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Институт проблем безопасного развития атомной энергетики

RUSSIAN ACADEMY OF SCIENCES
Nuclear Safety Institute (IBRAE)

# Corium debris configurations in course of accident

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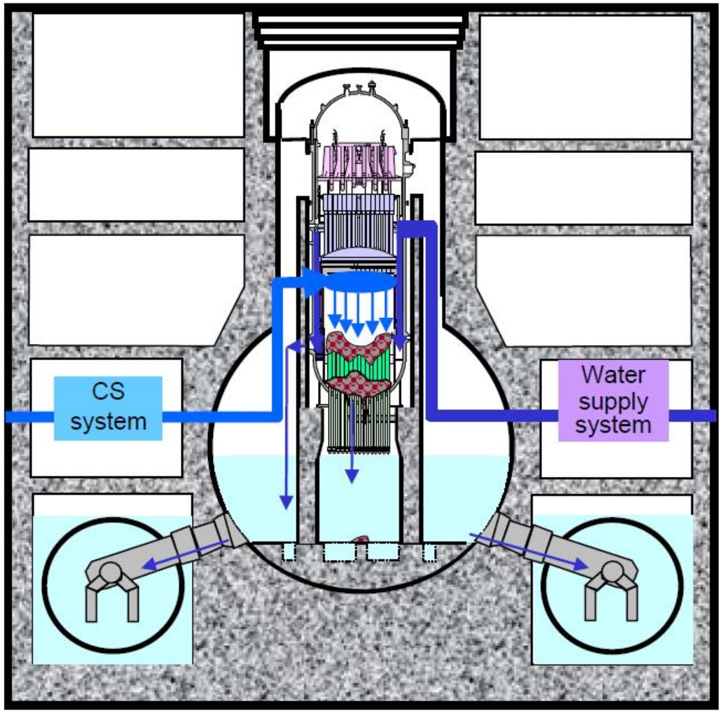
# Presentation outline

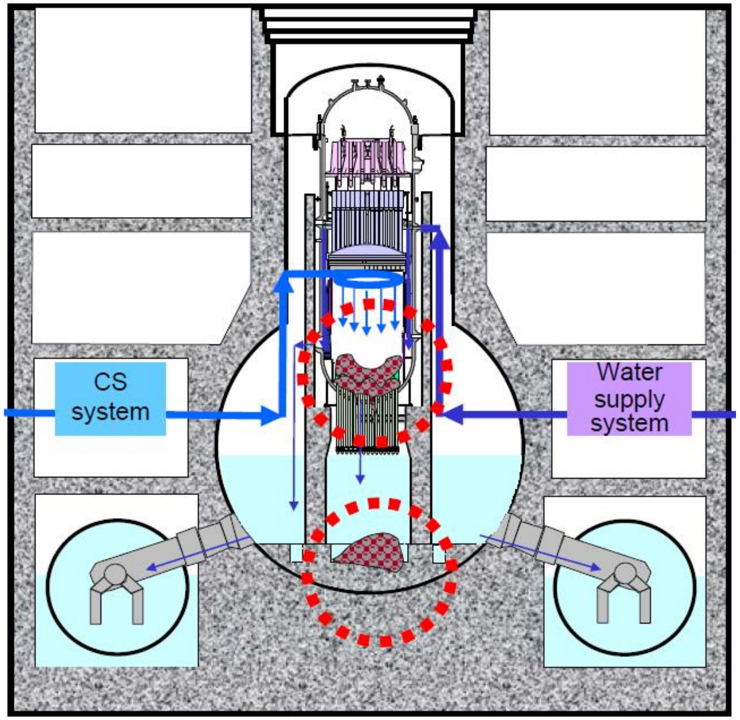
- Results of BSAF Project on corium location in the containment
- Configurations of molten materials in the reactor pressure vessel based on the results of OECD/NEA RASPLAV-MASCA Project
- Nuclear fuel behavior modeling during active phase of the Chernobyl accident (Results of ISTC-2916 Project)
  - Results of investigations lava-like Fuel Containing Masses (LFCM)
  - Modeling of formation, spreading and cooling of LFCM

# Corium debris stabilization in course of accident

**In-vessel:**
- TMI-2
- Fukushima unit 2 (?)




**Ex-vessel:**
- Chernobyl-4
- Fukushima units 1 and 3




"Reactor core conditions of unit 1 – 3 of Fukushima Daiichi Nuclear Power Station" (Nov.30, 2011)
"Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression" (Aug 6, 2014)
BSAF Project Summary Report (June 2015)

