DE LA RECHERCHE À L'INDUSTRIE

ICE Program: the CEA experimental program devoted to FCI studies with prototypical corium

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ERMSAR 2015-MARSEILLE-PAPER 2015-69

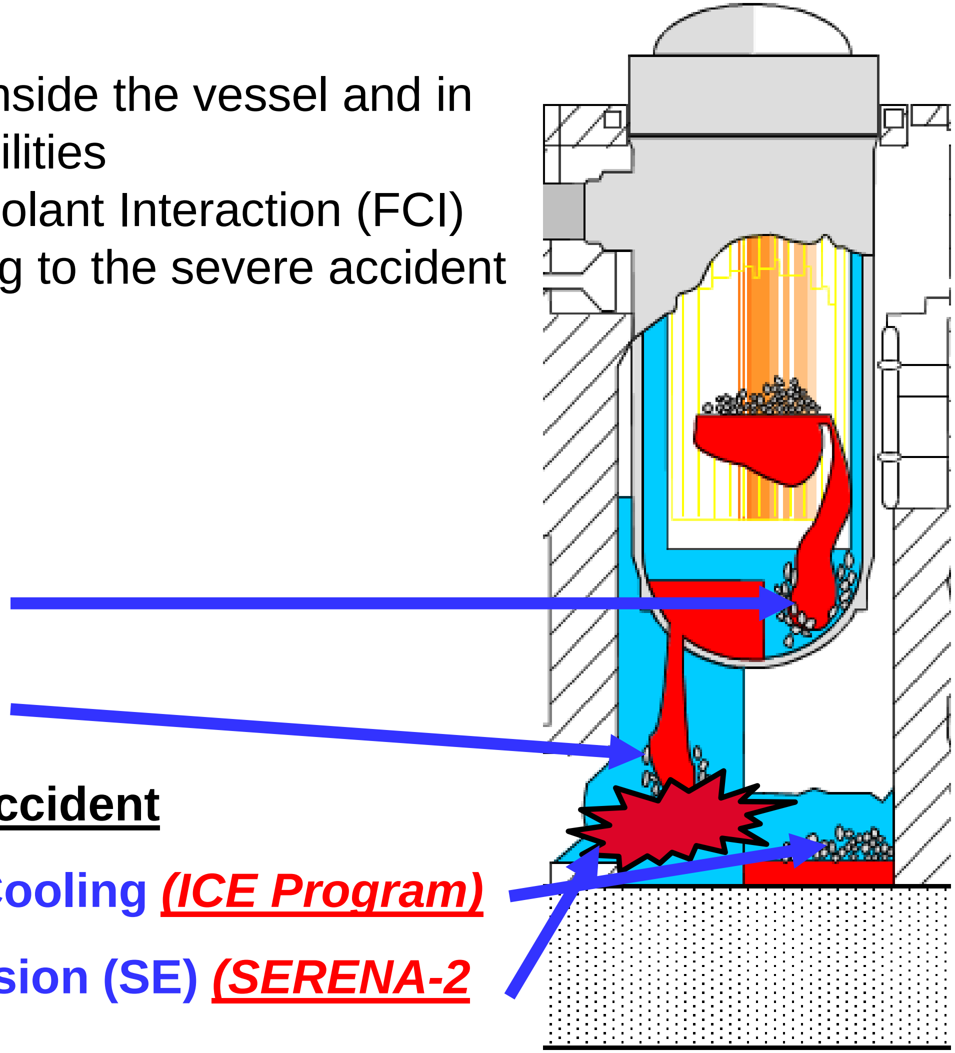
CONTENTS

FCI STUDIES-CONTEXT

- **Initial Severe Accident conditions:**
  - Formation of a corium melt pool inside the vessel and in the absence of any cooling capabilities
  - Corium jet into water and Fuel Coolant Interaction (FCI)
  - Different kinds of corium according to the severe accident scenario

- **FCI configurations**
  - In-Vessel configuration
  - Ex-Vessel configuration

- **Two possible progressions of the accident**
  - Fragmentation and **Debris Bed Cooling** ***(ICE Program)***
  - Fragmentation and **Steam Explosion (SE)** ***(SERENA-2 and ICE Programs)***



OECD/SERENA PHASE 2 PROGRAM

-OECD/SERENA phase 2 international program (2007-2012):

- 3 tasks

1. **Experimental Steam Explosion program**
   - KROTOS:1 D geometry
   - TROI: 2 D geometry
   - *6 tests in both facilities with the same conditions: steam explosion is artificially triggered*

2. **Analytical Program**
   - Increasing the capabilities of FCI models/codes for reactor analyses integrating the results of the experimental program of Phase 2

