ÚJV Řež, a. s.

Research Needs for Improvement of Severe Accident Management Strategies at Czech NPPs

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International Experts' Meeting on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

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Outline

- Background
- Research Needs - Phenomenology
- Application to NPP SAM Program
- Specific Needs from SAM Application at Czech NPPs
- Conclusions

Background

- **ÚJV Řež provides complex services in the areas connected to severe accident management to Czech NPPs owned and operated by ČEZ a.s.**
  - Evaluation of source term
  - Accident progression
  - Identification of severe accident management strategies
    - Supporting analyses for optimization
  - Validation of existing SAMGs
  - Supporting analyses for
    - Control room habitability
  - Development of layout of hydrogen mitigation system

- **Regimes during initiating event covered in SA analyses**
  - Operation at nominal power
  - Reactor outage
    - Non-leaktight RPV
    - Open reactor head
  - Spent fuel pool accidents

List of Examples – Background

- **Participant in SARNET and SARNET-II projects (recently in NUGENIA)**
  - WP5, WP6, WP7 and contribution to WP8.3 benchmark of SARNET-II
- **Participant in OECD Projects and activities (ISP, CAPS)**
  - THAI, THAI2, STEM, MCCI, MCCI2, SFP, OLHF, RASPLAV, MASCA and others
- **Many contributions to CSARP/MCAP meetings, NURETH, NUTHOS or other conferences**
- **JRC Petten organized benchmark on IVR strategy for VVER-1000/320**
  - MELCOR calculations of whole plant response (2013-2014)
- **Analytical support of PAR Layout for Temelin NPP**
  - Subcontractor of Westinghouse Electric Germany (2013-2014)
- **Validation of SAMGs for Temelin NPP**
  - Set of projects in period of 2005-2012
  - To be updated in upcoming period after implementation of post-Fukushima measures
- **Strategies for long containment integrity control at Temelin NPP**
  - Project for utility in period 2013-2014
  - Corium stabilization and containment condition control issues
- **Analyses of severe accident progression initiated in SFP at Temelin NPP**
  - Project for utility in period 2012-2013
- **Identification of conditions for entry to SAMG in shutdown modes or for SA in SFP**
  - Initiating phase for methodology development and first set of cases analyzed in 2014
  - Objective – to correlate dose rate in location of measurement to core degradation progression and “core exit” temperature

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Research Needs - Phenomenology

- **SARNET-2 project – SARP group**
  - Identification of research priorities and their ranking
    - W. Klein-Hessling et al.: Conclusions on SA Research Priorities, ERMSAR-2013, Avignon, October 2-4, 2013
      - Updated revision with impact of Fukushima Daiichi event
- **NUGENIA – Technical Area 2: Severe Accident**
  - Roadmap prepared based on conclusions of SARNET2 SARP
    http://s538600174.onlinehome.fr/nugenia/nugenia-roadmap-released-and-available-online/
  - Seven technical sub-areas
    - In-vessel corium/debris coolability
    - Ex-vessel corium interactions and coolability Containment behavior, including hydrogen explosion risk
    - Source term
    - Impact of severe accidents on environment
    - Severe accident scenarios
    - Emergency preparedness and response

Research Needs - Phenomenology

- **Technical Sub-Areas of TA2: Severe Accident**
  - In-vessel corium/debris coolability
    - Debris bed refooding, PEARL experiments, IVR strategy (corium, CHF)
  - Ex-vessel corium interactions and coolability
    - Stratified steam explosion, corium coolability during MCCI
  - Containment behavior, including hydrogen explosion risk
    - Atm. mixing, impact of mitigation measures – PAR
  - Source term
    - Filtered venting, FP release, transport and retention (chemistry of FP)
  - Impact of severe accidents on environment
    - Atmospheric dispersion models
  - Severe accident scenarios
    - Development of ASTEC code, evaluation of SAM measures, extensive validation
  - Emergency preparedness and response
    - Fast running tool on source term evaluation

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Applications to NPP SAM Program