# Significant issues

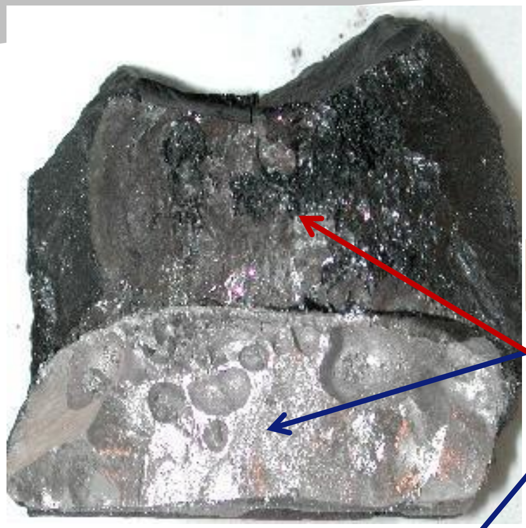
In-vessel:

- Debris composition: $UO_2$-Zr-$ZrO_2$-SS
- Melt configurations: Depends upon composition
- Chemical Interactions: OECD RASPLAV-MASCA Project
- Fission products partitioning between phases

Ex-vessel:

- Debris composition: $UO_2$-$ZrO_2$-FeO-CC
- Melt configurations: Usually metal phase below oxides
- MCCI: Extensive experimental database (USA, Germany)
- Fission products release
- Spreading of molten materials (France, Chernobyl accident)

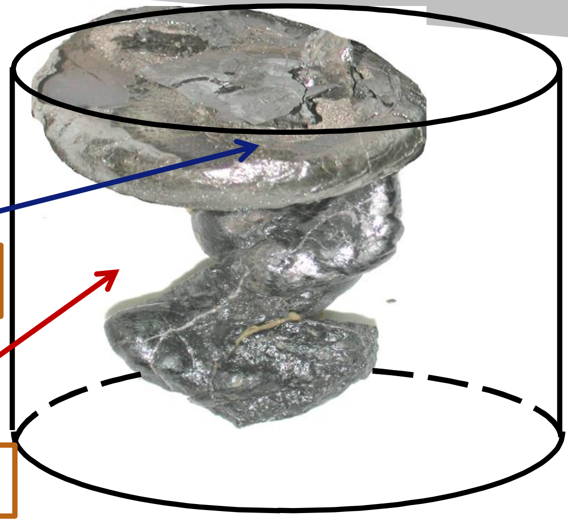
# Possible melt configurations in the reactor pressure vessel



Metal phase

Oxide phase

Test MA-3



Test MA-2 (reconstruction)

Test MA-6

Three possible configurations of molten materials in the lower head

- Top left – Low zirconium oxidation degree, small amount of steel (30 – 40%)
- Top right – High zirconium oxidation degree (>70%)
- Left down – Large amount of steel, high Zr oxidation degree

# Melt in the reactor pressure vessel

- Goals of OECD RASPLAV-MASCA Project
  - Material interactions at high temperatures (U-Zr-O-Fe)
  - Conditions for pool stratifications (U/Zr ratio, degree of oxidation)
  - U-Zr-O-Fe(SS)+Oxidation atmosphere (steam/air)
- Assessments of corium debris for Fukushima Daiichi Unit 1 in the RPV:
  - Zirconium oxidation degree about 50%
  - U to Zr ratio 0,8
  - Mass ratio of steel in the melt: 0,3
- This parameters indicate that most probably the classic configuration of phases (metal layer atop of oxides) will be observed

