# Chernobyl and Fukushima lessons and modern concepts of severe accident management

Corresponding member of RAS
**L.A.Bolshov**
Director of IBRAE RAN

May 25, 2016

# Evaluation of causes and consequences of Chernobyl NPP accident

**USSR/Russia**

Ministry of Health
Ministry of Medium Machine building
Academy of Sciences/RAN
EMERCOM
Rosatom
Rosenergoatom
Ministry of Agriculture, etc.

**World community**

ICRP
WHO
FAO
IAEA
NEA OECD
European Commission
UNDP, etc.

**Health consequences for population are limited**

**Consequences for countries and global energetics are huge**

# Medical consequences of the Chernobyl accident

- **28 deaths of 134 individuals with acute radiation syndrome** (firemen and ChNPP personnel);
- **Up to 40% of 748 cases of thyroid gland cancer** observed at children (at the moment of the accident) in 4 Russian regions; 1 death, others have been cured;

**Death rate for liquidators is at the average level for the Russian population**

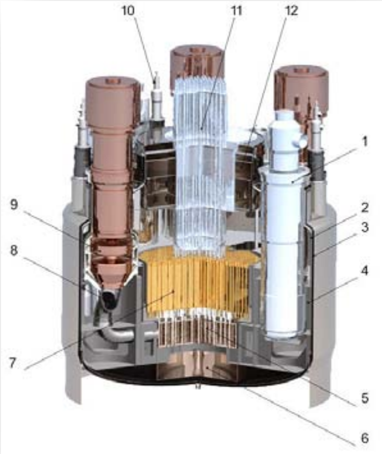
# Significance and lessons learnt of the Chernobyl accident

- Change of Russian society attitude towards NPP severe accidents:
  - NPP modernization and safety system enhancing;
  - Elevation of safety culture due to regulation and rule harmonization;
  - Introduction of defense-in-depth concept and scientifically justified approach to analysis of emergency processes.
- Introduction of the safety priorities in design, construction, operation and management.
- Improvement of professional training of personnel due to application of full-scale simulators at NPP.


4

# Reactor installation safety at the turn of the 21st century

- Culture of safety, independent regulator, responsibility of operator.
- Modernization of installations in operation, development of generation 3+.
- Creation of new safety systems (core catcher, double containment …).
- Calculations and experiments out of the design modes.
- New principles of safety (natural safety).




# Modelling is a basic tool to avoid the severe accidents

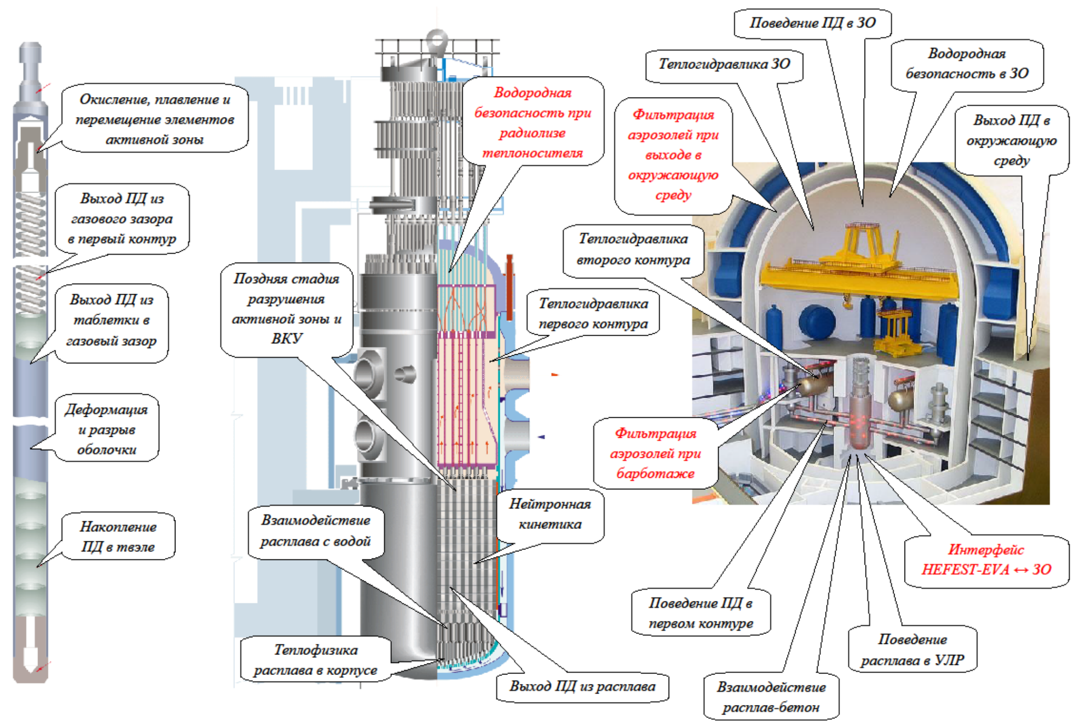
## <u>Russian code SOCRAT is one of the best severe accident codes in the world</u>