- **Transfer of existing knowledge in SA phenomenology to plant applications is limited**
  - Knowledge gaps
  - Assumptions in experimental research
  - Assumptions in code developments
- **Application of recent knowledge (data, computer codes) to SAM development identified extensive set of needs in various areas**
  - Material properties
  - Reduction of loads
  - Reduction of uncertainties
  - Computer codes limitations
  - Design specific solutions

Applications to NPP SAM Program
Material Properties

- **Key feature of event progression into severe accident is fuel overheating**
  - Many SA phenomena are related with very high temperature and radioactive conditions ⇨ determination of
    - Conditions of experimental research (non-irradiated vs. irradiated samples)
    - Limitations of experimental conditions (temperature limits)
    - Measurement capabilities
    - Expenses of research activities
- **Recent material property DB covers practically all basic materials, but**
  - Only generic (or one representative) material is usually known
  - Industry does not open data to research community
  - Corium properties – implementation of newly applied material (ATF …)
    - More complex compositions – usually binary and ternary phase diagrams exist

Applications to NPP SAM Program
Material Properties

- **Only generic (or one representative) material is usually known**
  - Cladding oxidation
    - Extensive research done for Zry-4
      - KIT Karlsruhe significantly contributed in closure of this gap, but limited access to material samples and always delay in comparison with industry
  - Creep conditions of lower head
    - Full temperature range only for US steel SA533B1, but for carbon steel at VVER reactor data available only below 1000 K
  - Material interactions
    - Corium to lower head interaction
      - ISTC Projects METCOR and THOMAS (M.Veschunov et al.: Preliminary results of ISTC Project #3876 (THOMAS) (<u>T</u>hermal <u>H</u>ydraulics of <u>O</u>xidizing <u>M</u>elt in <u>S</u>evere (⇔) <u>A</u>ccidents) on physico-chemical interactions of molten corium with vessel walls under oxidizing conditions, 17th International QUENCH Workshop, Karlsruhe Institute of Technology, November 22-24, 2011)
      - Impact of corium convection, heat flux on steel oxidation

Applications to NPP SAM Program
Reduction of loads

- **Some SA phenomena results forming of risk conditions**
  - Cladding oxidation resulting in hydrogen generation ⇨ risk of H_2 deflagration or detonation ⇨ threat of containment integrity
  - MCCI results in non-condensable generation (H_2, CO, CO_2) ⇨ over-pressurization of containment ⇨ threat of containment integrity
  - HPME results in DCH ⇨ heat-up and pressurization of containment atmosphere ⇨ threat of containment integrity
  - Melt relocation into water pool ⇨ risk of steam explosion ⇨ threat of containment integrity
- **Many of risks are eliminated or significantly reduced within various SAM strategies**
  - Primary circuit depressurization ⇨ elimination of HPME with DCH
  - Cntn pressure reduction with filtered venting of containment
  - Slow-down of MCCI with reflooding of corium
  - Hydrogen removal system – PAR or igniters or their combination

Applications to NPP SAM Program
Reduction of loads

Can we reduce some other load with new approaches?

- **Development of new cladding materials (advanced cladding materials or accident tolerant fuel) is focused on elimination of hydrogen generation**
  - Specific surface coating or application of new materials
- **Generic question**
  - Is hydrogen the most serious SA threat for NPPs, if they implemented hydrogen removal system dedicated to SA conditions? **Not**
  - The most limiting phase, concerning H_2 issue, is very intensive generation during early phase of core degradation due to
    - Significant impact of positive feed back of exothermic oxidation of Zr based materials
- **Application of new cladding materials has eliminate intensive heat generation during oxidation (exothermic reaction), rather than hydrogen production, because**
  - Endothermic or energetically neutral oxidation (even with H2 generation) will result in lower generated hydrogen mass rate due to absence of positive feedback
  - Impact of hydrogen in containment is solved for higher hydrogen sources

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Applications to NPP SAM Program
Reduction of uncertainties