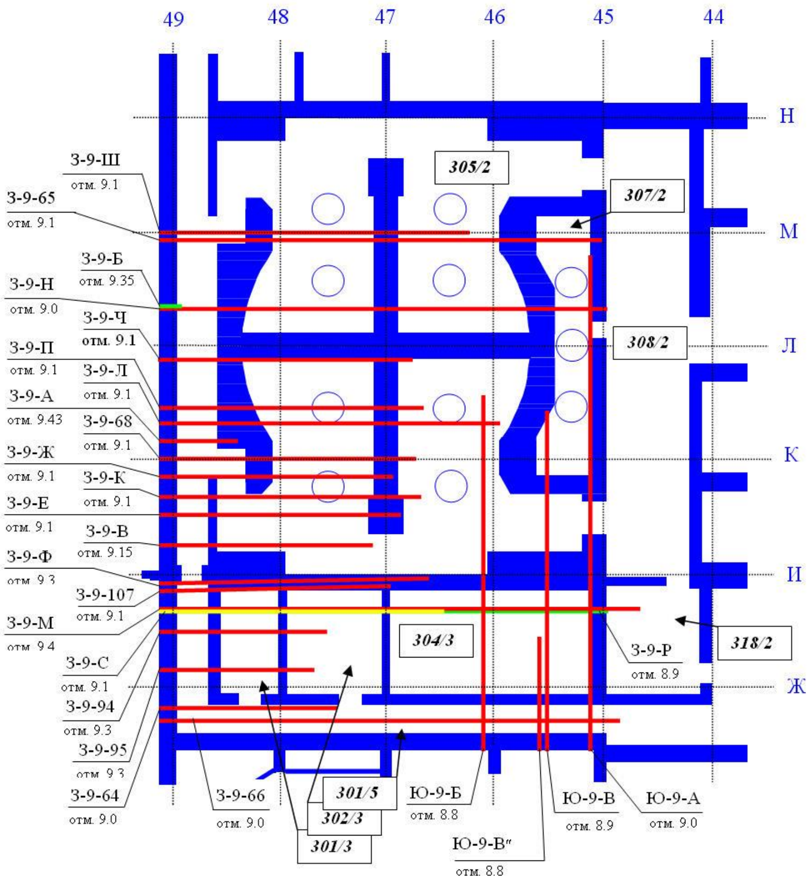
# Accident initiation

- April 26, 1986 reactor shut down was planned for maintanance purposes
- The test of was planned on electric power supply due to turbine rundown
- Some safety systems were turned off
- Due to different reasons reactor operated with the violation of requirements for save operation
- Operation at small power and reactor shut down by emergency protection rods lead to introduction of positive reactivity
- All these reasons lead to the positive reactivity and reactor explosion

# Stages of Fuel Investigations

- 1986 – 87: Study of contaminated areas
  - Study of fallouts
  - More than 95% of fuel was located inside the Shelter
- 1988 – 92: Investigations in the Shelter
  - Observations of lava-like fuel containing masses (LFCM)
  - Drilling of boreholes and data accumulation of
- 1991 – 95: Extensive analysis of samples
  - Methods for LFCM mass assessments
  - Chemical analysis and generalization of data
- 2005 – 2007: ISTC-2916 Project
  - Systematic data analyses
  - Development of the model for molten fuel behavior and interactions

# Molten core concrete interaction

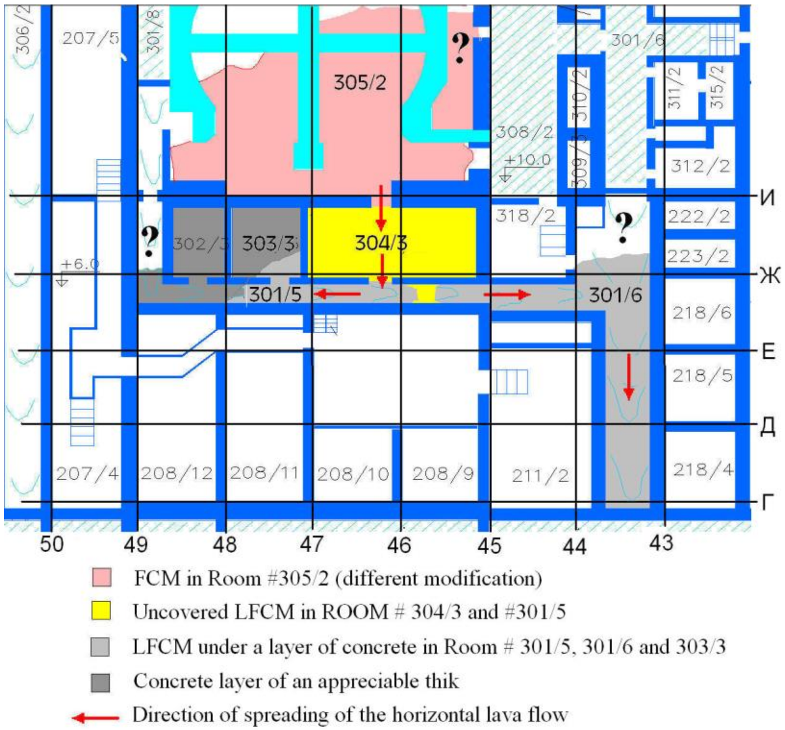



Sources of data:

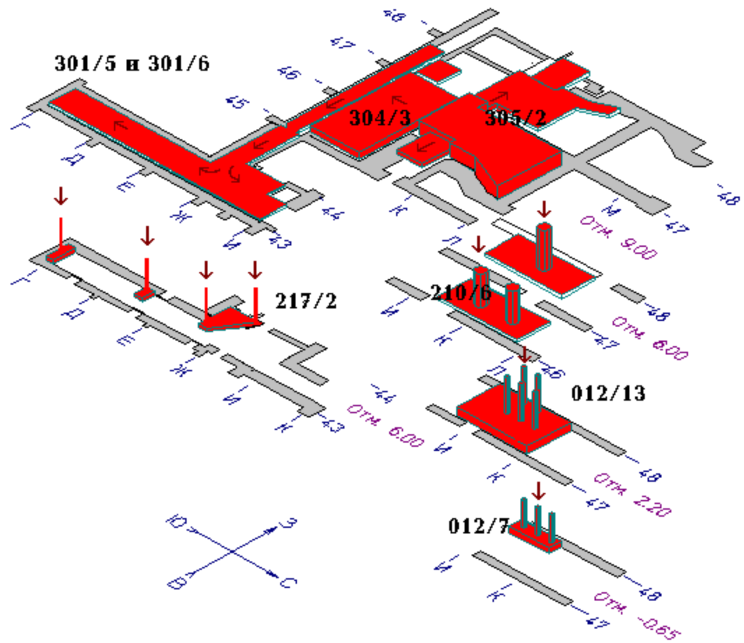
- Visual and remote observations
- Bore holes data obtained in 1988 – 1992
  - level of about 9m: 25 holes
  - level of about 10 m: 10 holes
  - level of about 11 m: 8 holes

# Main streams of LFCM

Horizontal flow

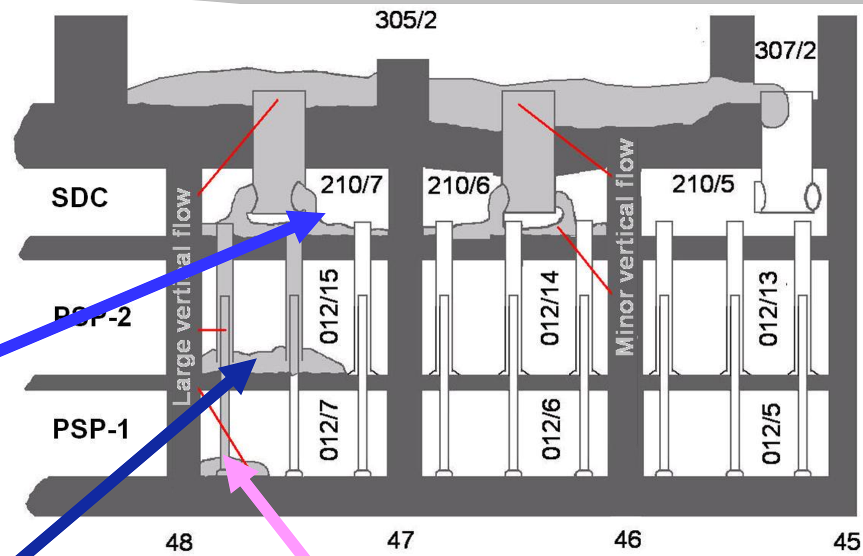



Vertical flow

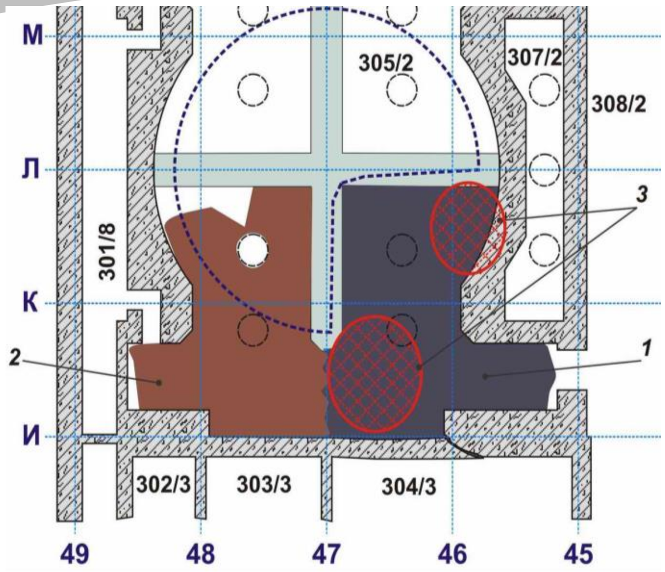



- Initial melt was formed in the south-eastern part of the reactor after interaction with the serpentine filling of the “OR” scheme
- Spreading of the melt was in horizontal (through the breach through the wall between rooms 305/2 and 304/3)
- Spreading in the vertical directions (through the steam outlet valves of the accident localization system)
- Interaction with the concrete