3. **FCI codes applications:**
   - 2 sub-tasks: pre and post test calculation, PWR/BWR reactor case calculation
   - 5 codes
     - IKEMIX/IKEJET+IDEMO: user/developer IKE (Germany)
     - JASMINE: user: JRA/developer: JAEA (Japan)
     - MC3D: users: AECL, CEA, IKE, IRSN, EDF,JSI, KAERI, KINS, GdF/Suez developer: IRSN (France)
     - TEXAS-V: users UWM, VTT/developer: UWM (USA)
     - TRACER: user/developer KMU (Korea)

SERENA-PHASE 2/ EXPERIMENTAL GRID

-Four prototypical material compositions representative of different reactor case scenarios

Material [wt%]	Composition	Situation / Related effect
Mat 1	***In-vessel Corium*** ***“ eutectic ”*** **$70\%UO_2$-$30\%ZrO_2$**	Reference material
Mat 2	***In-vessel Corium*** ***“ non-eutectic ”*** **$80\%UO_2$-$20\%ZrO_2$**	Prototypical material in FARO and KROTOS Oxide Corium representative of reactor case
Mat 3	***In-vessel Corium*** **$70\%UO_2$-$15\%ZrO_2$ + 15%Zr**	Prototypical material Metal content in corium representative of reactor case
Mat 4	***In-vessel Corium*** **$73\%UO_2$- $20.4\%ZrO_2$** ***Structural material:*** **$4.1\%Fe_2O_3$** ***Fission products:*** **$1.3\%Cr_2O_3$,0.3%BaO,0.8%LaO 0.2%SrO**	Focus on role of large liquidus-solidus large interval Low volatile fission products representative of reactor case

MAIN KNOWLEDGE GAINED WITH KROTOS TESTS (1/3)

- <u>**Material 1 and Material 2: close thermodynamic and thermophysical properties**</u>

- Corium jet fragmentation, coarse and fine corium fragmentation:
  - if the jet break-up occurs before the entrance into water (KS-2- initial jet diameter 10 mm), the dynamic of void production in water is higher (void 27%) than if the jet break-up occurs into water (KS4- initial jet diameter 30 mm) (void ~ 6%)
  - the jet break-up directly in the water (KS4-jet diameter 30 mm) helps high energetics steam explosion => coupling between corium droplet distribution and void formation
  - Kim-Corradini mechanism is dominant for melt fine fragmentation

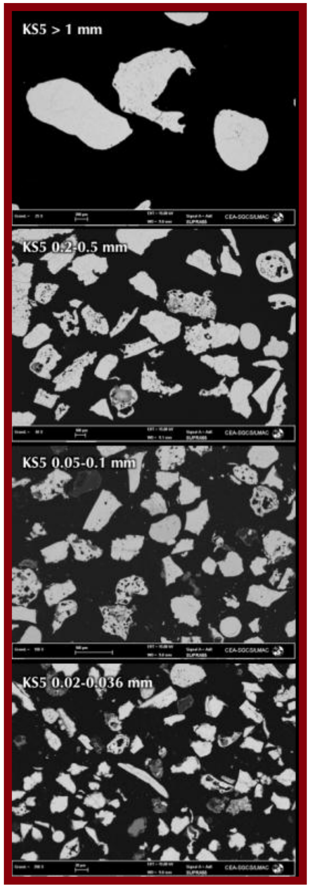
- “Void” production:
  - Void collapse before steam explosion for KROTOS KS-4 =>high energetics steam explosion <u>***(Max dynamic pressure: 447 bars)***</u>

- Corium composition:
  - No effect of the composition between “eutectic” and “non-eutectic” compositions on steam explosion phenomena
  - No “spontaneous” explosion

MAIN KNOWLEDGE GAINED WITH KROTOS TESTS (2/3)

Material 3: sub-stoechiometric and intermediate solidification interval

- Corium jet fragmentation, coarse and fine corium fragmentation:
  - Almost no fine fragmentation, just coarse fragmentation
  - Jet beak-up into water is accompanied by energetic reaction between water and corium which can be attributed to rapid oxidation reaction and production of hydrogen
- Void production:
  - Impact of hydrogen production on steam film stability and void formation ?
  - Formation of large "void" pocket: acting as mitigation of steam explosion ?
- Corium composition:
  - Production of hydrogen (void fraction) and oxidation (local heat release, higher amount of available liquid corium) => no propagation of steam explosion
  - ***Impact of these mechanisms on steam explosion energetics: understanding needs to be improved***



MAIN KNOWLEDGE GAINED WITH KROTOS TESTS (3/3)