- **Uncertainties in knowledge of SA phenomena exist, their ranges varying from percent to hundreds of percent case by case**
- **Reduction of uncertainties depends on continuation of experimental programs to fulfill gaps in knowledge or various initial and boundary conditions - Examples**
  - Nitriding of cladding during core degradation in air atmosphere
    - Recent experiments show that even very low concentration of nitrogen in inert atmosphere results in nitride formation ⇦ important in air ingress scenarios or accidents initiated in SFP
    - In case of consequent inlet of oxidizing atmosphere, nitrides are re-oxidized with very fast kinetics and exothermic reaction
  - MCCI – corium as well as concrete compositions strongly influence ablation and coolability
    - Experiments performed for limited number of concrete compositions
      - Siliceous concrete – anisotropic ablation, low intensity of melt eruptions
      - Limestone concrete – isotropic ablation, high intensity of melt eruptions
  - Steam explosion
    - Triggering conditions are very uncertain

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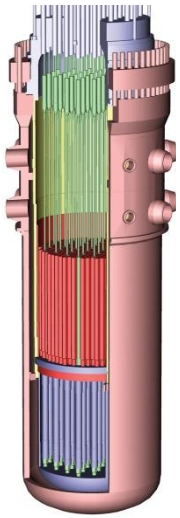
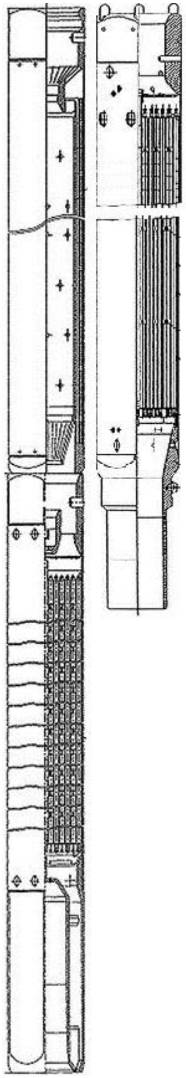
Applications to NPP SAM Program
Computer codes

- **Uncertainties in knowledge penetrate to computer code**
  - Code development is always delayed to experimental knowledge
    - Order of research activities – experimental investigation, collection of experimental data, evaluation of data with development of model, its verification and validation, implementation into system code, validation, and application
  - Three main contributors on side of computer code
    - Physical correlations
    - Governing equations
    - Nodalization
- **New areas for computer code development**
  - Multi-unit accident – only one "core" in existing codes
    - Simultaneous accident of reactor and in SFP
  - Q? Is it possible to modify recent SA codes?

Applications to NPP SAM Program
Computer codes

- **Additional effects contribute to overall uncertainty of analytical results**
  - User effect
    - Knowledge of phenomenology
    - Knowledge of code models and their assumptions
    - User experience in model development (influenced by validation on experiments)
    - Experience sharing – within team or among members of user community and with developers
    - QA procedures
    - Detailed analysis and interpretation of results
  - Model assumptions vs. plant design specificity
    - LWR standard core design vs. VVER-440 core with control assemblies





Is it really user effect?

2 + 2 = 5

Emilio Baglietto, NURETH-10, Dec 2014

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SAM Application at Czech NPPs
Measures Applied or under Preparation

- **Several measures applied with aim to prevent accident progression into SA**
  - Mobile power and water sources (equipment and measurement)
  - Diverse equipment (SBO DG, SG-RCS-SFP water supply)
  - Communication equipment, radiation monitoring
- **Mitigation measures for SA conditions**
  - PAR
  - In-vessel retention
  - Molten corium localization
  - Long term containment heat removal
- **Preparation identified some weak points**

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SAM Application at Czech NPPs
In-Vessel Retention Strategy