## <u>Code SOCRAT:</u>

**Modelling of emergency processes starting from initial event up to radioactivity release from containment.**

## <u>Key tasks:</u>

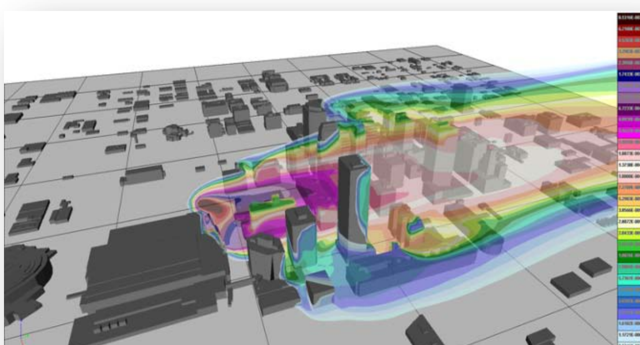
- **Hydrogen safety justification for NPP.**
- **Justification of initial data for core catcher design of NPP-2006.**
- **Radiation safety justification.**



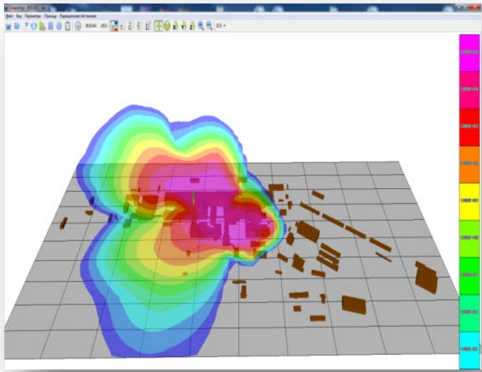

**<u>Designers:</u> IBRAE RAN, FSUE RFNC-VNIIEF, RSC «Kurchatov Institute», JSC SPbAEP ltd., SSC RF-IPPE, JSC «EREC», JSC “GIDROPRESS”, OKBM**

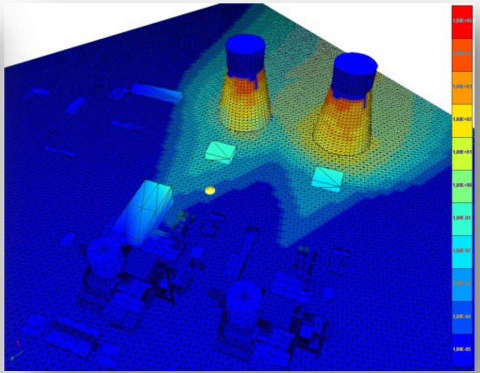
# Radiation monitoring and emergency response

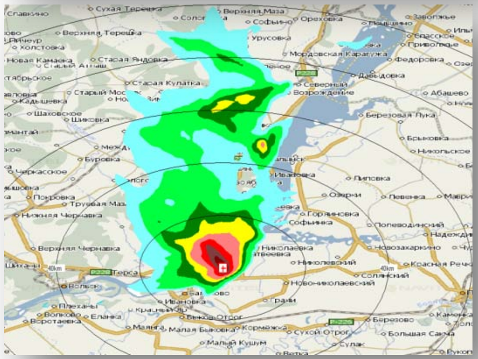
- Smart interdepartmental system of preparedness to respond on radiological threats.
- Automated departmental and territorial radiation monitoring systems.
- High-speed redundant systems of communications, notifications; specialized technics, hi-tech equipment.
- System of scientific and technical support centers, software-hardware complexes for express assessment, analysis, and forecast of situation, expertise.
- Professional emergency rescue services of ministries and departments.