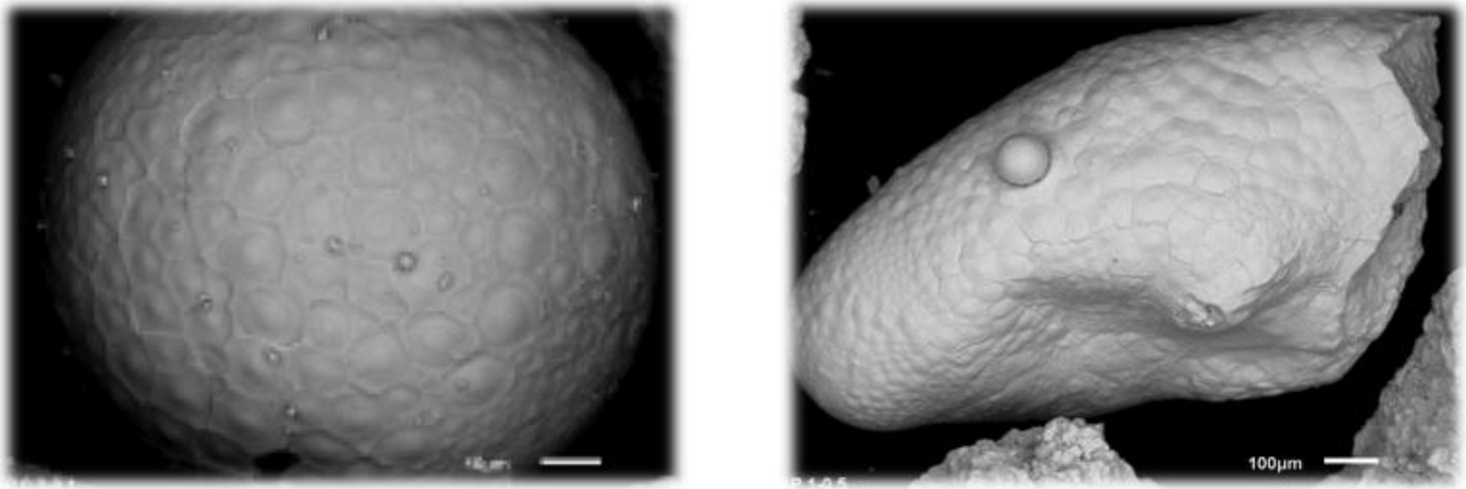
Material 4: stoechiometric and large solidification interval

- Corium jet fragmentation, coarse and fine corium fragmentation:
  - Almost no fine fragmentation, just coarse fragmentation

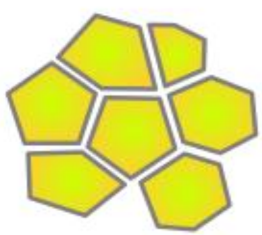
- Corium composition:
  - Interval of solidification is large, impact of the available liquid corium at triggering time => KROTOS, no propagation of steam explosion, TROI: strongest steam explosion of TROI series
  - ***Impact of these mechanisms on steam explosion energetics: understanding needs to be improved***

DEBRIS MORPHOLOGY

Benard-Marangoni cells on the droplet's surface without steam explosion (premixing)



KROTOS KS2 premixed droplets



Surface cell structure

Marangoni number

$$Ma = \frac{\sigma' \Delta T d}{\mu a}$$

σ' = d(surface tension)/ d(Temperature)
ΔT – Temperature difference
d – Depth
μ – Viscosity
a – Thermal diffusivity

- **Important impact on the heat exchange during premixing**
- Quasi steady heat exchange
- Surface layer in interaction
- Gradient of surface tension

ICE PROGRAM: WATER CORIUM INTERACTION

- FCI national activities

ICE FRENCH NATIONAL PROJECT LED BY IRSN (2013-2018)

CEA Tasks in the frame of ICE program:

1. 5 integral KROTOS tests using prototypic corium- Post-test analyse- Debris bed characterization- 2d X-ray source
2. Measurements of corium thermophysical properties and solidification tests in CEA VITI facility before and after FCI
3. Measurements of corium thermodynamic properties and solidification tests in DPC facility before and after FCI
4. *MC3D activities: KROTOS tests, reactor case calculations*

