

THE VVER SEVERE ACCIDENT MANAGEMENT

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The basic approach to the VVER safety management is based on the defence-in-depth principle the main idea of which is the multiplicity of physical barriers on the way of dangerous propagation on the one hand and the diversity of measures to protect each of them on the other hand.

For the loss of core cooling accident the realisation of the defence-in-depth principle occurs due to:

- 1) justifications of accident prevention measures provided by the NPP design;
- 2) justifications of measures of accident consequences mitigation (accident management) , if the safety design limits are exceeded because of safety system failure or the operator's errors beyond the single failure principle.

For the accidents with the uncontrollable reactor power growth for which the management procedures are inapplicable, the defence-in-depth principle is realized in the following way. This principle is based on the afforded in the course of safety justification proofs of the fact that in any probable initial event resulting in the uncontrollable power growth, energy deposition will not result in failure of a fuel rod cladding.

The main events of severe accident with loss of core cooling at NPP with WWER can be represented as a sequence of NPP states, in which each subsequent state is more severe, that is, it is characterised by heavier destruction of physical barriers in comparison with the previous one.

The following sequence of states (phases) of the accident progression is supposed to be realistic and most probable for NPP with WWER:

1. Loss of efficient core cooling.
2. Core melting, relocation of the molten core to the lower head and molten pool formation.
3. Reactor vessel damage, the melt release into the environments.
4. Containment damage and fission products release.

For each severe accident state, its own safety specific goal should be determined and the strategy and tactics of the accident management should be aimed at the achievement of that:

- prevention of fuel damage;
- fuel retention inside the reactor vessel;
- prevention of the containment damage.

Hierarchy of the safety management should be based on formulating of the well understood safety objectives for each stage of the accident progression.

The certain safety functions correspond to the formulated safety objectives.

The loss of safety function forms the query for its recovering, depending on the situation determined by the appropriate parameters of physical processes.

The effective strategy and recovering procedure for the lost function, i. e. strategy and procedure of the accident management is chosen depending on the knowledge of the certain processes and phenomena parameters during a severe accident.

If the knowledge level for the different stages of the accident progression is insufficient the query for additional researches of the appropriate processes and phenomena is formed.

The most probable sequence of main accident events described above can be realised during the progression of large variety of loss-of-coolant accident sequences with any initial event (within the design basis) with failures independent from initial event or the operator's error.

The assumptions concerning operation or safety systems failures, the operator's actions, the equipment characteristics and (instrumentation) response set-points form the boundary conditions of the considered accident process.

The progression of transient thermohydraulic process taking into account the reactor power change (neutron kinetics) can lead to the following results. Engineering features and organisation measures included in the NPP design can limit its negative consequences within the framework of the design basis accident (not exceeding the acceptance criteria). Otherwise, due to the initial events not taken into account for a design basis accident or due to additional failures of safety systems beyond the single failure principle, the safe operation limits (design limits) are exceeded and the accident is treated as a severe accident requiring the special safety systems and special accident management measures (accident mitigation).

Thus, the correct analysis of neutronics and physical and thermohydraulic transient processes results in the formation of boundary conditions for the further analysis of severe accident progression.

The objectives of accident management at the design basis stage, the determining factors and appropriate determining parameters of processes are formulated in Table 1. Their knowledge allows to justify the accident management measures, the calculation instrument condition and its availability to perform the design calculations.

During development of the technical requirements to safety systems for the beyond design basis accidents management, it is suggested to use the realistic approach based on:

- elimination from the consideration of the initial events with the confidence probability less than 10^{-7} ;
- realistic estimation of key parameters of the processes obtained using the detailed best estimated codes.

Table 1

Event	Accident management goals and measures	Determining factors	Determining parameters	Tools	Comment
Core heat-up	<p><u>To prevent core heat-up and avoid exceeding the safety design limits.</u></p> <p>MEASURES:</p> <p>1. To maintain the possible heat removal from the core:</p> <ul style="list-style-type: none"> - ECCS; - Heat removal through the primary circuit; - Heat removal through the secondary circuit. <p>2. To avoid the accident progression with high pressure.</p>	<ul style="list-style-type: none"> - The critical outflow through break; - Hydrodynamics and heat transfer in RPV with active and passive ECCS systems operating; - Presence of water in the primary circuit and its possibility to enter the RPV; - Heat removal to the secondary circuit; - Hydrodynamics of the primary circulation with switched-off reactor coolant pumps (RCP) (natural convection) 	<ul style="list-style-type: none"> - Outflow rate through break - $T_{core} = f(\tau)$ °C - $P_{l, llc} = f(\tau)$, MPa 	<p>TRAP RELAP CATHARE ATHLET</p> <p>under development: KORSAR RATEG</p>	<p>The set of the calculation codes allows to adequately estimate the process.</p> <p>Problems:</p> <ul style="list-style-type: none"> • Validation of LOCA DBA acceptance criteria; • Fuel rod thermomechanics

The same approach is advisable to be used for the estimation of processes parameters at beyond design basis accident progression.