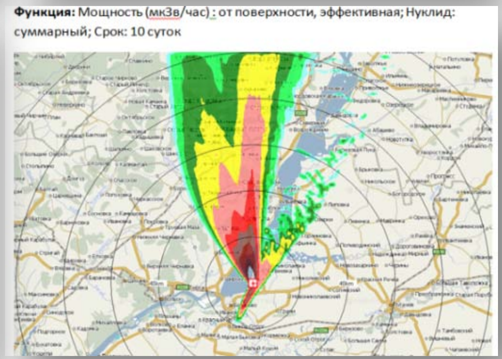


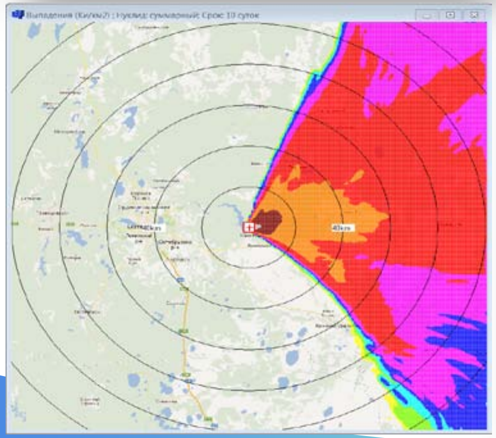
# Software-hardware complexes for assessment and analysis of accident consequences

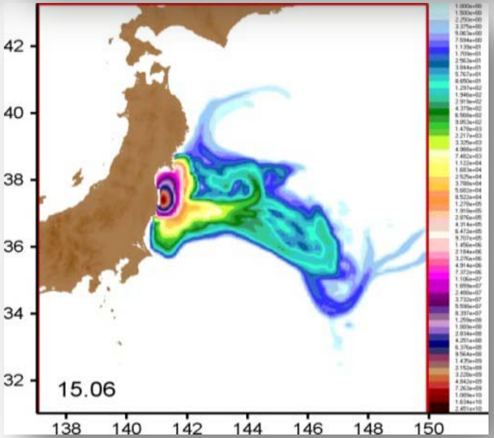











- Set of modern models.
- Effective numerical algorithms.
- Databases and knowledge.

- <u>Analysis and the forecast</u>

- Development of possible incidents and accidents at NRHF.
- Radioactivity distributions in air, water, and soil.
- Radiation situation parameters .
- Exposure doses for population.
- Recommendations on response and measures of protection of the population, territories and mitigation of accident consequences.

# Analysis of the accident at Fukishima-1 NPP

Readiness of the Russian system of emergency response to fast evolution of events.

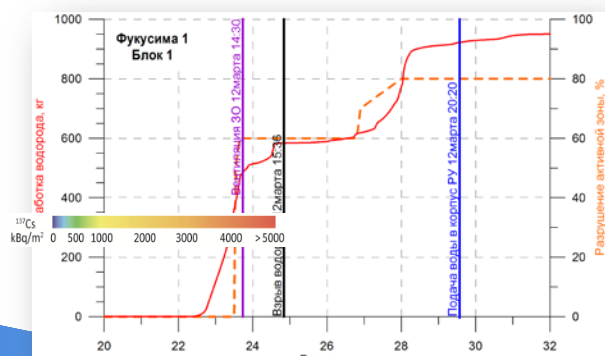
Less than for one day:

- **Initial data for reactor installation at Fukushima-1 NPP (BWR) were prepared.**
- **Time and quantity of the generated hydrogen were estimated, and the forecast on dynamics of accident evolution was given.**
- **Fission product releases were estimated.**
- **Initial data were prepared and atmospheric transport was modelled.**

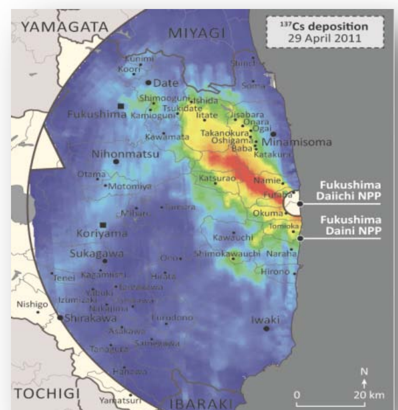
| Unit | Activity of release, Ci | | |
|---|---|---|---|
| | $^{131}$I | $^{134}$Cs | $^{137}$Cs |
| 1 | $1.68\cdot10^{7}$ (release in 31.2 hours) | $0.5\cdot10^{7}$ (release in 35.5 hours) | $0.35\cdot10^{7}$ (release in 35.5 hours) |
| 2 | $0.47\cdot10^{8}$ (release in 77.3 hours) | $2.24\cdot10^{7}$ (release in 84 hours) | $1.3\cdot10^{7}$ (release in 84 hours) |
| 3 | $0.27\cdot10^{8}$ (release in 60 hours) | $1.14\cdot10^{7}$ (release in 62.4 hours) | $0.65\cdot10^{7}$ (release in 62.4 hours) |