INVESTISSEMENTS D'AVENIR

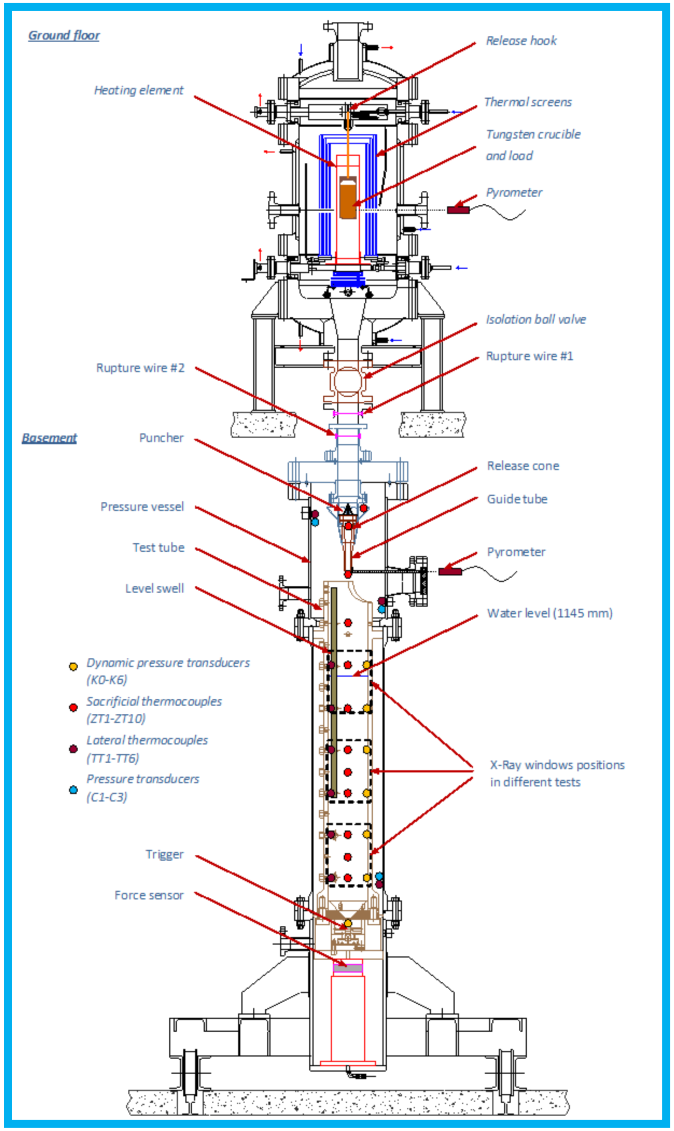
IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Lemta

eDF
CHANGER L'ÉNERGIE ENSEMBLE

AREVA

KROTOS FACILITY



Furnace

- Max pressure: 40 Bar
- Three-phase tungsten heating element
- Maximum temperature: 2900 °C
- Operation: inert atmosphere
- Tungsten crucible: 1 liter
- Load: up to 8-9kg of prototypical corium
- Melt temperature: measured by a bichromatic pyrometer at the lateral surface of the crucible

Transfer zone

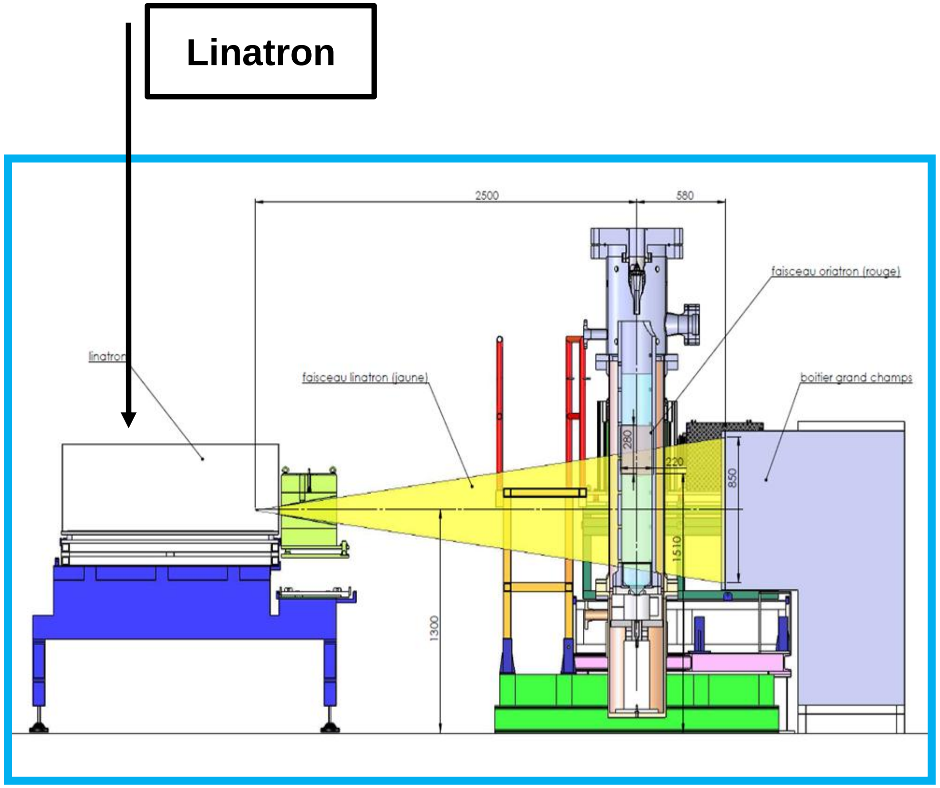
- Puncher: zero-velocity of corium melt
- Tin membrane
- Specific device to produce coherent jet-30 mm

Test section

- Max pressure: 25 Bar
- Melt temperature: measured by a bichromatic pyrometer at the tip of the guide tube
- Sacrificial thermocouples: melt front detection
- Lateral thermocouples: melt spreading
- Level swell: global void fraction
- Vessel Pressure transducers: pressure evolution
- Dynamic pressure transducers: explosion wave propagation
- Force sensor: explosion impulse
- X-Ray radioscopy: premixing-fragmentation