- **Application of IVR strategy to VVER-1000 is under investigation**
  - Application to VVER-440/213 decided in CR, Hu, SR, and also in RF
- **Several areas of high uncertainty identified**
  - Corium composition
  - Corium configuration ⇨ heat flux density distribution along RPV
  - Coolant supply into cavity (initial reflooding and long term water supply)
  - Cooling conditions (CHF profile for specific geometry and flow conditions)
  - Residual risks
  - Feasibility and acceptability of proposed solution
- **Many activities initiated**
  - IVR workshop in collaboration with IAEA (July 2013)
  - Benchmark on analytical evaluation of heat flux to RPV (coordinated by JRC IET Petten, 11-2013 to 11-2014)
  - Experimental investigation of coolant impact on surface and surface coolability
  - EC H2020 September 2014 call – IVMR Project (labeled by NUGENIA)

SAM Application at Czech NPPs
IVR – Corium Composition

- **Strategy has cover all accident scenarios – only limited cases calculated**
- **Experimental program (RASPLAV, MASCA, MASCA2) used only few examples of corium composition (based on oxidation ratio of Zr)**
  - Compositions with 100%, 70% and 30% of Zr oxidized
- **MELCOR simulation of LB LOCA with loss of all active ECCs for VVER-1000/320 identified oxidation ratio only 20.5 % Zr oxidized**
  - Historically, the oxidation ratio was understood as part of cladding oxidized, but for SA, and corium composition specifically, total mass of Zr in core has to be evaluated
- **Research needs – more detailed matrix of corium compositions**
  - More cases in range for lower oxidation ratio, no data for the highest
    - case with 100 % of Zr oxidized is theoretical only and can be reached in very specific condition they don't lead to corium formation – Cleaning Tank Accident (Hungary)

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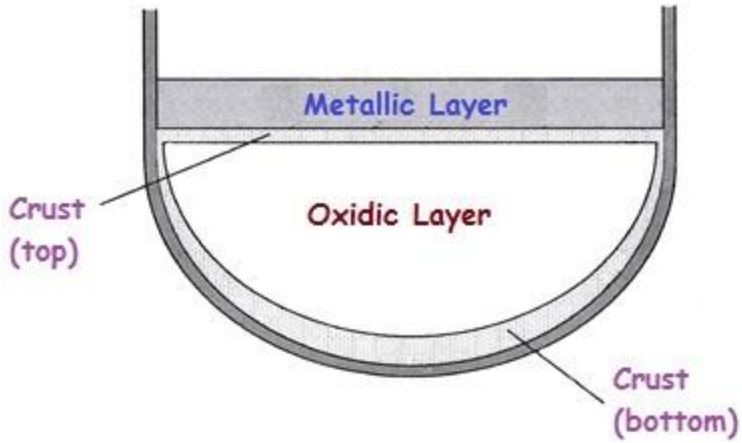
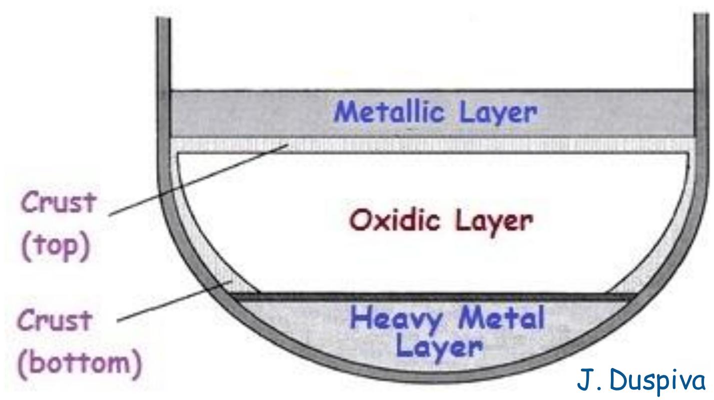
SAM Application at Czech NPPs
IVR – Corium Configuration

- **Decision on applicability of IVR strategy is strongly influenced by interpretation of OECD/MASCA2 project results**
  - Some countries conclude formation of three layer configuration ⇨ thinner upper metallic layer ⇨ intensification of focusing effect (higher maxima of heat flux density in profile)
  - Some countries argue that no formation of lower heavy metal layer occurred
    - Only formation of some local particals with reduced uranium observed ⇦ experiment terminated too early for final conclusion on formation of layer ⇨ continuation in such tests is necessary
- **Impact of core degradation process and corium/debris relocation on melt pool formation**
  - Water in lower head ⇨ cooling and refreezing of relocating debris ⇨ re-melting