**Assessment of hydrogen explosion times at NPP Fukushima-1**

| Unit | Calculated time of explosion | Real time of explosion |
|---|---|---|
| Unit 1 | 12.03 15:16 | 12.03 15:36 |
| Unit 2 | 15.03 05:45 | 15.03 06:14 |




**Assessment of Cs-137 fallout density**




Data of MEXT radiation survey, Japan (2011), Maximum - 15.5 MBq/m²

IBRAE modelling (2011), Maximum – 70.0 MBq/m²

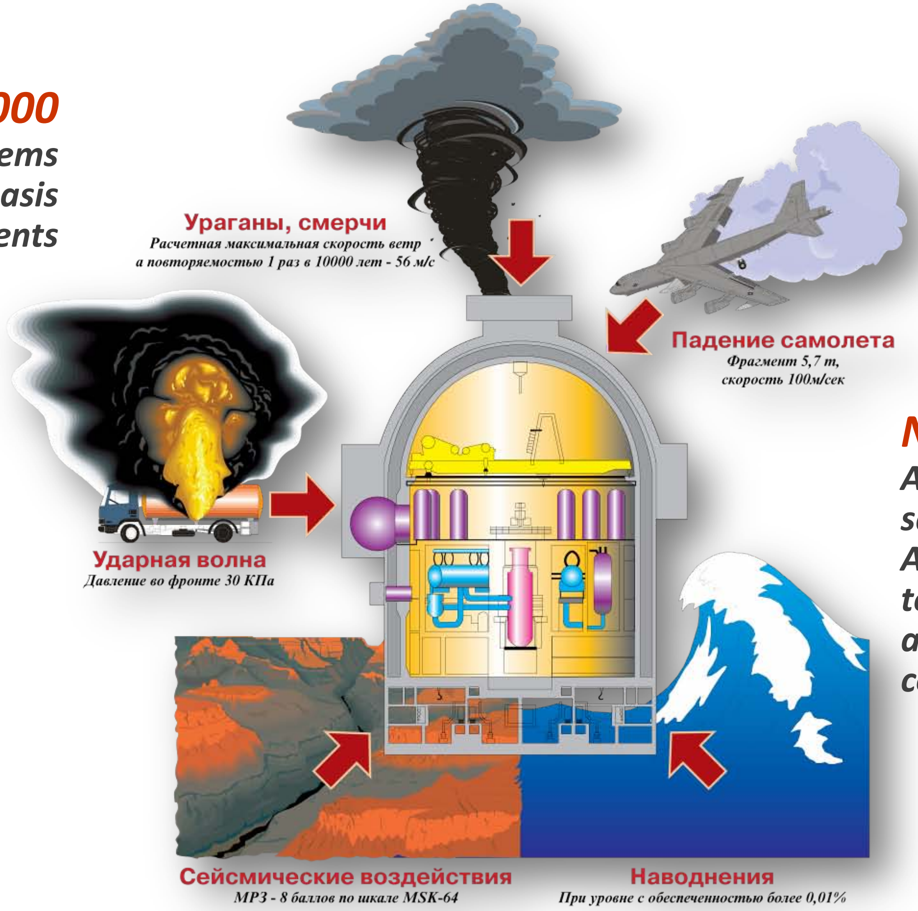
# Fukushima: general lessons

- Confirmation of main safety principles,  deterministic approach.
- New class of accidents - extreme impacts caused by natural cataclysms and/or other external events followed by failure of all or nearly all safety systems.
- Multiple accidents occurring simultaneously at several units.
- Contradiction between the modern level of severe accident science and readiness of personnel to analize and operate in severe accident conditions.

# Provision of the modern level of safety, assessment of external impacts

***NPP with VVER-1000***

*Application of safety systems to overcome the design-basis accidents*




***NPP-2006 (VVER-1200)***

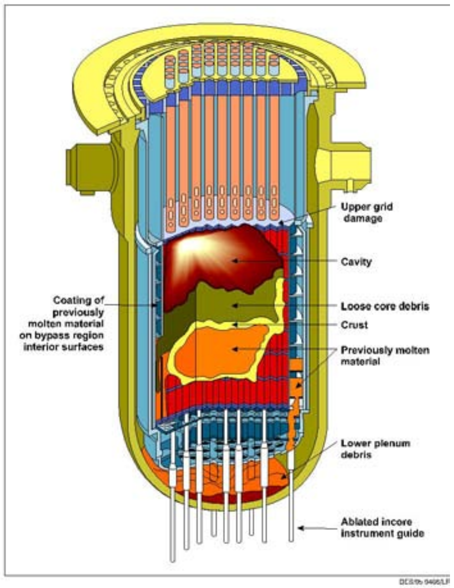
*Application of passive elements in safety systems.*
*Application of management system to control beyond-design basis accidents – second containment, core catcher*

| 3 км ← | Радиус санитарной зоны | → 0,8 км |
|---|---|---|
| 25 км ← | Радиус зоны послеаварийных мероприятий | → 3 км |