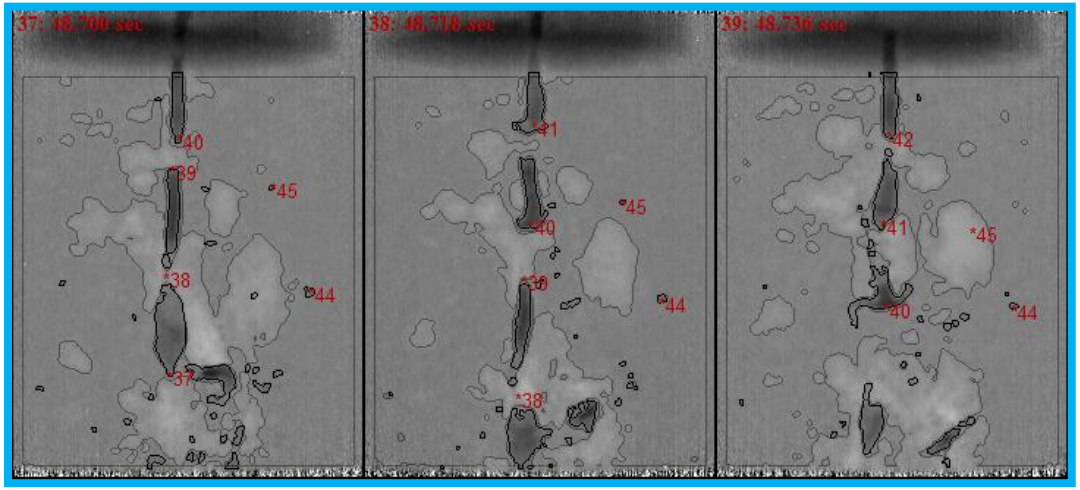
- **Instrumentation**
  - **X-Ray source to characterize the full jet fragmentation process:**

LINATRON (already used for SERENA-2) : 9 MeV; larger window than for SERENA-2



- Instrumentation

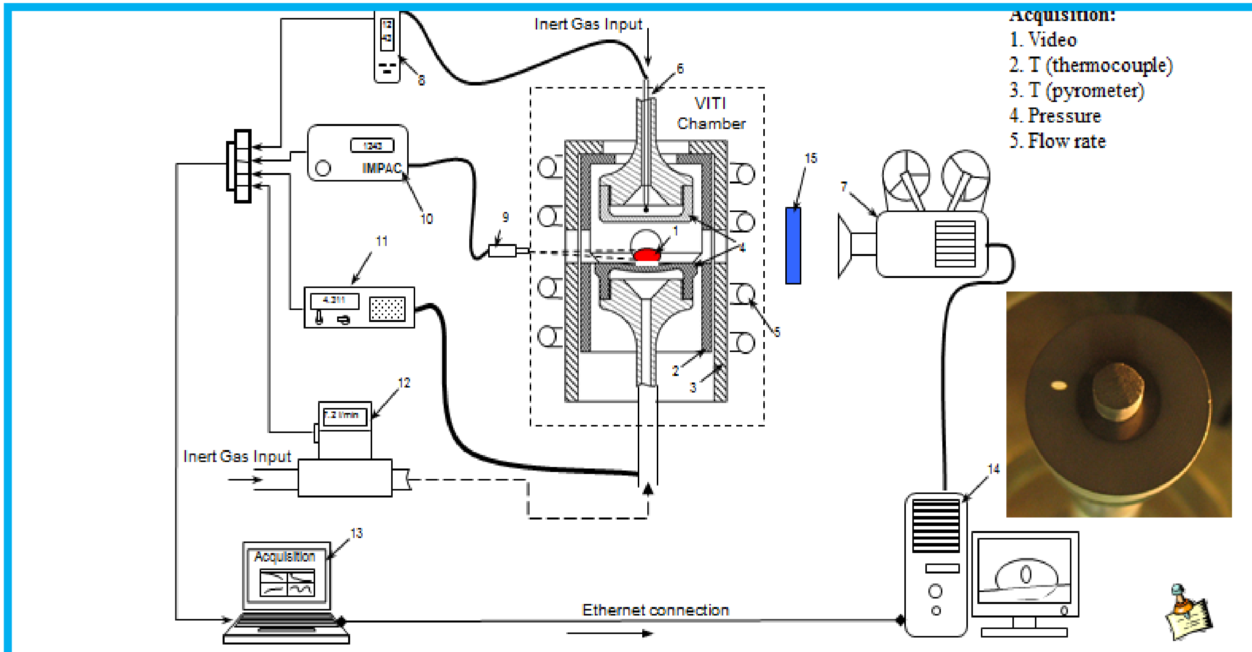
- Specific Instrumentation of KROTOS test section : X-Ray Linatron (50 to 250 frames/second)- KIWI software developed by CEA
- Qualitative and quantitative data