Using of this approach allows to estimate the time period of the thermohydraulic transient process from the initial event up to the time when the design temperature limit of fuel rods cladding is 1200°C. It occurs to be the characteristic time for a small break LOCA, i. e. about 2-4 hours.

The exceeding of design limits results in loss of integrity of the secondary protective barrier (fuel cladding), and the accident develops into the beyond design basis accident (Table 2).

Calculation modelling at this stage should determine the following time characteristics and key parameters:

- Time before the failure of fuel rods cladding and release of gaseous fission products;
- Time before the formation of metal blockages;
- Time before fuel melting and the melt relocation to the RPV bottom, melt composition;
- Time before the RPV degradation, the location and type of vessel failure;
- Rate of the melt relocation from the RPV;
- Melt composition.

It is necessary to note, that considering the uncertainties, implemented in the detailed calculation codes, the time from the beginning of core degradation up to melt relocation from the RPV does not depend much on the initial event and is about 2-3 hours.

Thus, realistic time from the accident beginning (reactor scram response) up to the melt relocation from the RPV is at least 4 hours.

Decay heat, melt composition and temperature, melt relocation rate and type of the RPV break are the initial data for designing of melt localisation system at the under-reactor space.

Table 2

Event	Accident management goals and measures	Determining factors	Determining parameters	Calculation codes	Note
<p>Escalation of core temperature increase, loss of fuel rod cladding integrity, melt forming within core</p>	<p><u>To prevent complete core melting</u></p> <p>MEASURES:</p> <ul style="list-style-type: none"> - To supply possible heat removal from the core - ECCS - Heat removal through the primary and secondary circuits 	<ul style="list-style-type: none"> - Oxidation of the fuel rods cladding and reactor internals materials; - Effects of control rods materials; - Fuel - cladding interaction; - Melting of fuel rods cladding; - Flow area blockage by metal melt; - Fuel melting; - Fission product release from the gas gap and fuel; - Melt interaction with structural materials; - Collapse of core plate, protective tubes unit and core shroud; - Melt relocation outside the core 	<ul style="list-style-type: none"> • $T_{core}=f(\tau)$, °C • Kinetics of physical and chemical reactions, • $H_2 =f(\tau)$, kg • $P_{1,k} = f(\tau)$, MPa • Level and mass dynamics of the remaining coolant; • Fission product release and thier transport in the circuit; • $M_{melt}=f(\tau)$, kg • Melt composition; • Heat losses from core; • Melt relocation rate; • Heat transfer during relocation; • Radial materials migration 	<p><u>The detailed analysis</u> RATEG/SVECHA CATHARE-ICARE RELAP-SCDAP</p> <p><u>Fast estimation</u> MARCH MELCOR ESCADRE MAAP</p>	<p>Estimation at the world standards level.</p> <p>Problems:</p> <ul style="list-style-type: none"> - Melt relocation to the RPV bottom; - Fission product release, decay heat estimation; - Oxidation degree of melt composition; - Estimation of radial materials relocation

Table 2 (continued)

Event	Accident management goals and measures	Determining factors	Determining parameters	Calculation codes	Note
<p>Melt relocation to the reactor lower head, formation of the molten pool</p>	<p><u>To retain the melt in the RPV</u></p> <p>MEASURES:</p> <ul style="list-style-type: none"> - To maintain the possible heat removal and core debris cooling within the RPV; - Reactor cavity flooding; - Pressure decrease at the RPV after melt relocation to the lower plenum 	<ul style="list-style-type: none"> - Melt-water interaction within the RPV; - Molten pool stratification; - Molten pool thermohydraulics; - Melt-RPV interaction; - Thermal mechanics of RPV behaviour, type and criterion of its failure; - Recriticality 	<ul style="list-style-type: none"> - Melt composition; - Timing of melt relocation to the RPV bottom; - $M_{melt}=f(\tau)$, kg - $Nu = f(Ra)$ - $Q_{to\ RPV}=f(\tau)$, kW/m²; - $P_1 = f(\tau)$, MPa 	<p><u>The detailed analysis</u> CONV-2D CATHARE-ICARE RELAP-SCDAP DINCOR</p> <p><u>Fast estimation</u> Integral codes MARCH-WWER MELCOR MAAP-WWER ESCADRE-WWER</p> <p>+ expert judgement</p>	<p>Estimation at the world standard level</p> <p><u>Problems:</u> There is no calculation codes:</p> <ul style="list-style-type: none"> - to calculate the distribution of volumetric heat release; - to estimate the possibility of steam explosion.