# Challenges

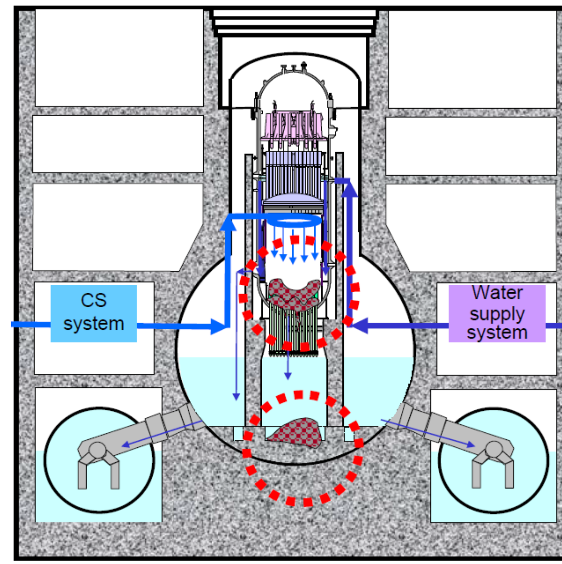
- Provision of integrity of the main circulation loop at design and beyond-design-basis accidents.
- Maintenance of integrity of containment as the last safety barrier and long-term residual heat removal at severe accidents:
  - Hydrogen safety;
  - Corium in-vessel retention;
  - Core catcher.
- Emergency preparedness and mitigation of radiation consequences.

# TMI – Chernobyl – Fukushima




**TMI – accident prevention due to in-vessel localization**

**4 Unit of ChNPP– solidified fuel-containing substance from steam-relief valve**

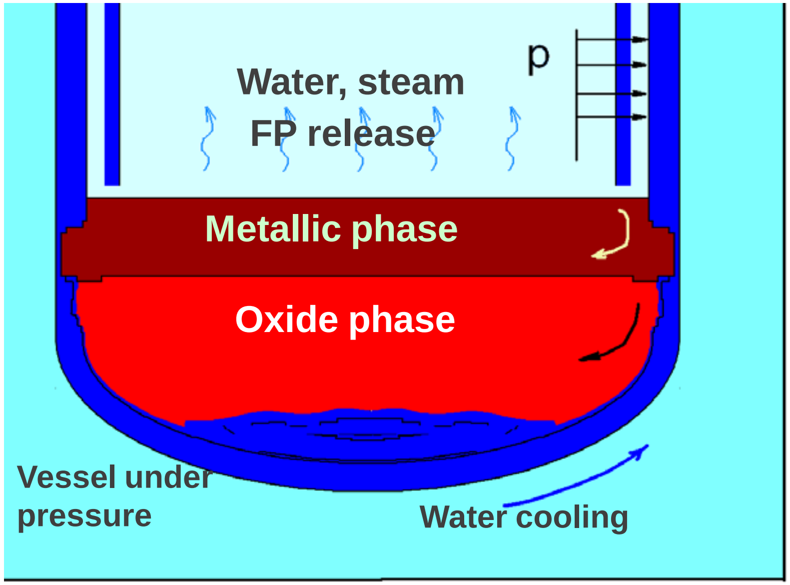



**Fukushima 1–3 – estimated configuration of fuel-containing substance**

# Corium retention in VVER/LWR vessel (1)

- Mechanisms of a heat transfer from melt to the reactor vessel (or catcher) due to convection and heat conductivity
- Physical and chemical processes in complex multicomponent melts (basic components - $UO_2$, $ZrO_2$, Zr, SS)
- Focusing of thermal flow due to separation of phases
- Heat-removal to surrounding water
- Mechanical behavior of bottom in the conditions of non-uniform heat loads
- Heave metallic phase is at the bottom

Classic picture, Theophanous




Upon results of the OECD Project RASPLAV-MASKA

# Corium retention in VVER/LWR vessel (2)

<u>**Low capacity NPP:**</u>

**Is possible and implemented in technical designs for VVER-440 abroad - NPP Loviisa (Finland), Paks (Hungary), Dukovany (Czechia), Mochovce (Slovakia).**