# Visual observations of LFCM



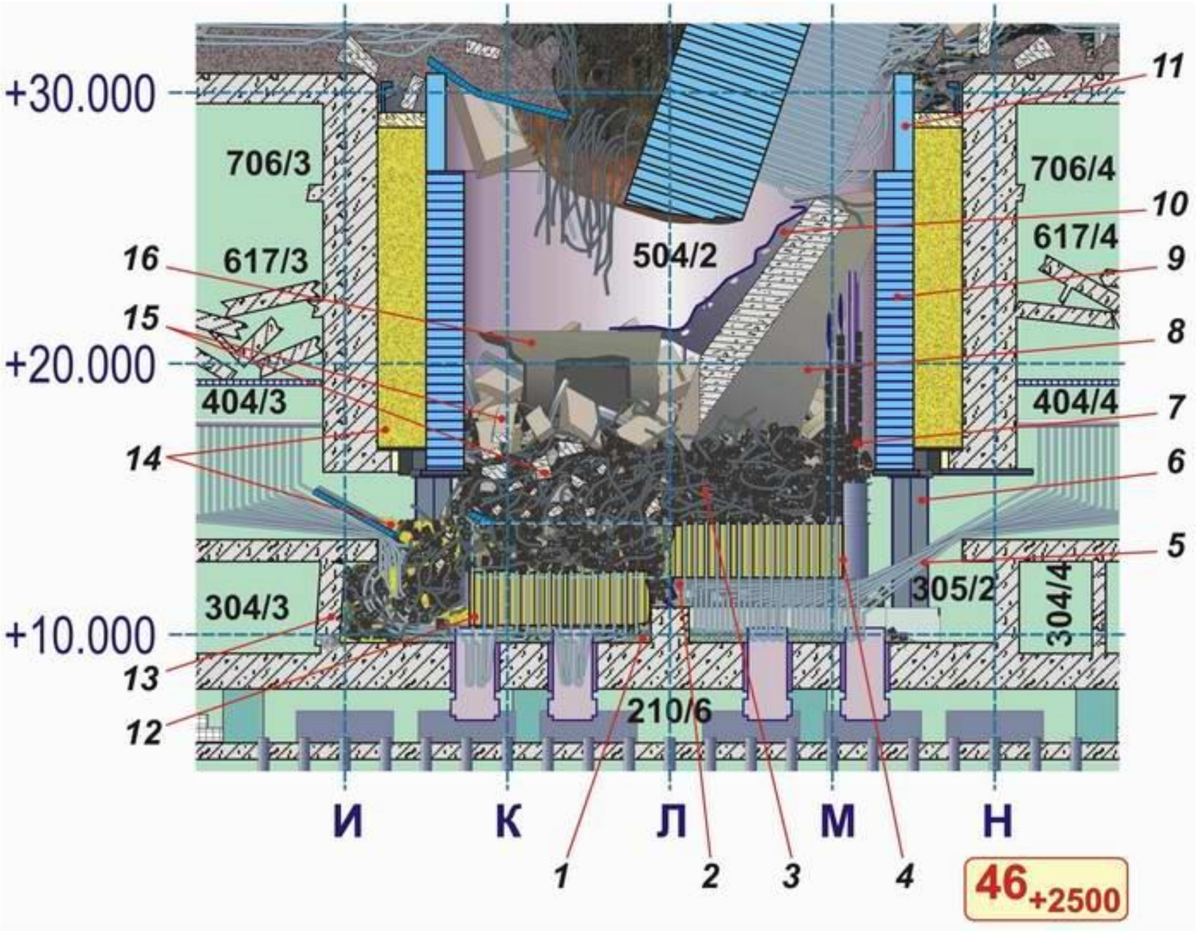

# LFCM Source – under reactor room




- *1 – Dominantly black ceramic*
- *2 – Dominantly brown ceramic*
- *3 – LFCM with high fuel concentration*