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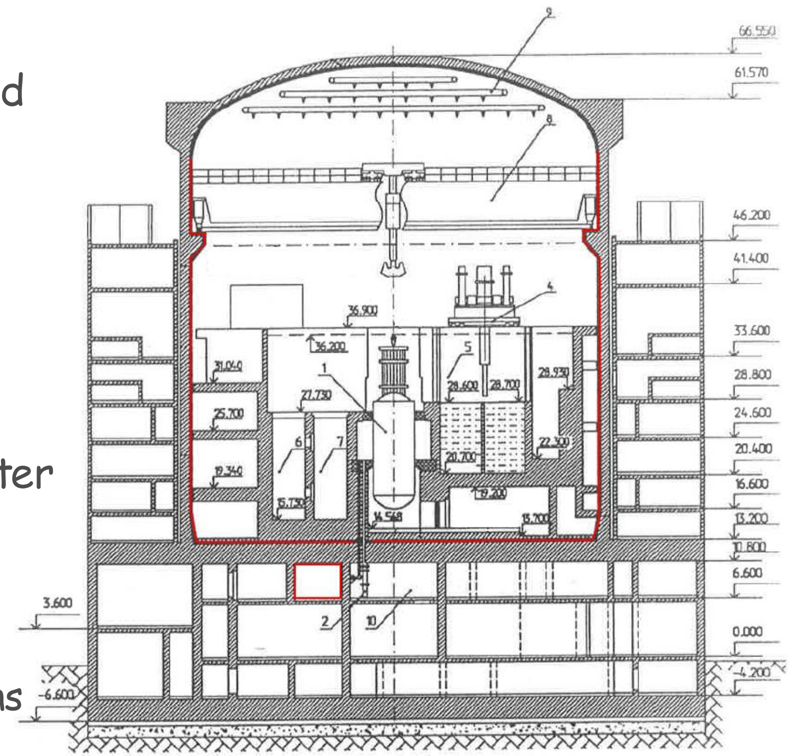
SAM Application at Czech NPPs
IVR – Coolant Supply

- **VVER-1000/320 specific design of containment**
  - Non-hermetic room below Cntn base mat
  - Drainage of water in containment redirected to recirculation sump below Cntn base mat
    - Passive water drainage to cavity impossible ⇨ active system for long term water supply necessary
- **Alternative water injection for initial fast cavity reflooding investigated**
  - Tanks on roof with sufficient amount of water for initial filling of cavity
    - Seismic study on feasibility performed
  - Remaining issues
    - Analysis of injection under typical SA conditions in containment (pressure in Cntn)
    - Pipeline design ⇦ availability of penetration of Cntn wall and cavity, but also timing and cavity volume determine final solution