- **Corium volume**
- **Corium surface area**

- **Void volume**
- **Void surface area**

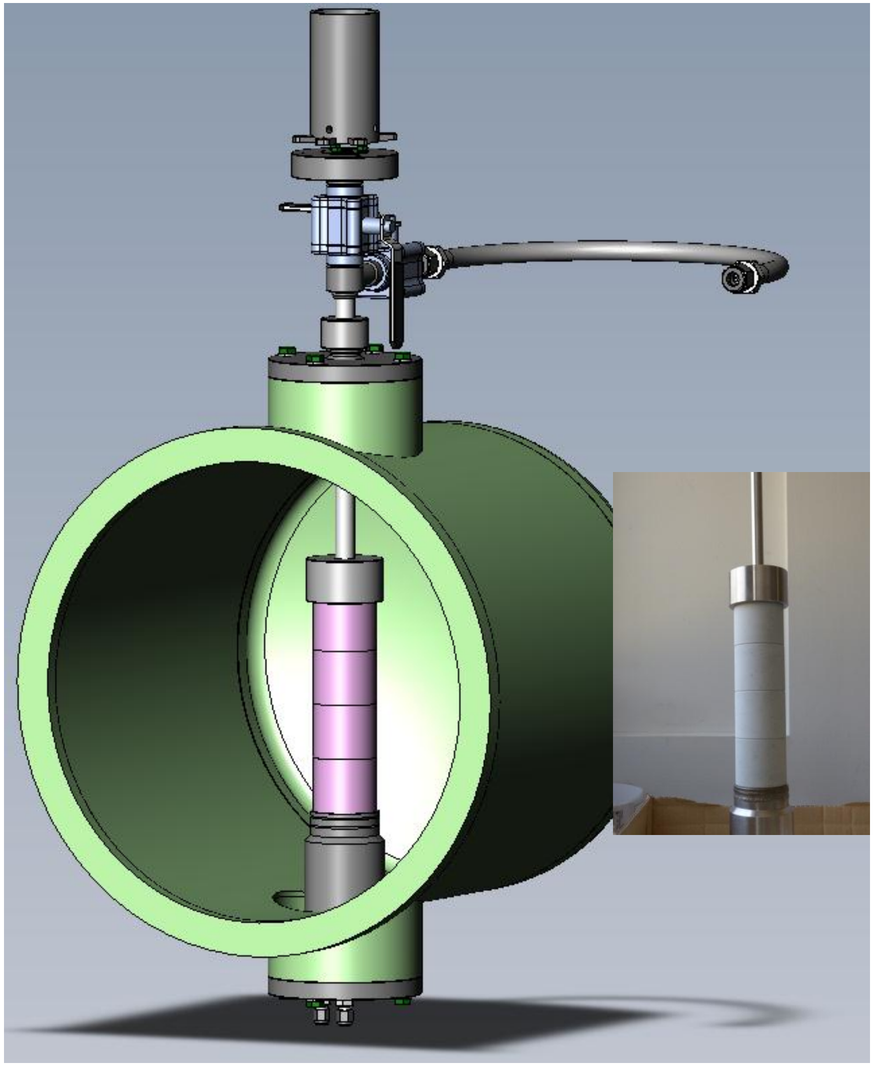
- **Measurements of corium thermophysical properties:**
  1. Density
  2. Viscosity
  3. Surface tension



1 – droplet; 2 – susceptor; 3 – thermal shield; 4 – lower and upper diffusers; 5 – inductor; 6 – thermocouple; 7 – high speed digital video camera; 8 – converter; 9 – focusing lens (fiber optic); 10 – pyrometer; 11 – manometer; 12 – mass flow meter; 13 – data acquisition computer; 14 – video acquisition computer; 15 – low pass filter 500 nm.