<u>**Average capacity NPP:**</u>

**Is proved for projects AP-600, VVER-600, VVER-640.**

<u>**Large capacity NPP (above 1000 MW):**</u>

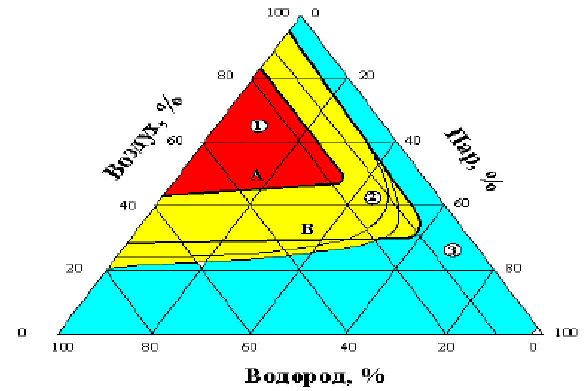
**Additional studies of retention possibility are necessary for scenarios with core melting in 72 hours.**

# Hydrogen safety

- **During a severe accident at NPP with pressurized water reactor installation, a large amount of hydrogen is released.**
- **There are the physical reasons assisting the formation of local areas of combustible and detonation mixes (stratification).**
- **There are the mechanisms destroying the concentration and temperature stratification.**

**Диаграмма Шапиро-Моффети**

- Процесс дефлаграции возможен при концентрациях $H_2$ 4-80 %, воздуха ≥ 20 % и водяного пара не более 60 %.
- Детонация возможна при концентрациях $H_2$ 20-55%, воздуха ≥ 35% и водяного пара ≤ 33%.




**Треугольная диаграмма Шапиро - Мофетти**

**А-область детонации**
**В-область дефлаграции**

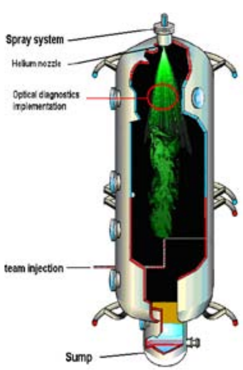
# Causes of formation and degradation of local heterogeneities

- Forces of flotage caused by the lowered density of steam and hydrogen (concentration and temperature stratification);
- Steam condensation - displaces composition of gas mix (air-steam-hydrogen) towards dangerous modes due to:
  - Operation of condensers-heat exchangers in containment (VVER-1200 and  KLT-40S);
  - Steam condensation on surfaces of walls and internal construction elements;
  - Steam condensation at water sprinkling in containment ;
- Passive catalytic  recombiners reducing amount of hydrogen in containment;
- Formation of convective flows caused, in particular, by:
  - Difference in temperatures of gas and construction elements (natural convection);
  - Gas cooling at condensers-heat exchangers operation (natural convection);
  - Injection of sprinkler solution (entrainment of gas by droplets – forced convection);
  - Injection of steam jet with elevated speed.

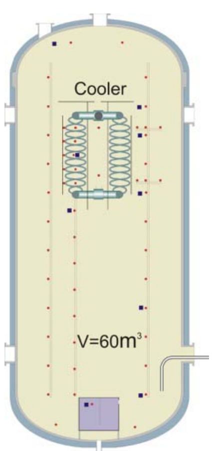
# Experimental projects ERCOSAM-SAMARA

- 5 installations of various  scale (16 tests);
- unified scenario for tests;
- interconnected initial and boundary conditions;
- 3 safety systems (sprinkler, STEAM, cooler);

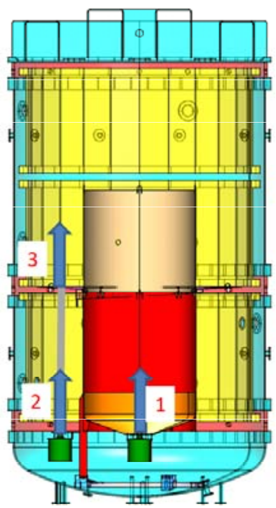
- Impact of scale factor;
- Effect of complex geometry.