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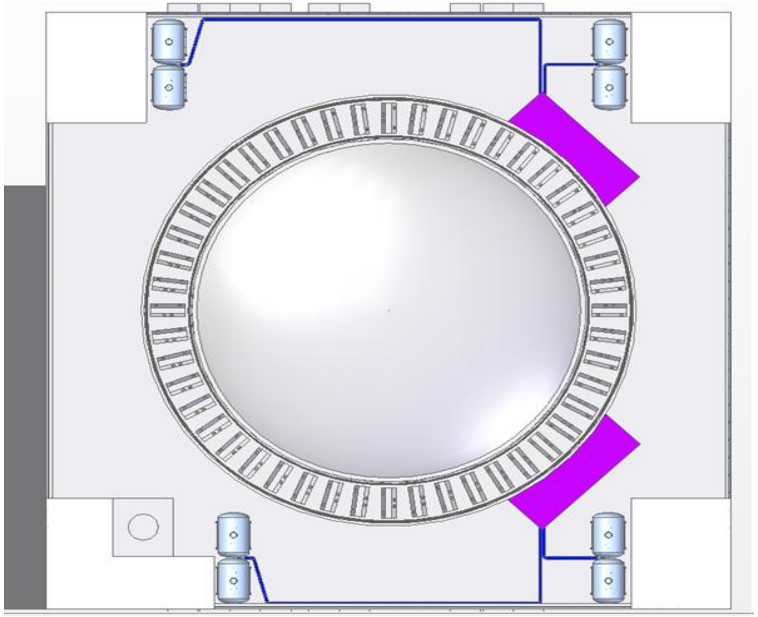
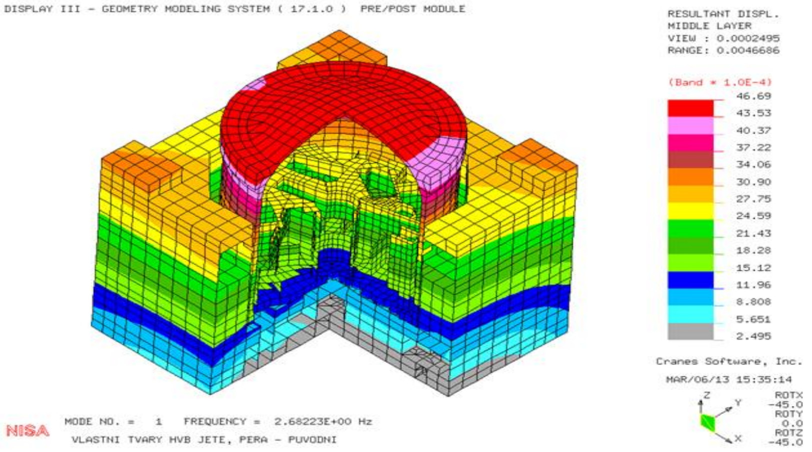
SAM Application at Czech NPPs
IVR – Coolant Supply

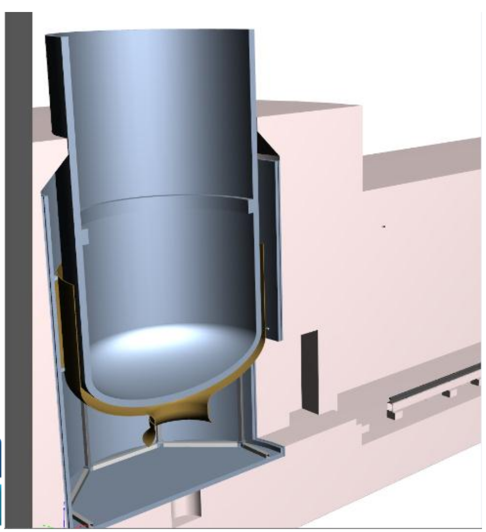
- **VVER-1000/320 Containment and auxiliary building**
  - Location of tanks