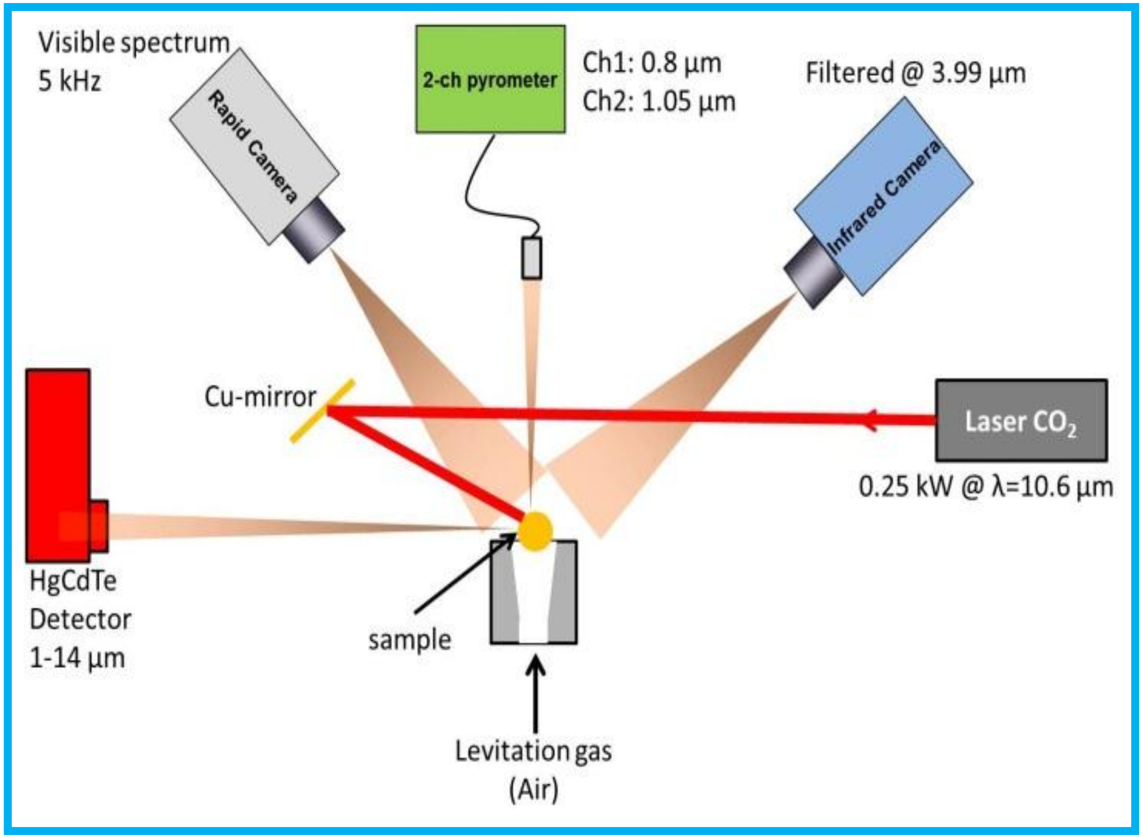
VITI: CORIUM OXIDATION STUDIES

- Use of leaktight hafnia tube (CEA patent)
  - 25 refractory pieces
  - Can contact UO_2-ZrO_2 melt
- Heat generated tanks to a tungsten susceptor (out of oxident atmosphere tube).
- Online gas spectroscopy
  - Online measurement of oxidation species
- Post Test material analyses (identification of formed phases, mechanisms, kinetics)



ATTILHA: CORIUM THERMODYNAMIC PROPERTIES

- **Measurements of corium thermodynamic properties (CEA-Saclay/DPC):**
  1. Liquidus temperature
  2. Solidus temperature
  3. Phases at liquid/solid state



ICE: KROTOS EXPERIMENTAL GRID

N°	Type	Corium composition	Jet
KA-1	*PREMEL*	*Mat. 2 (SERENA-2)*	*Gravitational*
KA-2	EXPLO	Mat . 3 (SERENA-2)	Gravitational
KA-3	PREMEL	Mat.2 (SERENA-2)	Rapid
KA-4	EXPLO	Mat 4 (SERENA-2)	Rapid
KA-5	EXPLO	To be defined	

=> First test of ICE program KROTOS KA-1 : successfully performed 20/03/2015

- FCI international activities:

TOP ON EX-VESSEL STEAM EXPLOSION (2014-2015)

1. Summarize the status of development and validation of existing Fuel Coolant Interaction (FCI)/Steam Explosion (SE) codes and the status of experimental database on FCI/SE phenomena, with particular reference to the recently completed OECD/SERENA and other national and international programs.
2. Summarize the status of the existing knowledge on the bounding conditions to estimate **the acceptable dynamic load on the structures of nuclear reactor** during a steam explosion event.
3. Identify the main parameters having first order influence on the energetics of steam explosion for various severe accident scenarios.
4. Identify, from an accident management perspective, if there is further need for improvements in the qualification of the FCI codes to reduce remaining uncertainties and possible positive/negative impact for the management of the water during the severe accident. **Also, identify any separate effect and/or integral experiment that may be needed in support of code improvements and assessment.**
5. Describe briefly the treatment of FCI/SE in the frame of national safety analyses and identification of possible evolution after Fukushima accidents.

The Technical Opinion Paper will be used as a guide for further R&D activities in the area of Fuel Coolant Interaction.

