached in several minutes or in several hours (possibly some days);

Succession of possible physical events:

- **Heat-up of uncovered fuel due to residual decay heat;**
- **Clad deformation and failure;**
- **Oxidation of metals (esp. Zr in the cladding) by steam and exothermic reaction (power > residual heat), which accelerates the core degradation (and releases large quantities of inflammable H_2 into the containment → may reach 1000 kg and more);**
- **Chemical interactions amongst all the materials, leading to liquefaction and first flows of molten materials along the rods;**

→If water can be injected early enough into the core, the accident may slow down and stop before vessel failure (see below).

Boildown Phase



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Hydrogen production

Illustration of the potential hydrogen production

Chemical reaction	Energy release	Mol. Weight
$Zr + 2\ H_2O \rightarrow ZrO_2 + 2\ H_2$	$\Delta H = 6.4\ MJ/kg_{Zr}$	91 g/mol
$2\ Fe + 3\ H_2O \rightarrow Fe_2O_3 + 3\ H_2$	Not significant	56 g/mol
$B_4C + 8\ H_2O \rightarrow 2B_2O_3 + CO_2 + 8\ H_2$	$\Delta H = 15\ MJ/kg_{B4C}$	56 g/mol

Component	Fuel Ass.	Canister	Absorber	Absorber	Hydrogen
Reactor type	Zr (kg)	Zr (kg)	Fe (kg)	B_4C (kg)	H_2 (kg)
French PWR 900 MW	20,000	--	300	--	900
Konvoi PWR 1300 MW	32,000	--	500	--	1,400
BWR-72 1300 MW	39,000	36,000	15,000	1,200	4,500

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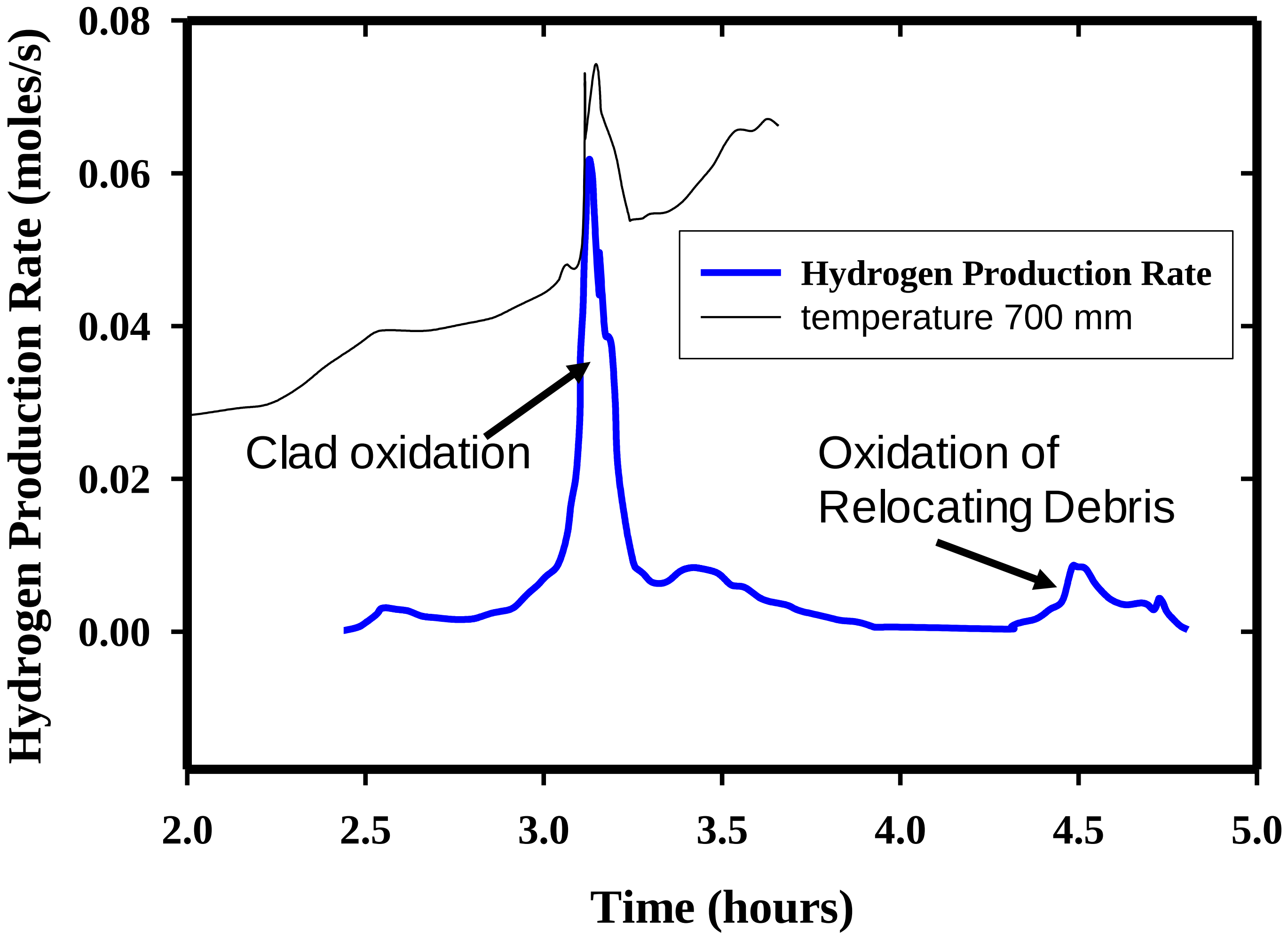
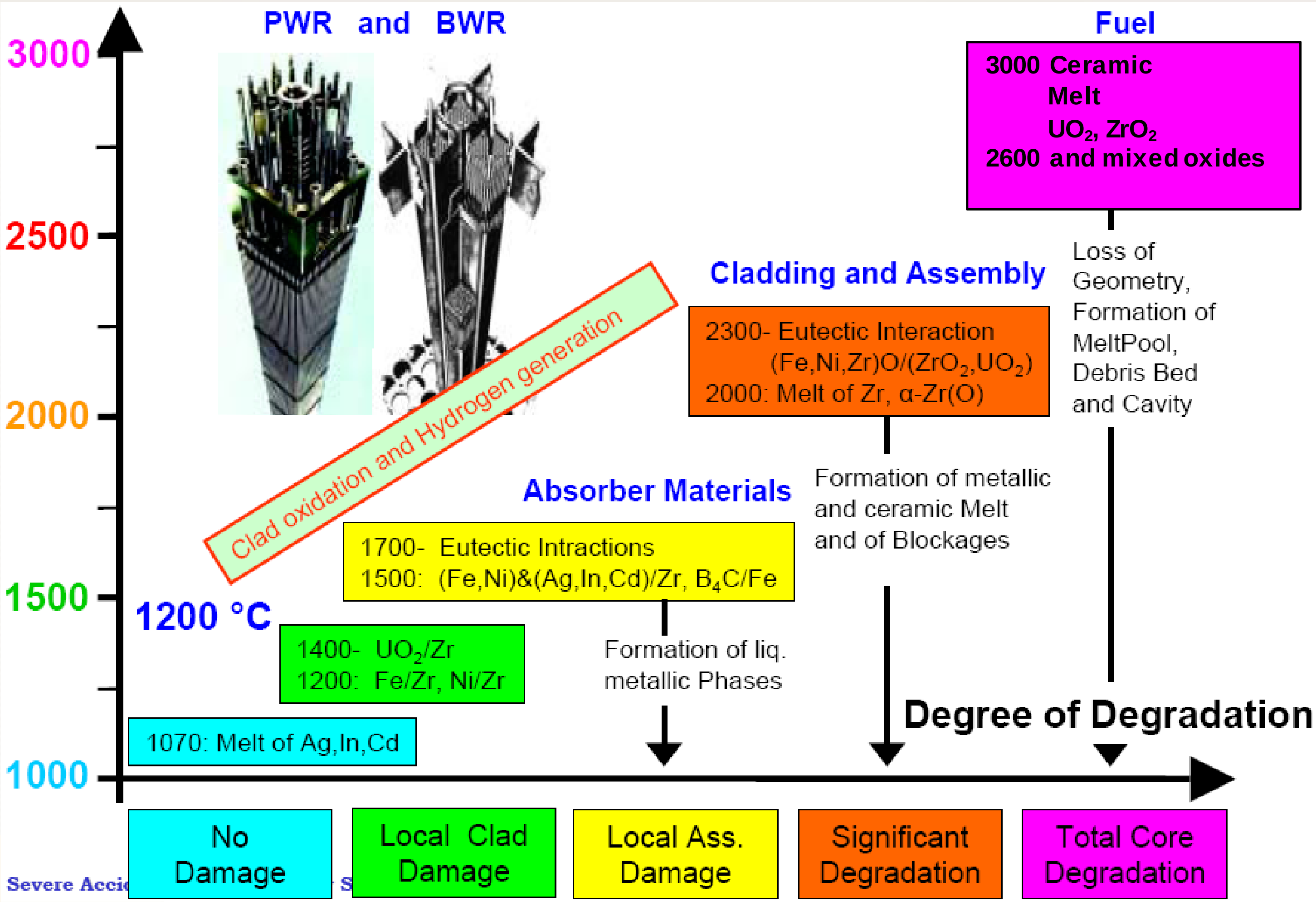
Tables from F. Fichot, IRSN, SARNET course, Pisa, January 2011