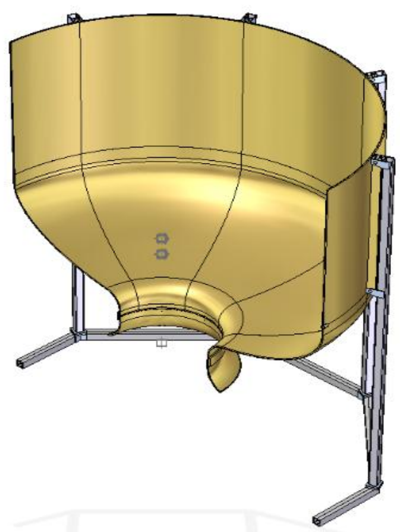


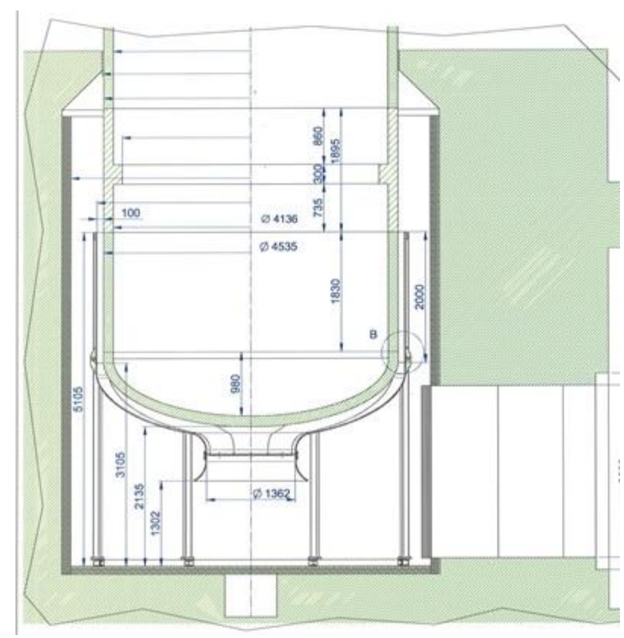


SAM Application at Czech NPPs
IVR – Cooling conditions

- **Design of VVER-1000/320 cavity doesn't enable natural circulation of coolant like other containment (AP-1000)**
  - Coolant convection strongly influence CHF
  - Elliptical bottom head of VVER-1000 RPV
- **Feasibility study on installation of deflector performed**
- **Initiating analysis on impact of deflector performed**
  - RELAP5-3D code for evaluation of impact of channel size and deflector height
    - Flow through or circulation loop in cavity







SAM Application at Czech NPPs
IVR - Benchmark

- **UJV initiated and JRC IET Petten coordinated benchmark on „In Vessel Retention on VVER1000“**
  - Many contributors from JRC, KI, IRSN, IRNRE, IVS, VTT, CEA and others
  - Goal of benchmark
    - Estimation of heat flux profile from corium to RPV wall
  - Analytical approaches
    - Integral – whole scenario simulation - KI (SOCRAT), IVS (ASTEC) and UJV (MELCOR)
    - Stand alone corium behaviour in lower plenum – mostly ASTEC, but also for example PROCOR (CEA)
- **Final report under preparation – to be released soon**
  - Very high scatter of results (maximum HFD from 800 kW/m^2 to ~ 2 MW/m^2 with extreme value of 6 MW/m^2)
    - Not only among different codes, but also among users of same code with identical base part of input for stand-alone simulation
    - Huge effort in code development and definition of best practice foreseen

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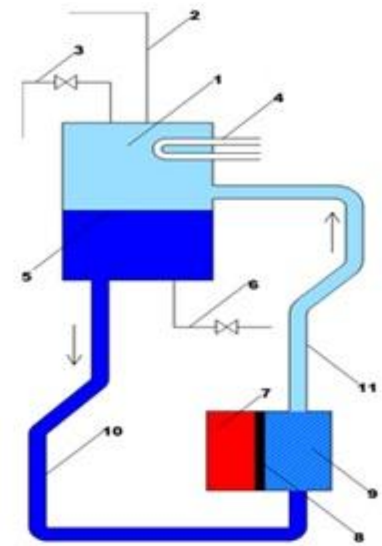
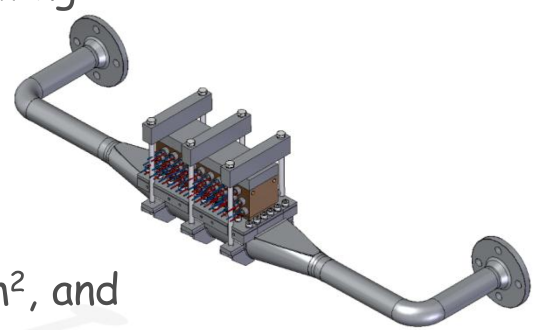
SAM Application at Czech NPPs
IVR – UJV Experiments



- **Extensive experimental investigation is ongoing in UJV (BESTH2 facility)**
- **Experimental program covers several topics**
  - Chemical processes on surface of specimen
    - Corrosion
    - Formation of boric acid crystals on surface
  - Natural convection formation
  - Impact of surface conditions on heat transfer
    - Polished, corroded, coating (High Velocity Particle Coating „cold spray“ technology – collaboration with PSU)
  - Impact of surface declination