| | Black ceramics | Brown ceramics | Slag like from PSP | “Pumice” |
|---|---|---|---|---|
| U | 4.7±1.1 | 8.4±0.2 | 8.3±0.2 | 8.3±1.0 |
| Zr | 3.2±1.2 | 4.8±1.1 | 4.5±1.4 | 3.3±0.5 |
| Mg | 2.4±0.8 | 4.0±0.9 | 6.2±2.2 | 4.6±0.4 |
| Si | 29.8 ±4.8 | 30.9±3.6 | 32.3±2.8 | 36.6±0.5 |
| Ca | 5.5 ±2.0 | 4.7 ±0.8 | 4.0 ±1.1 | 4.8 ±0.6 |
| Al | 4.8 ±1.3 | 3.5 ±0.7 | 3.4 ±1.4 | 2.8 ±0.4 |
| Na | 4.2 ±0.7 | 4.0 ±0.4 | 1.5 ±0.5 | 1.4 ±0.2 |

# Reconstruction of initial data for LFCM generation




*1 - Serpentinite of the "OR" component and the inter-compensatory gap*

*2 - Crushed "C" component ("Cross")*

*3 - Fuel, fuel assemblies, fuel elements, process channels, graphite blocks, fragmented concrete*

*4 - ¾ OR*

*5 - BWC tubes*

*6 - Additional support*

*7 - Reflector (channels and graphite blocks)*

*8 - Reinforced-concrete plate (fragments of wall of separator box)*

*9 - "L" tank*

*10 - Heat shielding lining of separator box's wall*

*11 - "D" tank*

*12 - ¼ OR*

*13 - Damaged wall*

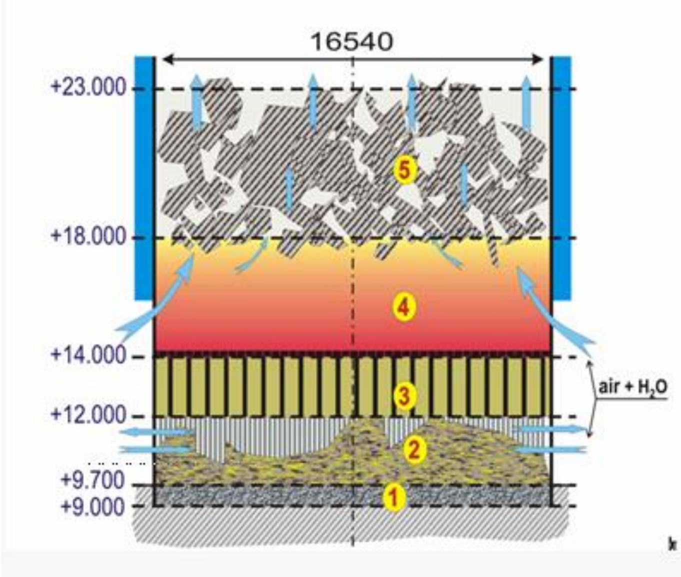
*14 - Vault's filling-up-origin sand*

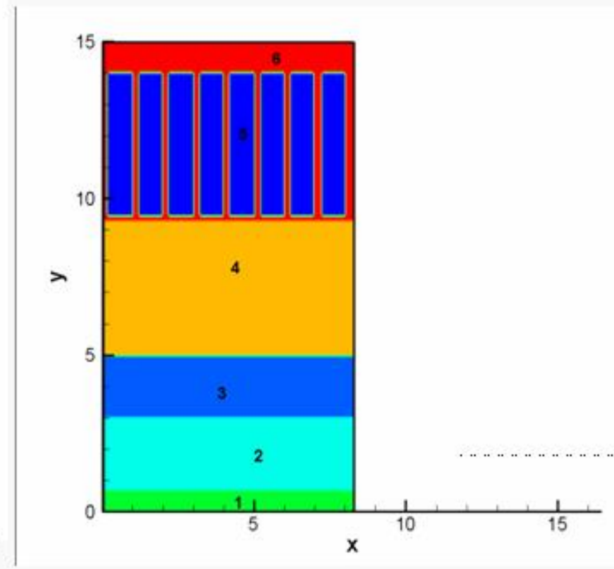
*15 - Debris of reinforced-concrete constructions*

*16 - Fragment of reinforced-concrete construction*

# Computational model (Pancake model)

1. Basemate concrete
2. Under reactor structures (Steel, sand)
3. "OR" Scheme (steel, serpentine)
4. Fuel containing masses (zirconium, steel, graphite, etc.)
5. Materials from upper structures (concrete, materials dropped into the reactor wreck)