Hydrogen Production Test FPT-1



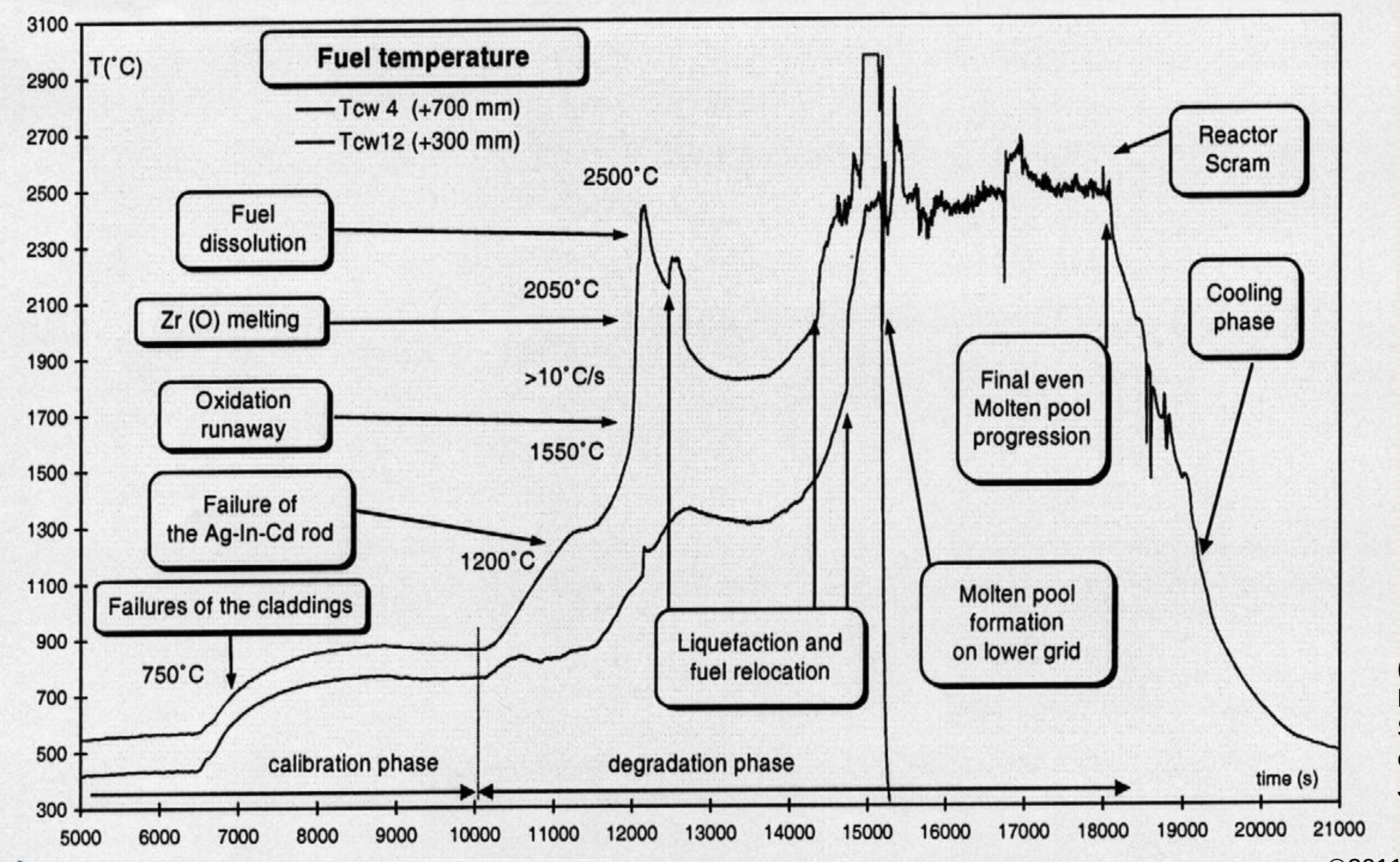
Early phase of core degradation (2/5)



(extract from F. Fichot, IRSN, SARNET Course in Jan. 2003)

Early phase of core degradation (3/5)

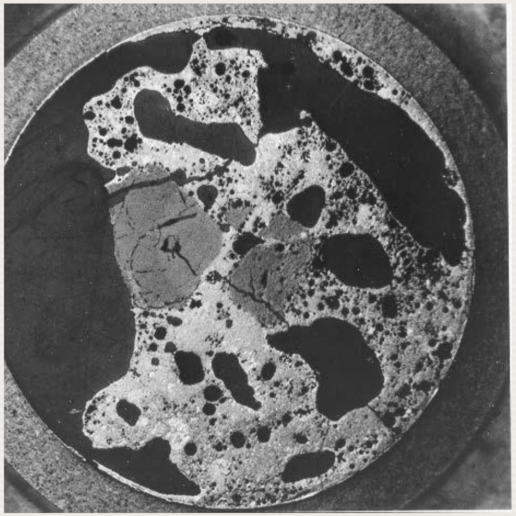
Illustration of the bundle degradation evolution from a Phébus FP in-reactor integral experiment



(From F. Fichot, IRSN, SARNET course, Pisa, January 2011)

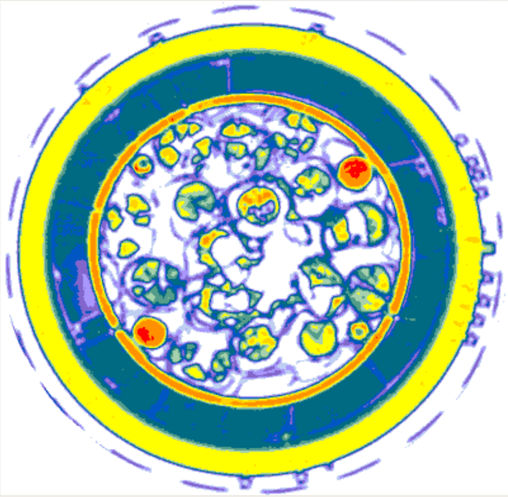
Fuel dissolution

Effect of irradiation on fuel dissolution



ITU SETs: Irradiated UO_2 rod segment (53 GWd/tU): 2000° C / 190s

ITU SETs: Fresh fuel rod segment: Dissolution at 2000° C / 190s



Phébus FPT1 test : Tomography showing fresh (intact) & irradiated fuel (24 GWd/tU)

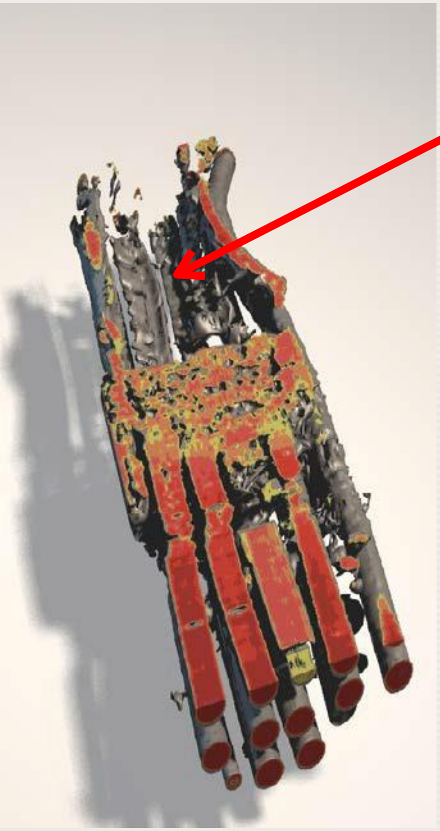
SET = separate-effect test

- **Burnup favours the dissolution of UO_2 by Zr;**
- **More rapid dissolution due to different fuel morphology: cracks, grain-boundary tunnels;**
- **Zr melt can penetrate cracks & porosities and lead to more UO_2 cracking resulting in more solid-liquid U-O-Zr mixtures & greater « apparent dissolution » / fresh fuel;**
- **Fuel swelling and foaming due to combined effect of FP release and UO_2 liquefaction.**

From F. Fichot, IRSN, SARNET course, Pisa, January 2011

Early phase of core degradation (4/5)

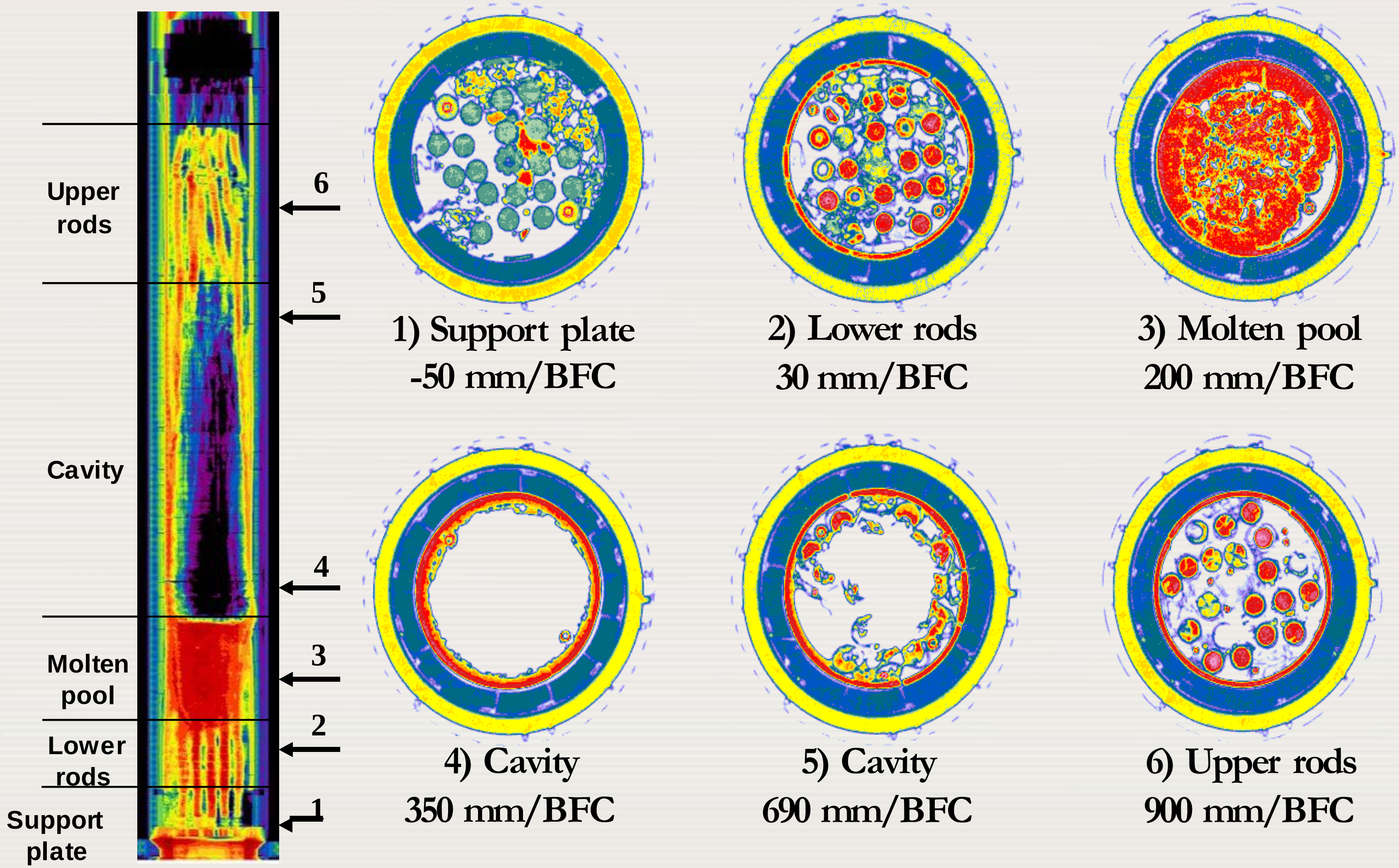
Illustration of the bundle degradation in the Phébus FP in-reactor integral experiments