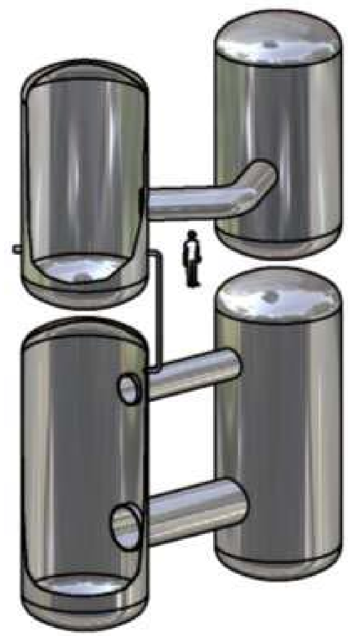

3 tests at TOSQAN (FR),  7m$^3$



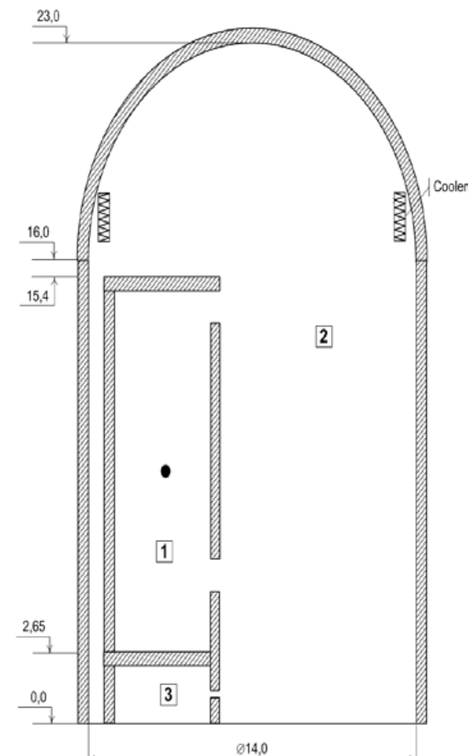

2 tests at SPOT (RU), 60m$^3$




4 tests at MISTRA (FR), 100м$^3$

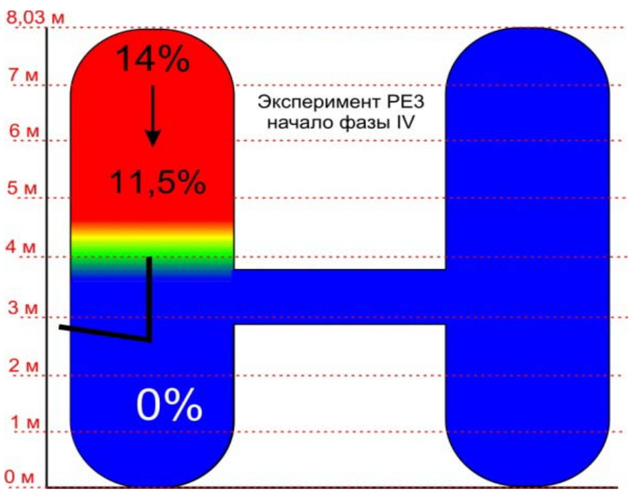


5 tests at PANDA (CH), 2x90 m$^3$

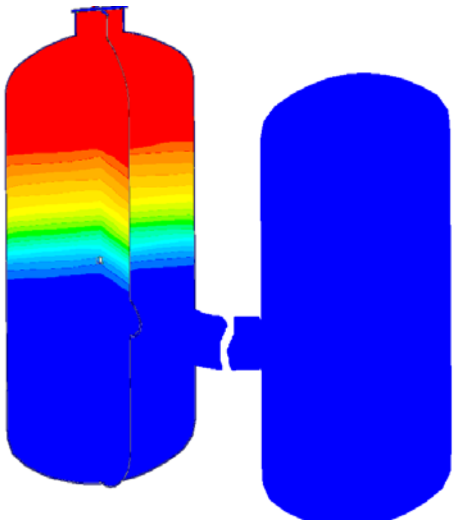



2 benchmarks  at conceptual HYMIX (RU), 3181 m$^3$

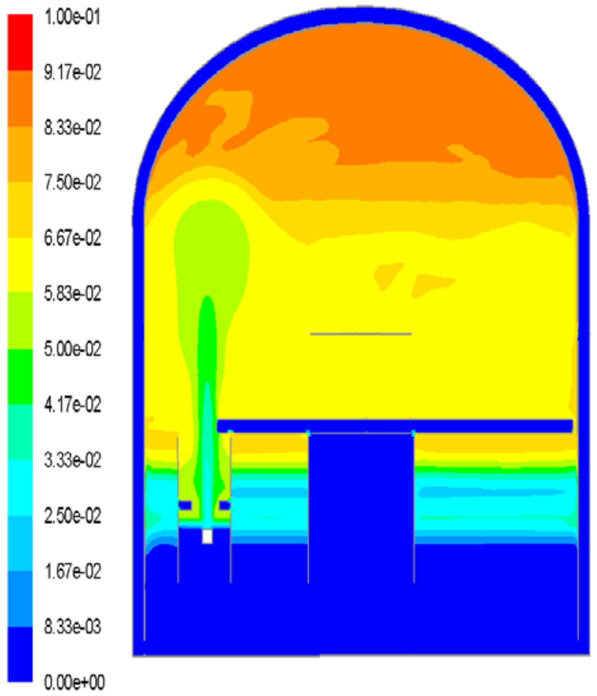
# Accumulation of hydrogen in the phase of core degradation