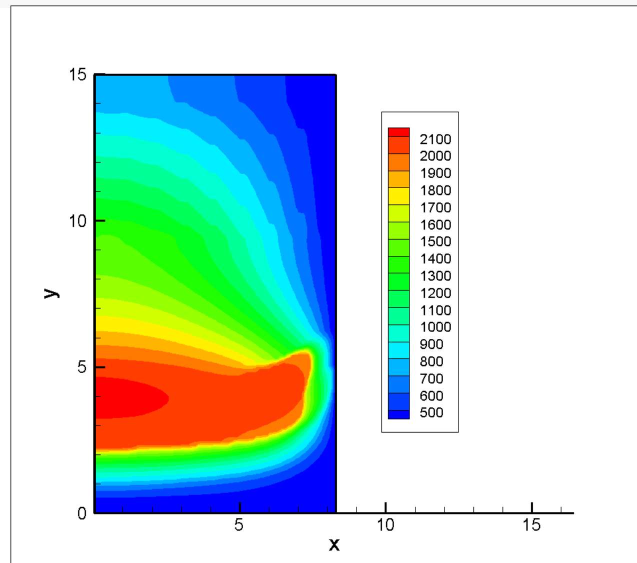


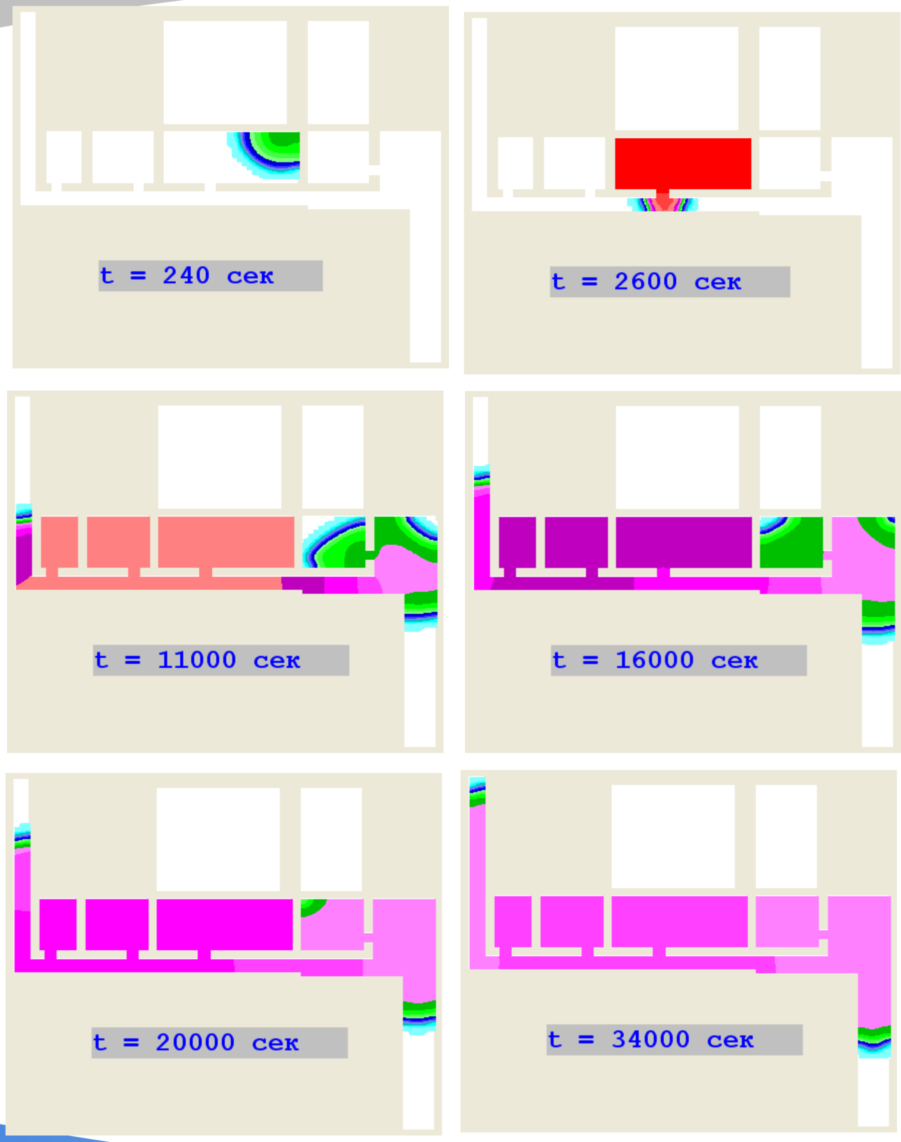

Initial data:
- 3D geometry of rooms
- Varied temperature (Base case 1400 K)
- Assume two layers: black ceramics atop