3D reconstruction of the bundle

Early phase of core degradation (5/5)

Phébus FPT2 post-test radiographs

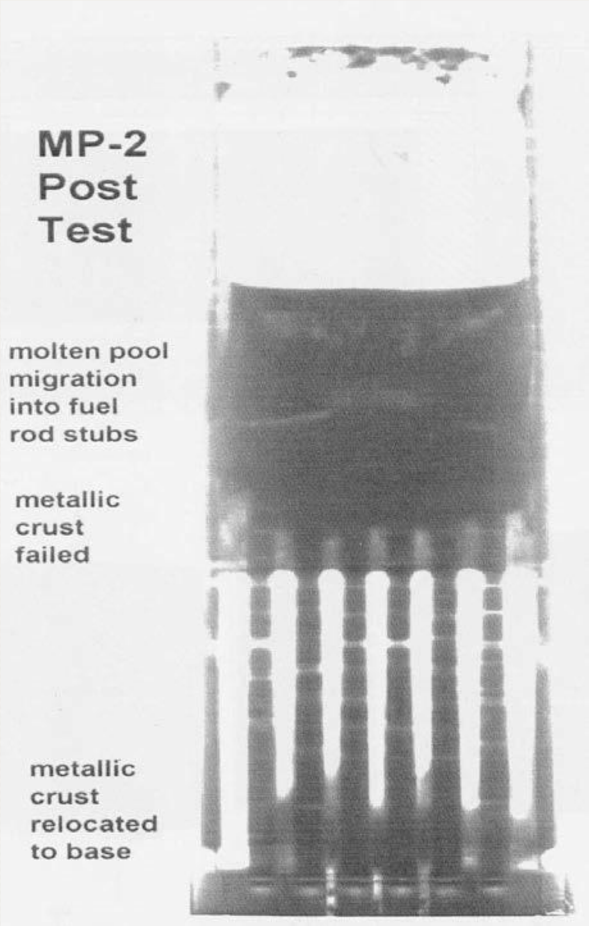


From F. Fichot, IRSN, SARNET course, Pisa, January 2011

Debris bed melting – ACRR MP2

ACRR series at SNL (USA)

- **A debris bed: UO_2 + ZrO_2 (TMI-2);**
- **Cylindrical zone: radius 3.5 cm and height 16.5 cm;**
- **A preformed metallic crust (3.5 cm thickness, Zr, SIC, steel and UO_2;**
- **32 rods in a square lattice. Each rod measures 14.81 cm in length, 3.5 cm in the crust and ~ 1 cm in the grid;**
- **Nuclear heated to above 2500 K.**

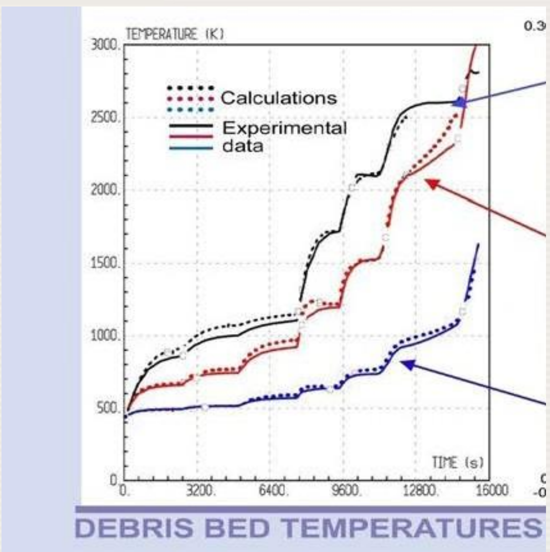


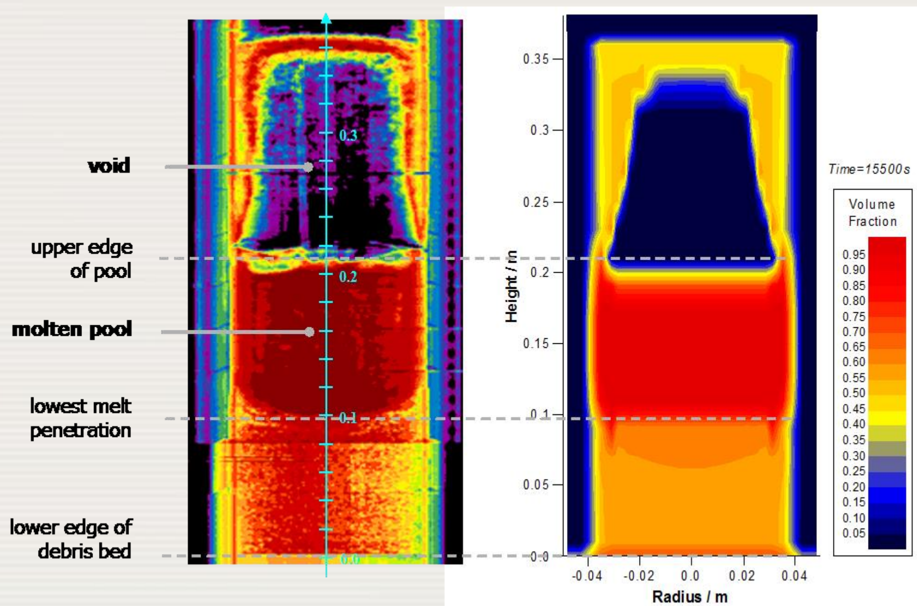
From F. Fichot, IRSN, SARNET course, Pisa, January 2011

Debris bed melting – Phébus FPT4

FPT4 studied melt progression and fission product release in a UO_2/ZrO_2 preformed debris bed under nuclear heating in a steam/H_2 atmosphere

ASTEC/ICARE calculations are well able to simulate the temperature evolution and the final state





Comparison of Phébus FPT4 post-test radiography of the test section (left) with calculated volume fraction of material (right)

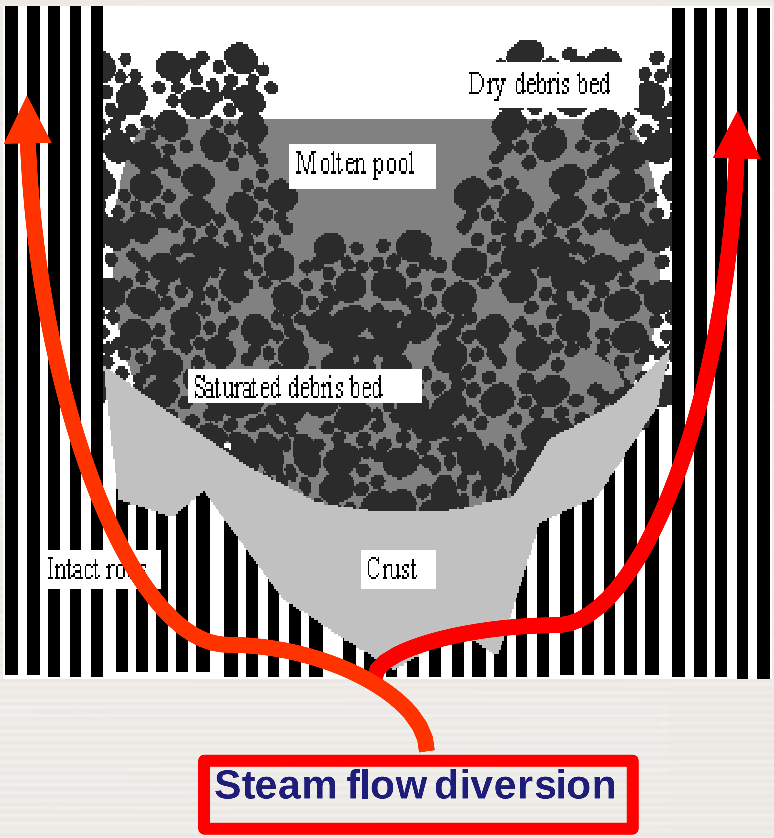
In-core molten corium progression

Relocation of U/Zr/O melt and oxide fragments downwards in the core region

Rapid transition from relocated solid-liquid debris to a molten pool due to limited cooling resulting from steam diversion by crust

Molten pool growth if the peripheral heat transfer could not compensate for the internal FP decay heat

TMI-2: molten pool supported by a lower bowl-shaped crust (thickness ~ 10 cm)

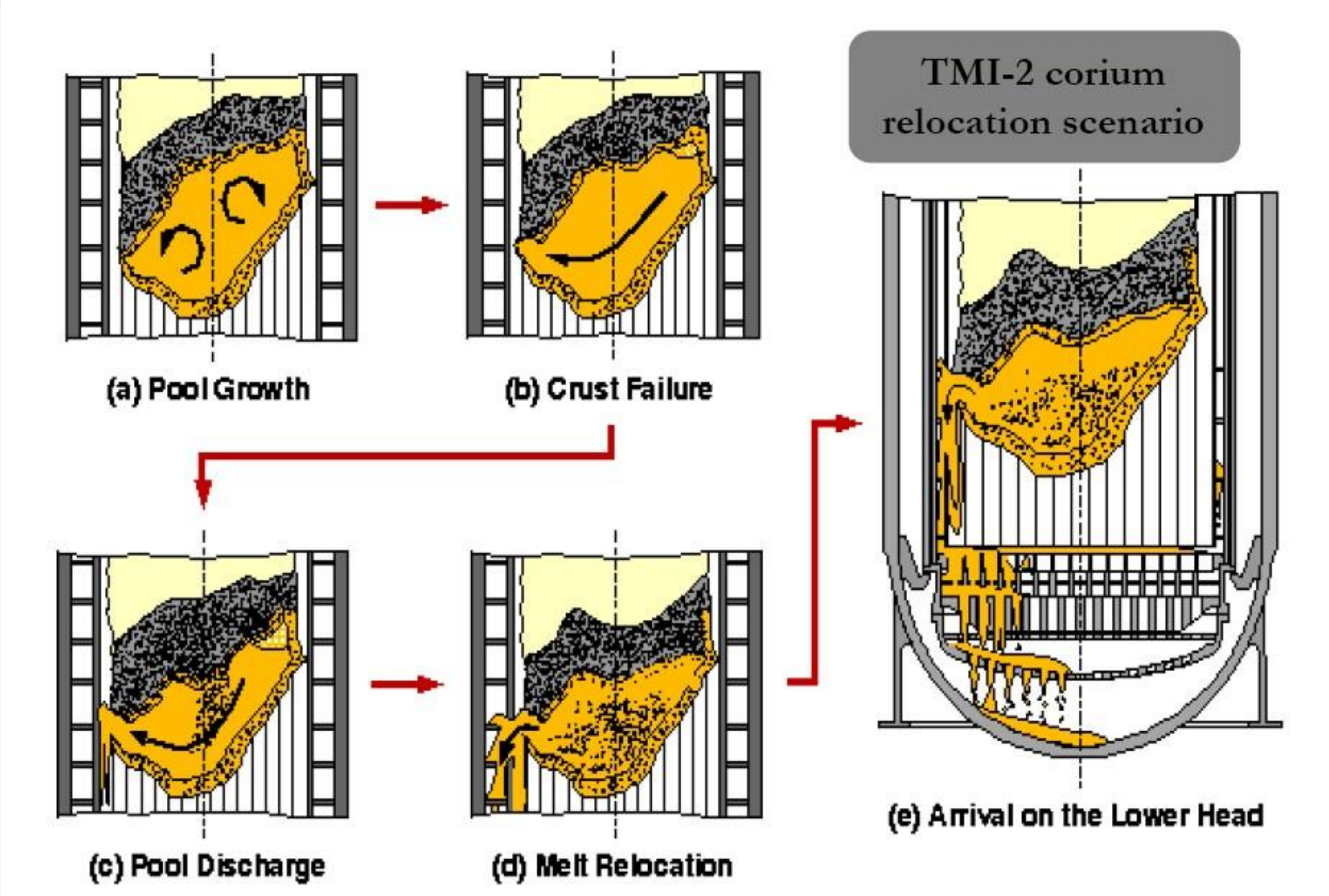


Experimental evidence:

- **Fuel-solid debris observed in PBF, LOFT LP-FP-2;**
- **Molten pool observed in Phébus-FP tests FPT0, FPT1, FPT2;**
- **Transition from solid debris bed to molten pool studied in ACRR-MP & Phébus FPT4 tests.**

From F. Fichot, IRSN, SARNET course, Pisa, January 2011

Late phase of core degradation

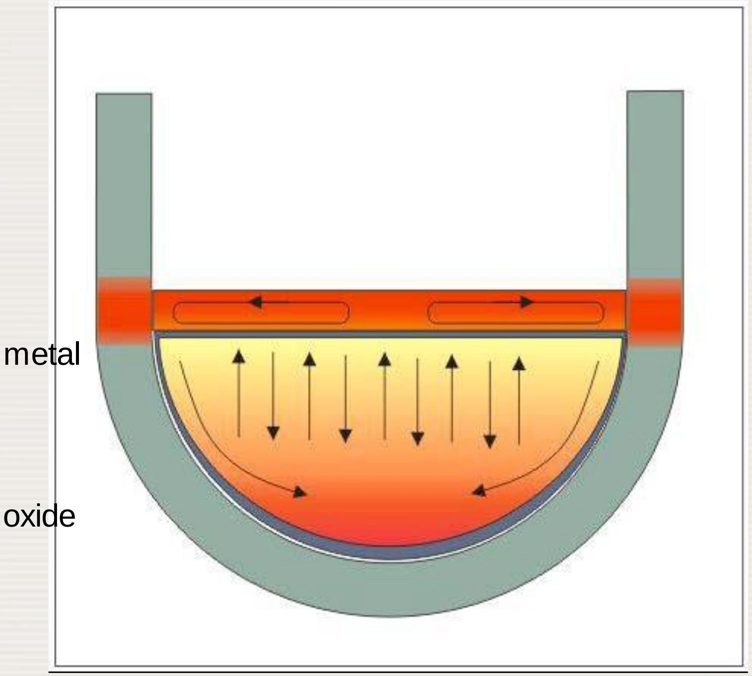


Accumulation of molten materials within the core region, forming a corium pool,

Collapse of structures (fuel rods, control rods, grids…),

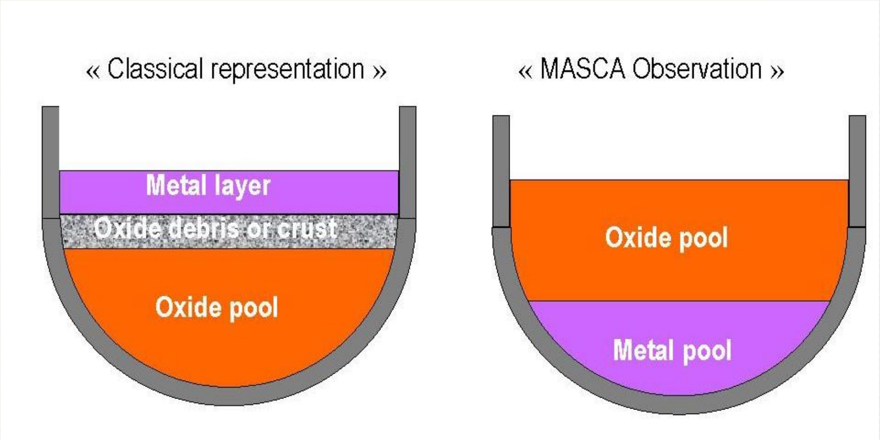
Corium relocation into the vessel lower head (other relocation modes than in TMI-2 may occur.. here just for illustration), with vaporisation of water present in lower head.

Late phase of core degradation (3/3)



Natural convection flows within the corium layers (oxide, metal) due to volumetric decay heat.

Focussing effect in the upper metallic layer: the thinner the layer is, the higher is the flux towards the vessel wall.



But the real situations may still be more complex !!!

Thanks to the MASCA experiments done in the Russian Kurchatov Institute (OECD project), some cases of **layer inversion** have been observed, due to chemical interactions.

- Molten steel favours the transfer of metallic U and Zr from sub-oxidized corium leading to a heavier metallic phase relocating below the oxide pool;
- Transient situations being studied now in the CORDEB programme at NITI (Russia).

Vessel lower head failure – general case

Loads on the vessel lower head:

- Difference between the reactor coolant system (RCS) pressure and the cavity pressure;
- Corium thermal loads;
- Corium weight.

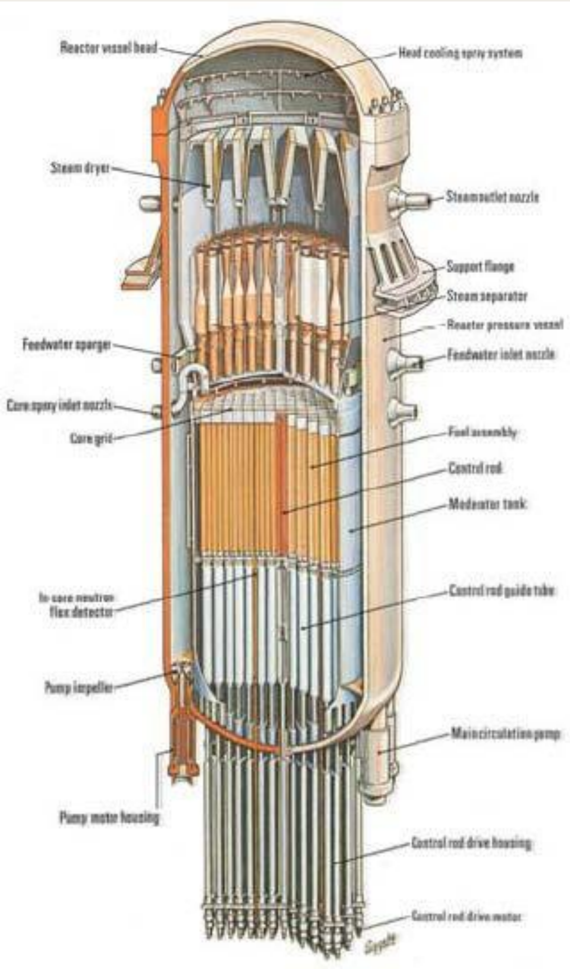
Failure modes of vessel:

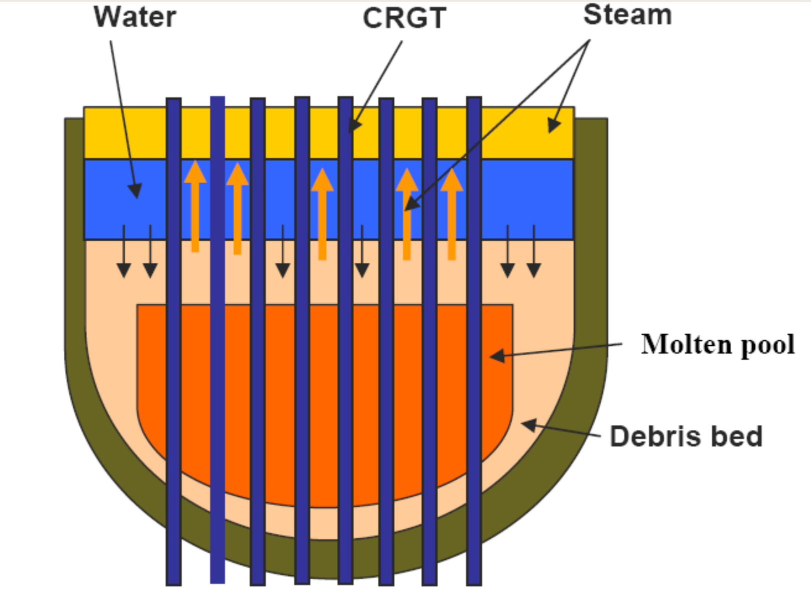
- Plastic failure (at high pressure);
- Creep failure (at medium pressure);
- Wall thermal melt-through (at low pressure).

→ ***Important impact on the following scenario: corium mass transferred into the cavity, composition and temperatures are the molten-core-concrete (MCCI) initial conditions.***

Examples of failed vessels in LHF experiments (SNL, USA) (*extract from SARNET 2007 Course*)

Vessel lower head failure - BWR





Configuration of melt pool in a BWR lower head with CRGT cooling (extract from SARNET textbook)

Much more metal relative to fuel in a BWR c.w. a PWR (SS, Zry…), so different melt composition

Additional BWR vessel failure modes

- Penetration failure owing to weld failure (melt through or drop-away of the guide tubes) believed to be most likely cause of LHF in BWR;
- But additional possibility of heat removal via control rod guide tube (CRGT) cooling.

Typically over 200 penetrations in the lower head of a BWR (control rod and instrument guide tubes etc.)

Vessel lower head failure – discharge into the containment

Two modes of corium discharge into the containment (see also ex-vessel):

- Under pressure, pressurised RCS;
  - P(RCS) >>P(containment);
  - Forced melt ejection leading to corium dispersion into the containment;
  - Fragmentation into dispersed corium drops owing to effect of jet instability or effect of pressurised gases;
  - Possible combustion of metal components (Fe, Zr etc.) leading to hydrogen production;
  - Possibility of direct containment heating (ex-vessel topic);
- Gravity drop, depressurised RCS;
  - P(RCS) ≤≥ P(containment);
  - Melt pouring by static head, leads to low fragmentation/dispersion (less abrupt heating);
  - Corium impact on the containment depends on the RCS pressure at failure, temperature and corium mass discharged, water presence in the reactor cavity, cavity structure, basemat concrete type.