Low-scale experiment PE3 at PANDA



Calculation of the experiment using a CFD model



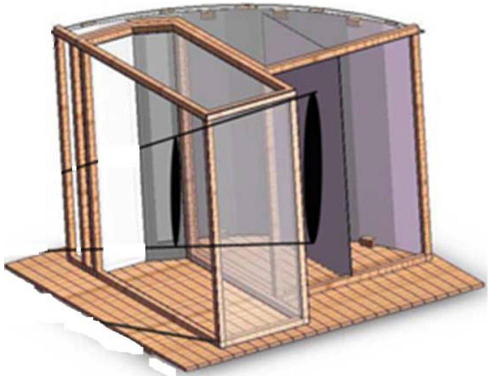

Calculation of real facility using a CFD model

# Calculation and experimental program of hydrogen propagation and combustion

## REA Concern, MosAEP, VNIIT, IBRAE RAN, SRC "KI"

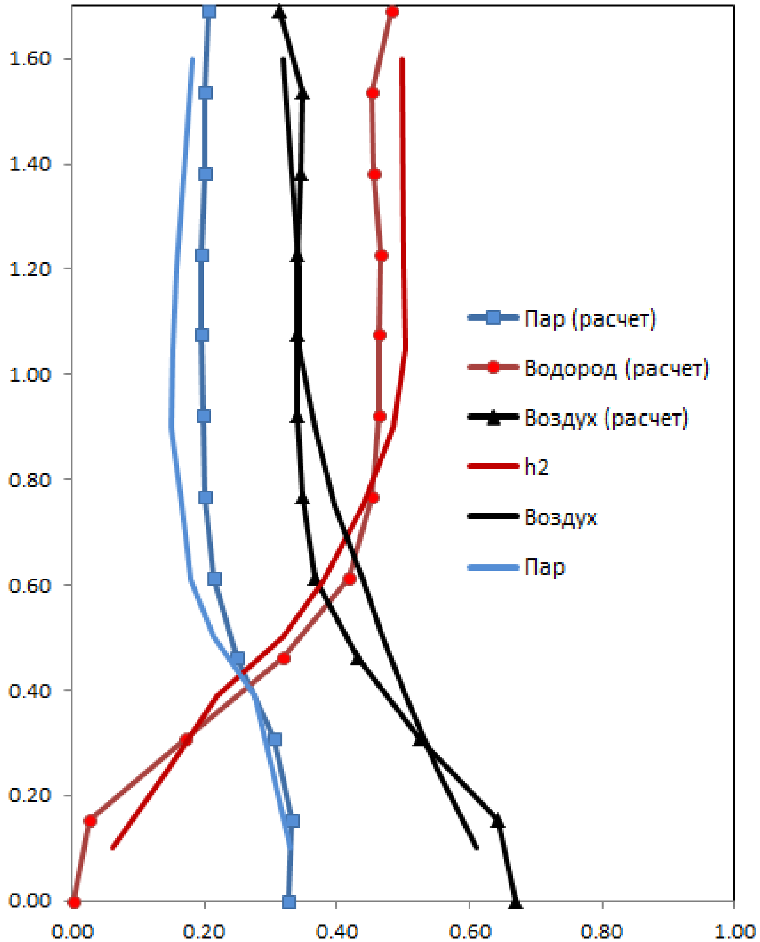
1. Local tests on combustion limits:
   at installation KEIP (sphere) – 419;
   at installation MUT (shock tube) - 79

2. Integral tests on propagation and combustion of hydrogen-steam-gas (light construction elements ) - 18



3. Integral tests on propagation and combustion of hydrogen-steam-gas (durable construction elements ) - 15

**Calculation of experiment BM-L3-2 (without PG mock-up) using CABARET code**




Change of mole [m] parts along height at the moment of the end of experiment

# Conclusion

- Importance of the deterministic approach in the safety concept - expansion of list of beyond-design-basis and severe accidents, lists of initial events taking into account technical failures, human factor, possible natural and technogenic accidents.
- Preservation of level of the competence in the severe accident area: decrease of level of works on NPP safety enhancement is inadmissible.
  - Maintenance at the due level of works and competences in the field of safety and severe accidents.
  - Maintenance at the due level of works and competences in the field of emergency response and emergency preparedness
  - Participation in international projects.