Model includes
- Advection of the melt
- Radiation from melt top surface
- Heat conductivity
- Temperature dependence of viscosity
- Melt source in the room 305/2

Characteristic time for graphite burning and melting through of reactor basemate was assessed (between 7 to 10 days)



# Spreading

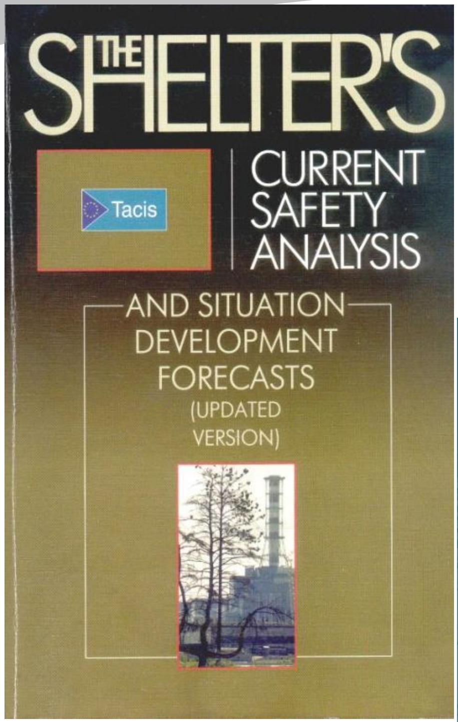



- Through wall break between 305 and 304 rooms (0.5 m)
- Melt flow rate through the wall break
  - Total volume of LFCM: 170 – 200 $m^3$ (Mass of  460 – 540 tons)
  - Mass source varied: 25 – 80 kg/s
  - Duration varied: 6000 – 20000 s
- Temperature: 1400 K

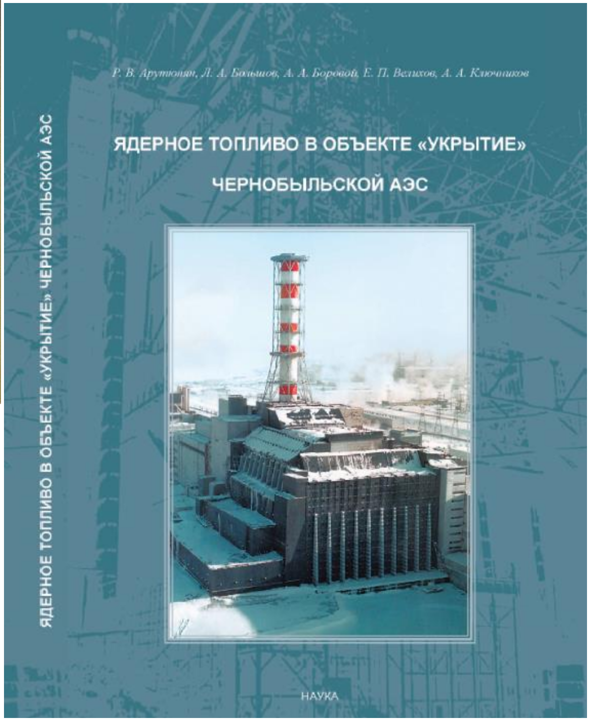
# Summary

- OECD RASPLAV-MASCA Project results demonstrate possible melt configuration in the reactor pressure vessel
- Chernobyl lava location demonstrates high corium flow-ability and long distances for spreading even for small uranium content
- There is significant differences in the geometry and  configuration of debris and its locations between Chernobyl and Fukushima
  - Fukushima has more difficulties in terms of the accessibility
  - Urania content of Fukushima corium seems to be higher
- Molten materials may spread up to PCV walls due to high corium flow-ability

# References




Detailed information on characteristics of Chernobyl fuel containing materials such as physical and chemical properties, structure, and other issues can be found in references:





- E.Anderson, B.Burakov, E.Pazukhin, Secondary variations of fuel containing masses (FCM) of 4-th Chernobyl NPP unit, Radiochemistry, 34, pp. 135-138, 1992 (In Russian).
- Object “Shelter” – 10 years. Main results of studies (In Russian) Chernobyl, 1996
- R. V. Arutyunyan, L. A. Bolshov, A. A. Borovoi, E. P. Velikhov, A. A. Klyuchnikov. Nuclear Fuel in the «Shelter» encasement of the Chernobyl NPP, 2010. Moscow, Nauka.