Reflooding of degraded cores

In-vessel water injection is a prime accident management measure:

- If *coolant and a method to deliver it are available*, it could allow maintenance of the reactor vessel integrity and increase the retention of the radioactive products in the reactor vessel;

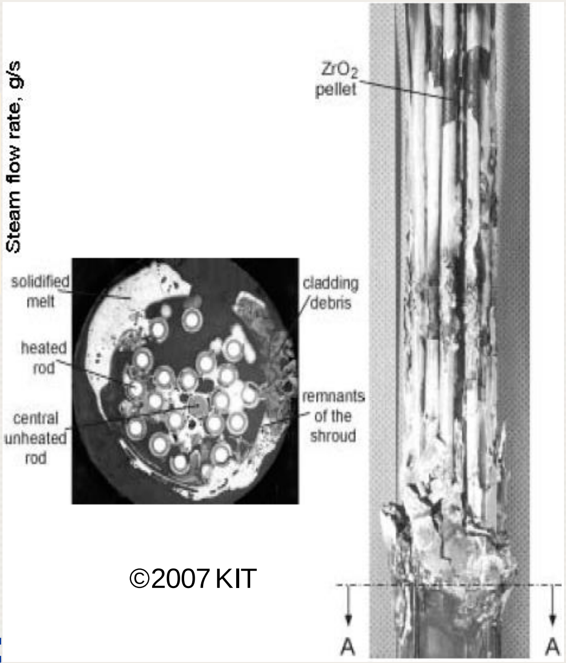
Based on TMI-2 feedback, most SAMGs advise to inject water into the RCS as soon as possible;

But some SAMGS (such as in France) take also into account diverse effects before any decision to inject water (see picture to the right);

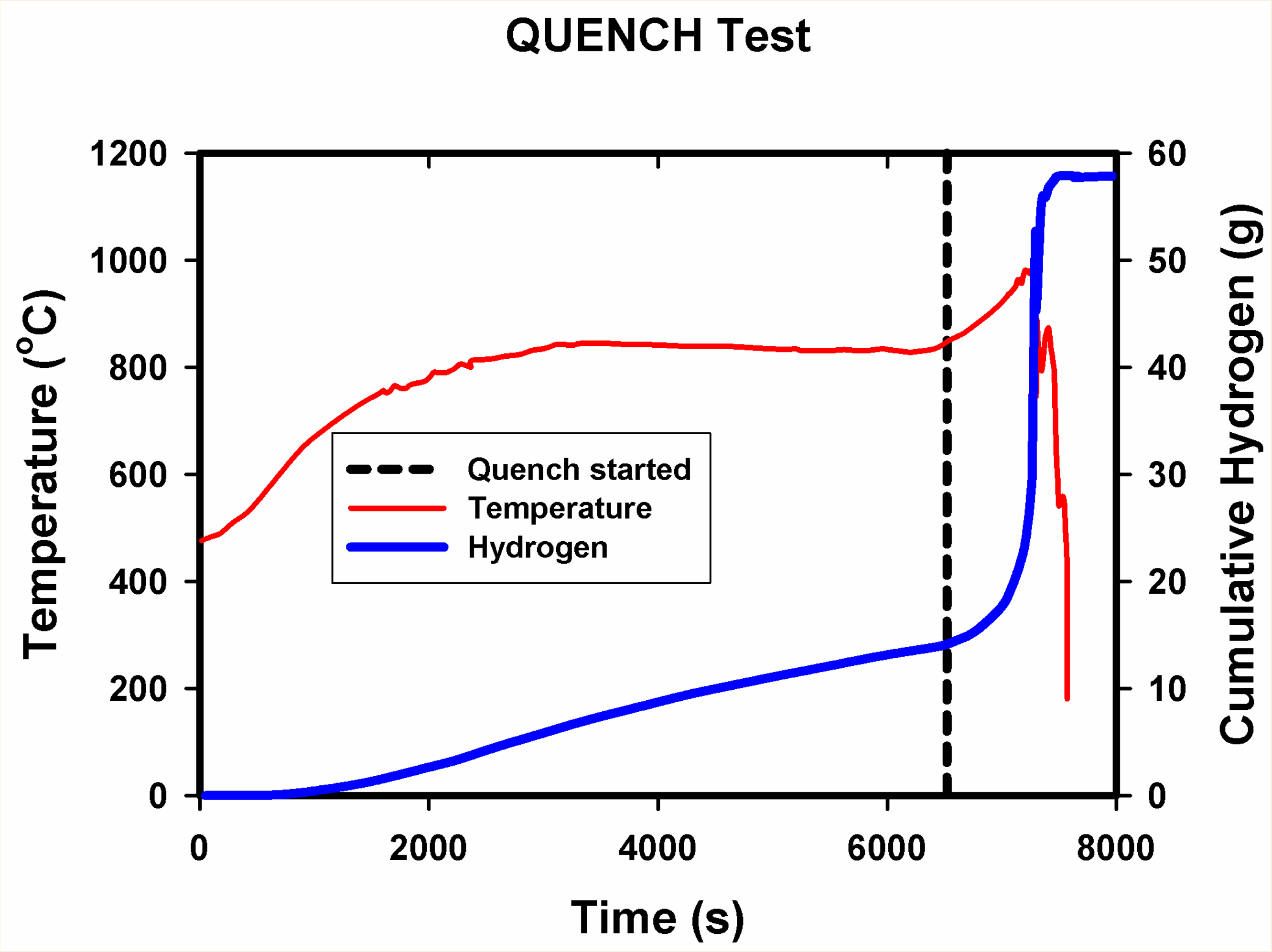
- Enhanced oxidation of Zr alloy and/or U/Zr/O if insufficient water injected and/or temperatures over melting point of Zr alloy, 2030 K ⇨ temporary temperature escalation and ↗ H_2 production and possible FP release, heat transfer to upper structures, before cooling starts;
- Additional core damage (thermal shock, debris formation);
- Similar behaviour seen for all Zr-based alloys (Zry-4, E110, M5™, Zirlo®).

Still uncertainties on coolability of some configurations:

- In-core molten corium pool & debris beds, research in progress.



End-state of QUENCH-02 bundle after reflooding



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Hydrogen production becomes an issue when quenching the core once degradation becomes extensive

Conclusions

- **The main physical phenomena that are involved in the in-vessel phase of severe accident in nuclear power plants (NPP) have been presented:**
  - Core degradation, early phase (mainly rod-like geometry, localised melting);
  - Core degradation, late phase (melt pool, crust formation, debris bed, large-scale relocation)
  - Fission product release from the damaged fuel;
  - Reflood phenomena;
- **Significant damage of the core, with more or less complete core melting, may have serious consequences such as release of radioactive elements out of the containment (so–called "source term") to the environment;**
- **Many fields of physics and chemistry are involved, so a multi-disciplinary approach is needed to understand the tightly-coupled phenomena involved.**

SEVERE ACCIDENT PHENOMENA
part 2: Ex-vessel

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11-15 December 2017, Vienna, Austria

presented by

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Outline

- **Severe accident phenomena part 2 : Ex-vessel**
  - Introduction
  - Release of corium into the containment / Direct containment heating
  - Modes of containment failure;
  - Fuel-Coolant Interaction / Steam explosion
  - Molten-Corium-Concrete-Interaction
  - Hydrogen in the containment
  - Steam generator tube rupture - example of containment bypass
  - Containment structural integrity
  - Fission product release ex-vessel
  - Fission product behaviour in the circuit and containment
  - Research priorities/Conclusions
  - Acknowledgements and References

Containment failure modes – current picture

Structural failure:

- Steam explosions -> shock waves and missiles (α)
- Hydrogen explosion -> pressure peaks (γ) ;
- Slow overpressurisation -> by non-condensable gases (MCCI) and steam (δ) ;
- Basemat melt-through -> thermal and chemical attack (ε);
- High pressure melt ejection (HPME) and direct containment heating (DCH) -> rapid pressurisation on vessel failure;
- Overtemperature -> organic material seals;

Confinement function failure (with no structural failure):

- Isolation failures (β) -> isolating valve failures, containment penetrations or hatch leak tightness faults;
- Containment bypass (V) – IS (interfacing systems) LOCA, SGTR (steam generator tube rupture) [can occur before vessel failure].

Containment failure - timing

Containment failure modes can be "early" or "late":

- **By reference to the time necessary for the public authorities to take off-site protection actions (population evacuation or shielding) by application of the off-site emergency response plan (in France, the rough order of magnitude is 1 day);**
  - "Early containment failure" events, associated with large source terms, are usually due to modes β, V (in fact all by-pass scenarios), α, γ and high pressure core meltdown events;
  - "Late containment failure" events are usually due to modes δ or ε;

Fission product release due to containment failure :

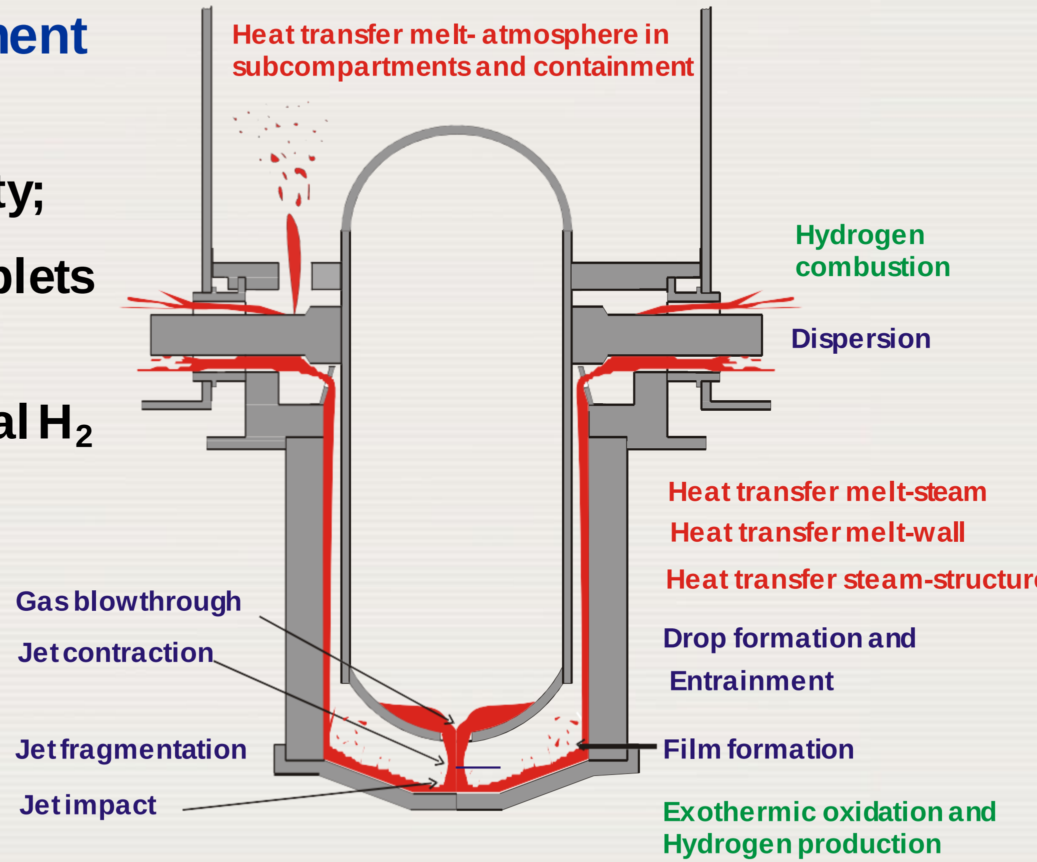
- ***Iodine*** **content of the source term drives the "short-term" radioactive risk after release (half-life of ^{131}I is 8 days);**
- ***Caesium*** **content of the source term drives the "long-term" radioactive risk after release (half-life of ^{137}Cs is 30 years).**