- **Facility improvement**
  - Increase of maximum heat flux densities
    - Recently only 0.8 MW/m^2, first upgrade to 1.2 MW/m^2, and target value about 2 MW/m^2 – conditions of CHF
- **Experience will be used for large experiment (scale 1:1) for confirmation of vessel coolability**

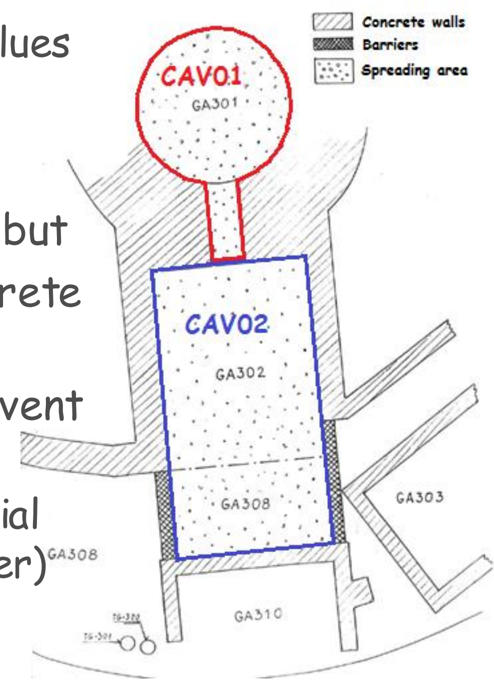
SAM Application at Czech NPPs
In-Vessel Retention Strategy

- **Residual risks – foreseen activities**
  - Evaluation of impact of partly flooded cavity or RPV lower head failure during strategy application – melt ejection into water
    - Risk of steam explosion
    - Cavity and containment loads
- **Feasibility and acceptability of proposed solution**
  - Many steps and effort have to be done before final confirmation of feasibility of IVR strategy application to VVER-1000/320
    - Confirmation that all configuration are coolable and with sufficient margin
      - Such margin has to be defined with the community of research, utility and authority personal
  - Acceptability of solution based on active system
    - Dedicated to SA mitigation only
    - Unique design solution – different to standard ECCs

<u>Philosophical question</u> ? is more safe NPP with new SA dedicated mitigation system than with new SA preventive system, if both are active, but different design solution than existing ECCs ?

SAM Application at Czech NPPs
Ex-Vessel Corium Stabilization

- **Optional solution to IVR strategy for VVER-1000/320**
- **First idea on corium spreading and cooling with top flooding from 90'**
  - Analyses confirmed positive effect on reduction of concrete ablation
  - Open issue – is corium fully coolable?
- **OECD MCCI and MCCI2 project**
  - Identification of potentiality for MCCI termination due to top cooling, but
    - Much higher for common sand/limestone than siliceous concrete
  - Extensive validation on CCI tests
    - CORQUENCH and ASTEC/MEDICIS against experimental values
    - MELCOR/CORCON - code to code comparison approach
- **Plant applications (siliceous concrete)**
  - Some analyses identified potentiality of MCCI termination, but
  - General conclusion - MCCI is not possible terminate, if concrete ablation already initiated
  - Recent approach – application of refractory material to prevent MCCI for time needed to cool down corium after spreading
    - Further research mainly on optimization of refractory material is foreseen as well as on spreading of corium (dry, under water)



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Conclusions

- **Many needs of research activities in Severe Accident phenomenology exist**
  - Basic phenomenology – closure of gaps and uncertainty reduction
  - Plant application – design specific features, material issues
- **Possible rule of IAEA (can't play a rule of sponsor)**
  - Coordination/Initiation of some research activities (jointly with OECD/NEA)
  - Organization of benchmark (parallel to or jointly with OECD/NEA)
  - Support in knowledge transfer (research to utilities and authorities) – workshops, training courses etc.
  - Implementation of new practices into legislation

Thank You for Your Attention

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