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AEN NEA

KAERI

CONCLUSION AND PERSPECTIVES

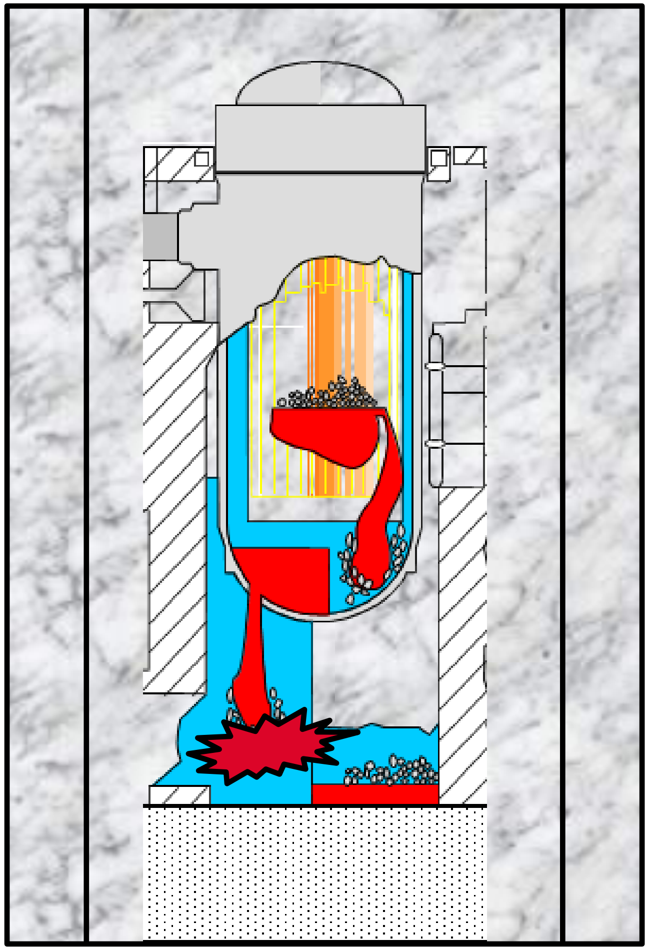
- **KROTOS FCI/OECD SERENA program:** new experimental data base close to reactor case severe accident conditions to qualify FCI codes:
  - **Material 1 and 2:** "eutectic" (BWR) 70%UO_2-30%ZrO_2/ "non-eutectic" 80%UO_2-20%ZrO_2(PWR)
  - **Material 3:** "Sub-oxide corium": 70%UO_2-15%ZrO_2 + 15%Zr
  - **Material 4:** Oxide corium : 73%UO_2-20,4%ZrO_2 + Structural material: 4.1% Fe_2O_3 1.3% Cr_2O_3+ Low volatile Fission Products: 0.3% BaO; 0.8% LaO; 0.2% SrO

- **KROTOS KS series: prototypic reactor materials less explosive than simulant materials:**
  - Conversion efficiency fraction < 1%
  - "Eutectic" composition is no more explosive than non-eutectic, contrary to earlier conjecture
  - **The oxidation process** during FCI phenomena: important role, especially on energetics (Material 3)
  - **Melt solidification :** effect on explosion potential (Material 4)

- **ICE national program: CEA /KROTOS : new data on the premixing/fragmentation and steam explosion phenomena:**
  - First test KROTOS KA-1 performed 20/03/2015: insight into the premixing phase: void production, fragmentation debris bed formation and steam release

- **ICE national program: CEA /VITI and ATTILHA :**
  - Complementary important information before and after FCI
  - Thermophysical and thermodynamic properties of prototypical corium

THANK YOU FOR YOUR ATTENTION!



NUGENIA
NUclear GENeration II & III Association

KTH

SARnet

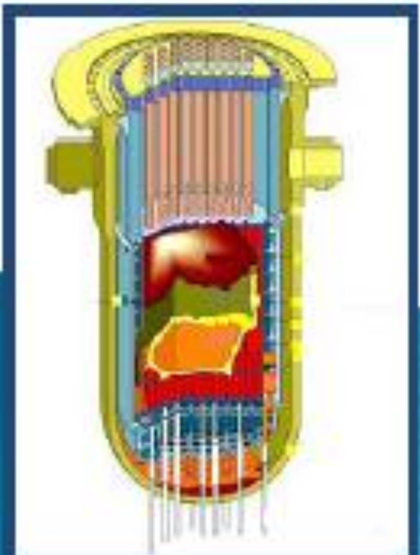
Short Course on

Severe Accident Phenomenology - 2015

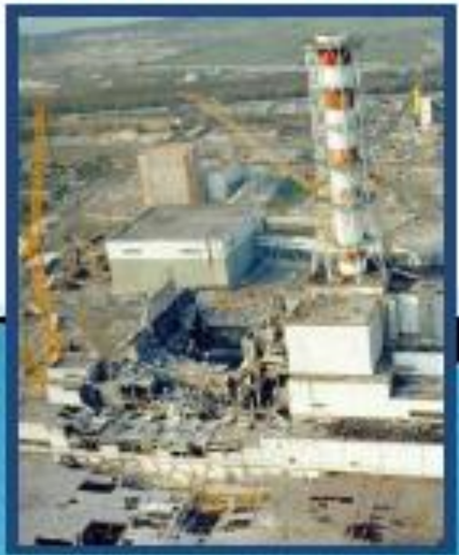
Stockholm (S)

July 6th-10th , 2015

jointly organized by KTH, CEA, IRSN and University of Pisa



TMI-2 Reactor Vessel-Core damage



Tchernobyl Reactor Building damage

Fukushima Daiichi