Direct Containment Heating

Succession of possible physical events in direct containment heating (DCH):

- **Dispersal of corium in the cavity;**
- **Ejection of hot corium droplets into the containment zones;**
- **Droplet oxidation and additional H_2 production.**

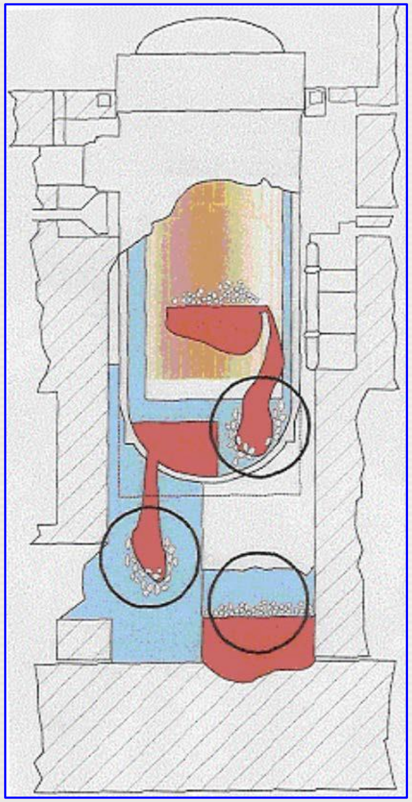
→ *No DCH if the primary circuit is depressurised early enough by the safety systems or manually by the NPP operators.*

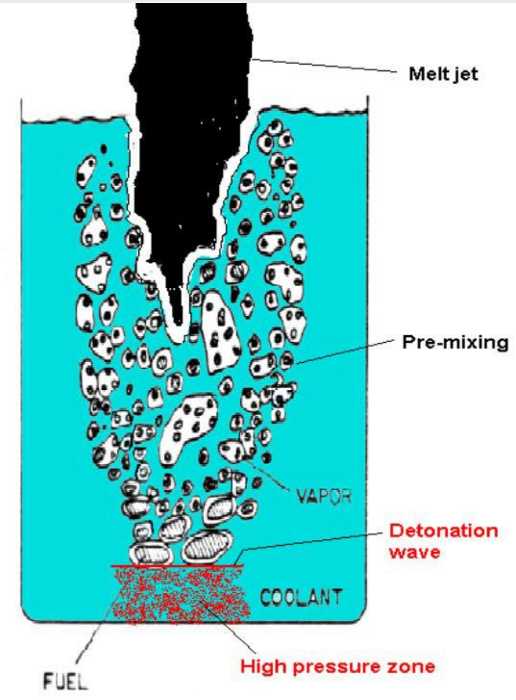


Fuel-Coolant Interaction / Steam explosion

Risk of Fuel-Coolant-Interaction (FCI) or steam explosion in different situations, within the vessel or in the cavity (see picture below)

- In the case of a wet cavity, FCI may endanger the integrity of structures (missiles..).





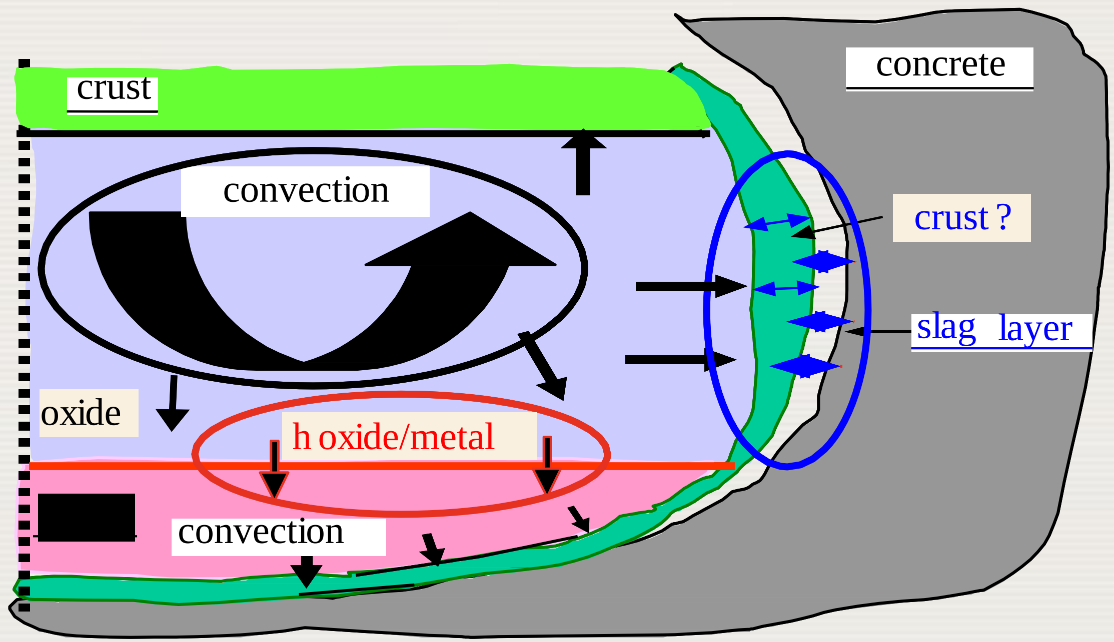
Conceptual picture of a steam explosion associated with melt pour

Molten-Corium-Concrete-Interaction

After vessel failure and slump of corium in the cavity, Molten-Corium-Concrete-Interaction (MCCI) may occur:

- Erosion of concrete, in two phases: rapid phase with metals oxidation (kinetics ~m/h) then slower phase (~cm/h) which may last several days; and
- Release of inflammable gases (CO etc.) (from concrete decomposition) that will increase containment pressure and the risk of gas combustion in the containment.

→*Possibility to slow down the erosion or even stop it in case of water injection on top of the corium*



- **MCCI experiment**
- **Decay heat liberates water from concrete**
- **Metals (Zr and steel) oxidize and produce H_2 and CO**
- **Exothermic energy from chemical reactions**
- **See Video Clip**

Molten-Corium-Concrete-Interaction

The following issues need to be addressed in safety assessments:

- Delay before basemat penetration (for source term assessment);
- Production of gases (H_2, CO, CO_2, ….);
- Combustion of inflammable gases (H_2, CO………..);
- Corium coolability (impact of water), effects of bulk cooling, water ingression though cracks in solidifying concrete, melt eruptions, crust breach;
- Influence of type of concrete (depends on plant vendor and site)
- Effect of reinforcing steel bars (rebar), not studied in the two OECD/MCCI projects at Argonne NL, new MOCKA experiments in Germany (KIT);
- Long-term behaviour.

Severe accident codes (ASTEC, MAAP, MELCOR) allow for calculations of the MCCI phase:

- Consider high uncertainties in the calculations/models;

Plant design specifics, such as concrete type, must be taken into account.

Hydrogen risk in containment

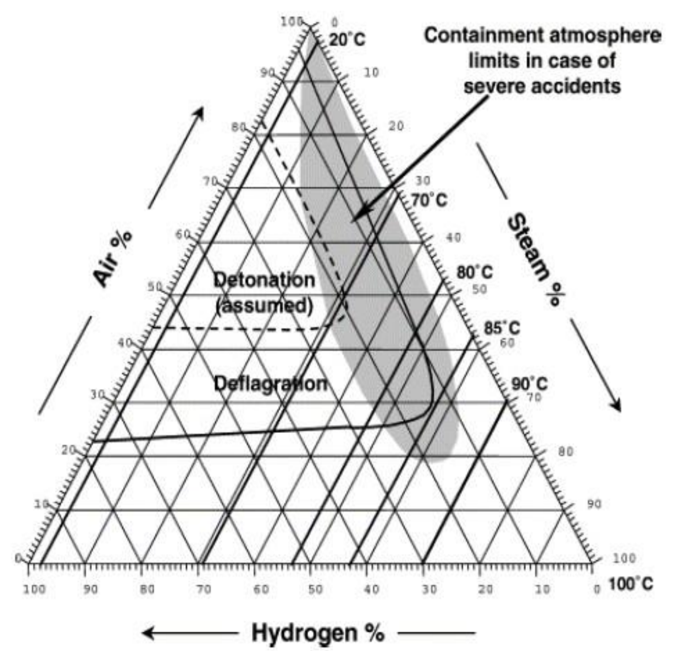
Combustion requires ignition sources and burnable mixture:

- Flammability limits for H_2-steam-air mixtures: see the Shapiro diagram to the right;

Deflagration:

- Subsonic propagation (by heating of unburnt gases) at a few m/s → pressure peak of a few bars;

(J.-C.. Sabroux, extract from SARNET 2007 Course)

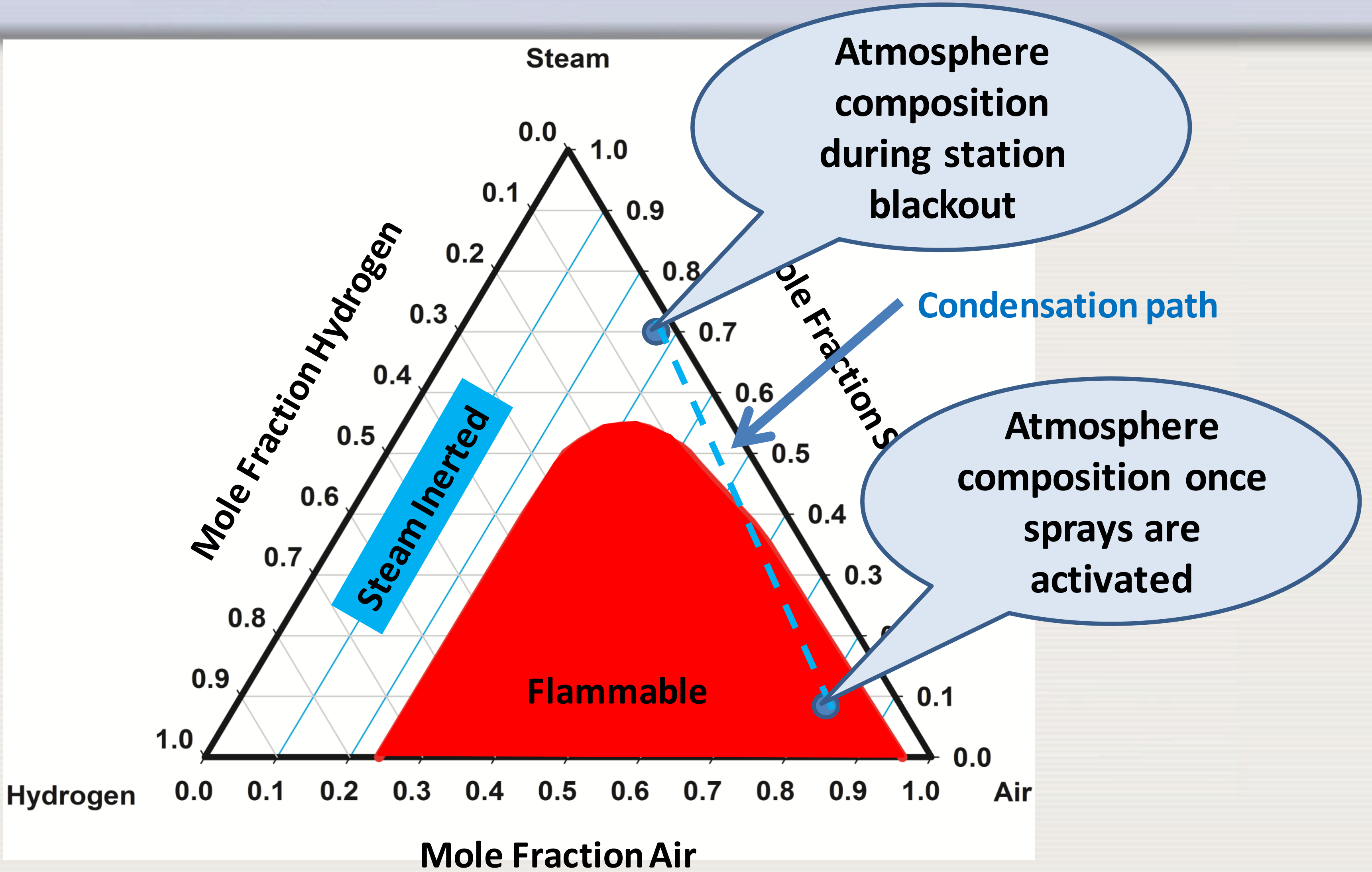


Detonation:

- The gas flame may accelerate in presence of obstacles (instabilities) and lead to detonation (supersonic wave and possible missile…) → need of local gas concentrations > 10%.

→ *Importance of spray systems, of presence of gas recombiners and of containment venting procedures*

Containment Spray De-Inerting



Fission Products are Releases as Gases and Aerosol Particles

Noble gases, Xe and Kr remain as gases

Volatile and semi-volatile fission products condense to form aerosol particles

- Particle sizes range from 0.1 to 10 micrometers
- Aerosol transports with gases: steam and hydrogen

Not all radioactive particles that are released from the fuel are ultimately released to the environment

- Gravitational settling
- Deposition on surfaces by thermo-gradient and steam condensation mechanisms (thermo-phoresis and diffusio-phoresis)
- Revaporization and resuspension (*recall FP have decay heat*)
- Water sprays and pool scrubbing

Ultimate release to the environment strongly affected by natural and engineered attenuation processes

Volatility of Fission Products

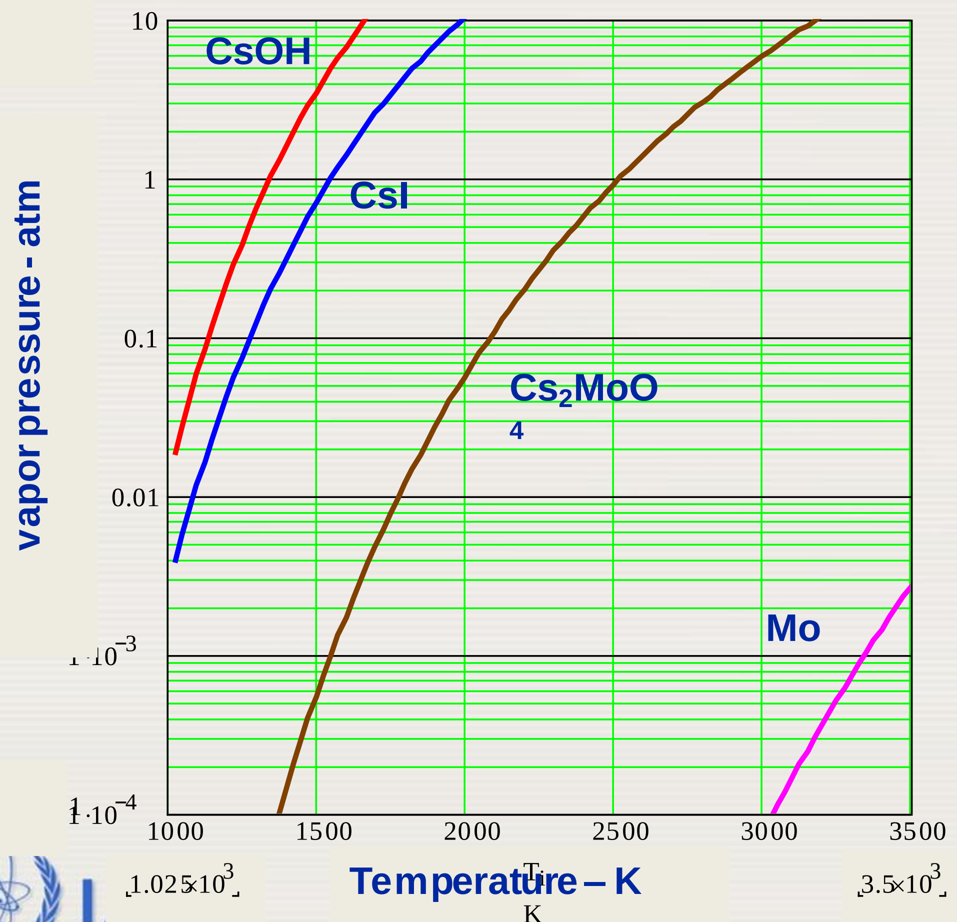
3300 MW_{th} LWR

Volatility	Elements	Inventory (Ci)
Noble Gases	Krypton (Kr) Xenon (Xe)	$1.7x10^8$ $2.2x10^8$
Very Volatile	Iodine (I) Cesium (Cs)	$7.5x10^8$ $2.3x10^7$
Moderately Volatile	Tellurium (Te) Strontium (Sr) Barium (Ba)	$1.8x10^8$ $3.5x10^8$ $3.4x10^8$
Less Volatile	Ruthenium (Ru) Lanthanum (La) Cerium (Ce)	$2.4x10^8$ $4.7x10^8$ $3.9x10^8$

Vapor Pressures of Some Important Species

$$\dot{m}_v = \left[\frac{Nu\mathcal{D}_k}{D_{fuel}}\right]\left(\frac{P_k - 0}{RT}\right)A_{fuel}$$

Vapor transport rate



Molybdenum vapor pressure extremely low
Cs_2MoO_4 considerably higher, but…

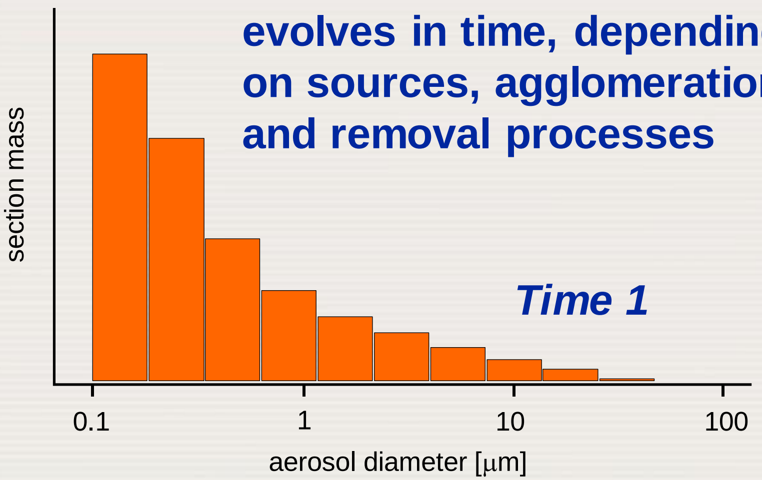
Less volatile than CsOH or CsI
MELCOR treatment

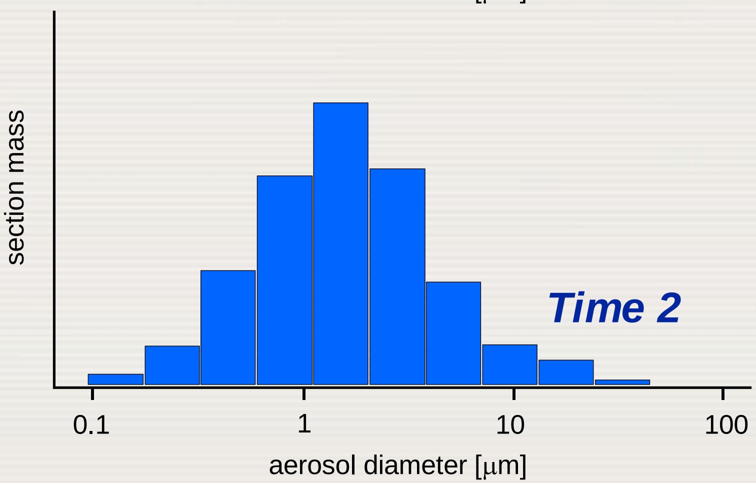
Cs and Mo treated as Cs_2MoO_4 with respect to volatility
CsI left unchanged

Synthesis of VERCORS and Phebus Data in Severe Accident Codes and Applications SAND2010-1633

Aerosol Mechanics Using Sectional Method MAEROS

Aerosol size distribution evolves in time, depending on sources, agglomeration and removal processes





MAEROS sectional model of Gelbard

- 10 sections [.1 - 50 µm]
- Condensed FP vapor sourced into smallest section

Particles grow in size

- Agglomeration
- Water condensation

Particle fallout by gravitational settling

Particle deposition processes

- Thermophoresis
- Diffusiophoresis
- Brownian motion

Fission Product Chemistry in Containment: basic processes

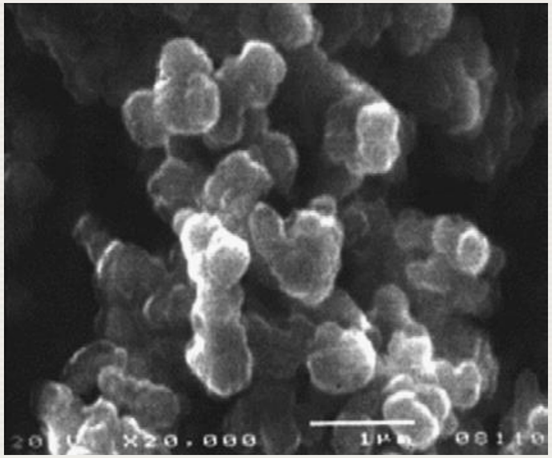
FPs are mostly released as aerosols into the containment:

- They will be deposited on walls and the floor, painted or not, by gravitational settling, thermophoresis and diffusiophoresis;
- Particles washed down from walls will go into sump water where they dissolve, or not, depending on their chemical speciation;
- Liquid phase chemistry under radiation is important – radiolytic reactions;

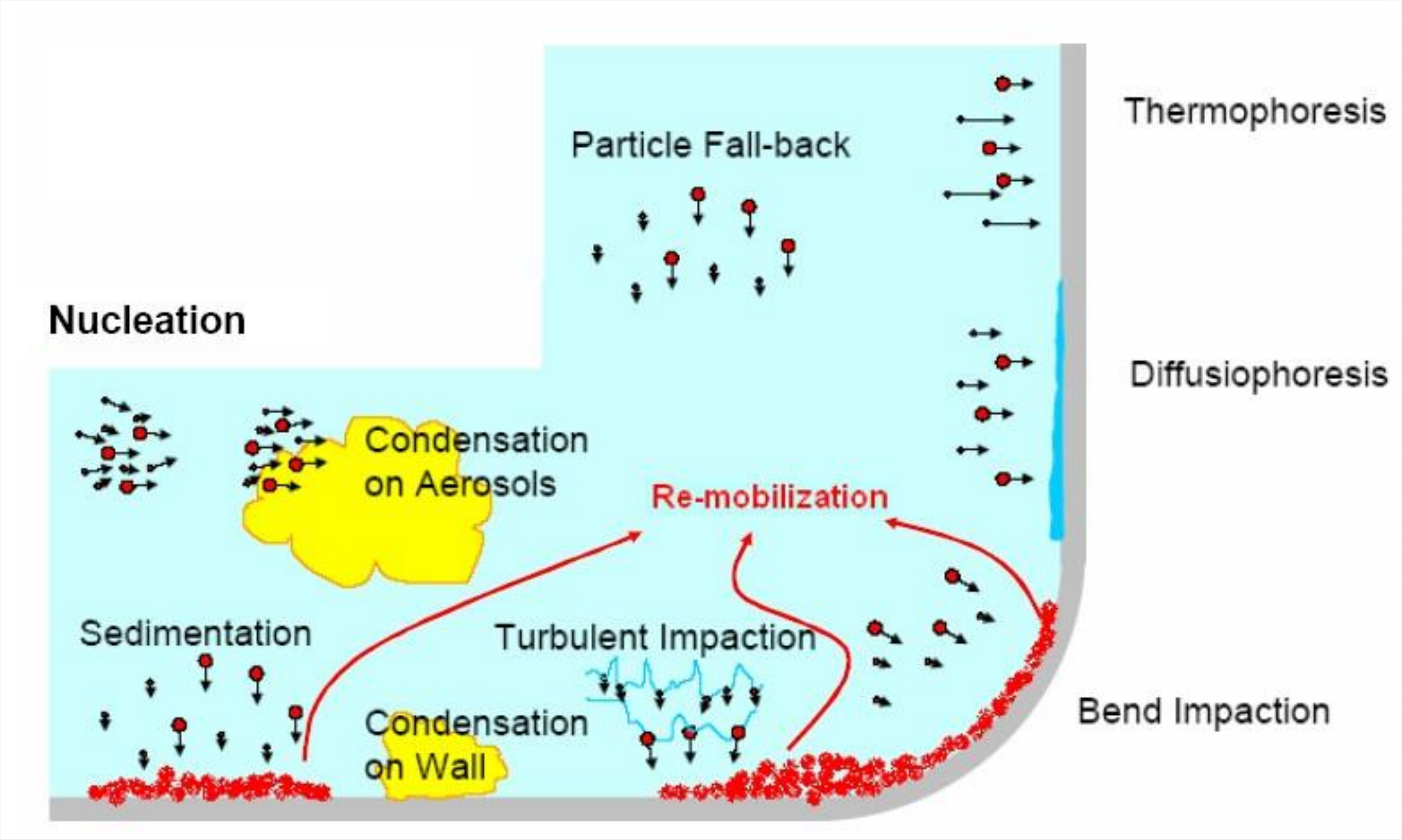
Some FPs are partly released as vapours (gas):

- They can react with surfaces through adsorption and desorption mechanisms;
- They can react with air radiolysis products;
- They can exchange with liquid phases.

SEM images of aerosols from an impactor plate in the circuit of the Phébus FPT0 test showing an agglomerated structure of particles typically in the range 0.1–0.5 micrometres. (Fig. 20 of Clément et al. (2003)).



Fission Product Transport in the RCS: Basic processes

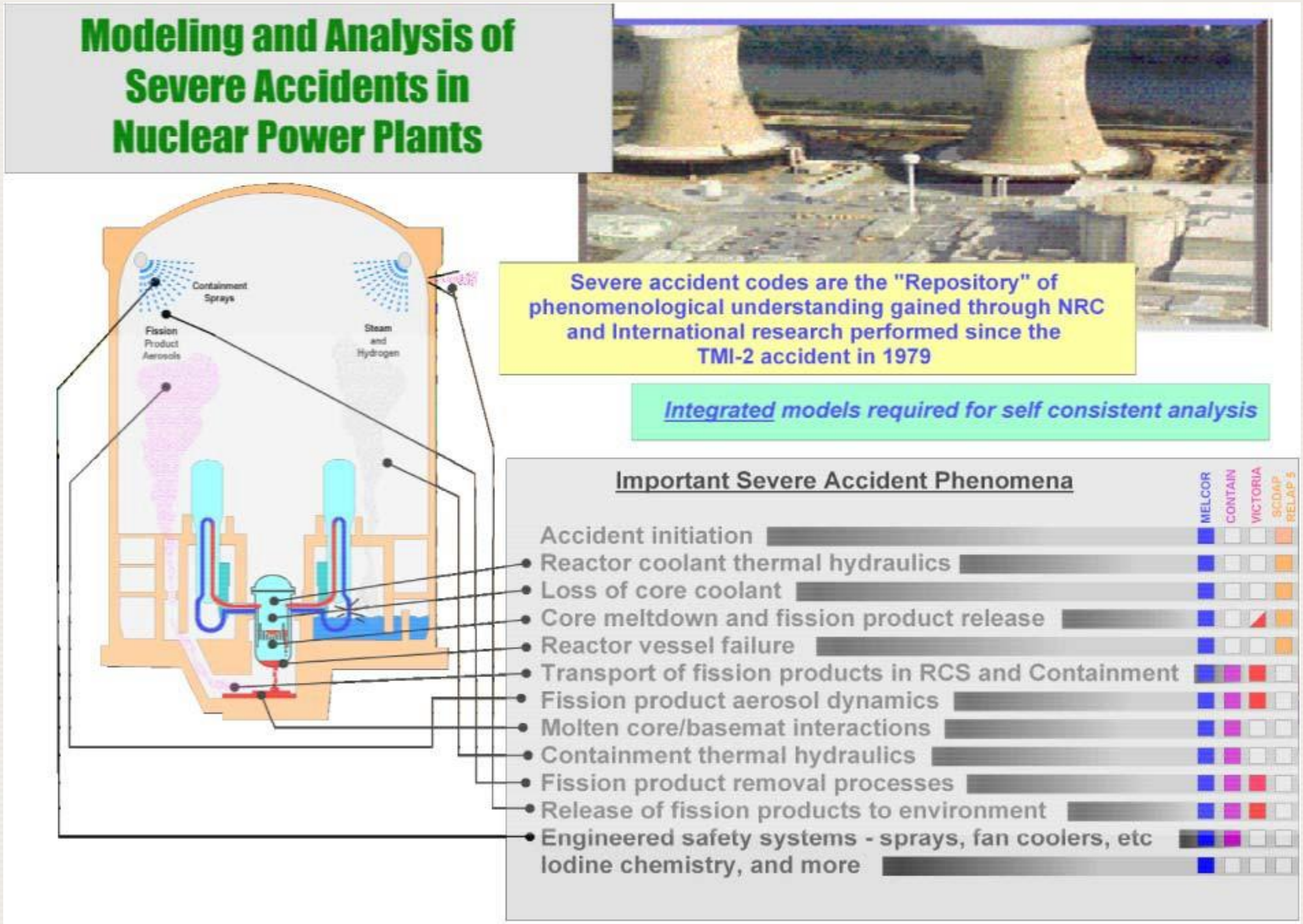


Overall behaviour in the circuit depends on the physico-chemical form of the released materials

Conclusions

- **The main physical phenomena that are involved in the ex-vessel phase of severe accident in nuclear power plants (NPP) have been presented:**
  - Release of corium into the containment and direct containment heating;
  - Modes of containment failure;
  - Fuel/coolant interaction / steam explosion;
  - Molten core concrete interaction;
  - Hydrogen in the containment;
  - Fission product release ex-vessel;
  - Transport of fission products and structural materials in the primary circuit (PWR) and their behaviour in the containment;
- **Many fields of physics and chemistry are involved, so a multi-disciplinary approach is needed to understand the tightly-coupled phenomena involved.**

System Level Accident Codes



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Questions?