Table 2 (continued)

Event	Accident management goals and measures	Determining factors	Determining parameters	Calculation codes	Note
<p>Molten pool generation in the under-reactor space, direct containment heating, possibility of hydrogen deflagration and detonation.</p>	<p><u>To prevent the containment damage</u></p> <p>MEASURES:</p> <ul style="list-style-type: none"> - Core catcher; - Hydrogen concentration decrease (burners, recombiners, containment environment inertisation); - Cooling within the containment; - Pressure release through special filters 	<ul style="list-style-type: none"> - Corium-concrete interaction (without core catcher); - Interaction of corium with core catcher materials; - Heat transfer (radiation, heat conduction, natural convection); - Additional release of fission products, non-condensable gases and aerosols; - Melt-water interaction (steam explosion?); - Hydrogen release (hydrogen explosion?); - Steam condensation and fission products deposition on the containment structures; - Recriticality; - Containment structures collapse; - Containment structures oxidation; - The loss of containment tightness 	<ul style="list-style-type: none"> - Concrete ablation rate - $M_{H2, fission, prod., aeros., gas} = f(\tau)$, kg; - Hydrogen concentration in containment compartments; - Parameters of core catcher state; - $P_{cont.} \sim f(\tau)$, MPa; - Thermal loadings on the containment structures elements 	<p>VAREX CORCON CONTAIN WECHL KUPOL PROBL 3ET.COM</p>	<p>Estimation at the world standards level</p> <p><u>Problems:</u></p> <ul style="list-style-type: none"> - Estimation of steam explosion opportunities - Dynamic prediction of the thermomechanical containment response

Estimation for the amount of core materials entering the under-reactor space has been obtained as a result of calculation modelling using detailed calculation codes and can be summarised as follows:

- Amount of U-Zr-O melt is no more than 100 t;
- Steel quantity is no more than 70 t not taking into account the vessel steel and is about 100 t taking into account the vessel steel;
- Melt composition is characterised by low Zr oxidation (no more than 50 %).

Accident management goal at the stage of core melt relocation from the RPV into containment can be put as follows:

- To ensure localisation of reactor core materials melt within the under-reactor space of the concrete cavity in case of severe accident with RPV degradation.

Realisation of the given purpose is based on knowledge base obtained during researches of core molten pool behaviour in the lower RPV part, thermomechanical effects in RPV and external heat removal from RPV when the reactor cavity is flooded by water. The obtained data can be used as a basis for designing of measures and structures supplying the long-term corium retention and cooling in the limited space of the concrete reactor cavity.

The formulated goal of the accident management allows to determine the requirements to the following basic functions; realisation of those should result in core-catcher efficiency:

- Providing the sufficient volume for localisation of liquid and solid components of core materials and structure reactor materials;
- Providing guaranteed cooling of melt, and prevention of melt relocation from the indicated borders of localisation zone;
- Providing melt subcriticality in case of its long retention within the localisation zone and subcriticality control;
- Providing minimal radioactive fission products release into containment;
- Providing minimal movement of the RPV bottom in case of its deformation;
- Not exceeding the maximum stresses in the structures located within the concrete cavity during thermal effects and possible local dynamic processes.

The realisation of these functions should be based on the passive management principle, i.e. it should be performed without operator or with minimum contribution from the operative staff. There must be no effects of core catcher additional structures on operating and maintenance of NPP systems at normal operation and the possibility of these structures restricted inspection during design term must be provided.

The schematic of the core-catcher is shown in Fig.1

Basic physical processes during the melt relocation from RPV into the core catcher and occurring during long-term melt retention in the core-catcher are listed below:

- Melt relocation from the RPV into the core catcher;
- Melt interaction with sacrificial materials in the core-catcher (change of composition density and melting temperature due to this interaction);
- Heat transfer from the melt to the cooled surfaces due to the natural convection of heat-generating fluid;
- Heat removal (cooling) from the core-catcher walls due to the natural convection of coolant fluid(water);
- Heat removal (cooling) from the upper melt surface due to radiation and water boiling after feeding of that onto the upper melt surface.

Based on analyses of the possible sequences of the severe accident progression, the following critical issues were determined in course of the core catcher justification research:

1) Accident in-vessel stage (input data determination on the basis of different accident scenario assessments)

- Conditions in RPV before LHF;
- Mode of LHF;
- Amount, composition and timing of core melt and structure materials relocation into the core catcher (input data).

2) Core catcher filling

- Choice of a sacrificial material and the interaction of that with corium;
- Determination of mixture thermal properties;
- Study of stratification and configuration of layers, the inversion justification (if necessary);
- Analysis of radiation heat transfer;
- Impact loads, hydraulic shocks.

3) Long-term corium retention in the core catcher

- Analyses of possible dynamic processes consequences;
- Heat transfer to the cooled border and to the melt surface (natural convection);
- Analyses of thermohydraulics and crisis of heat transfer in water-cooled structures;
- Fission products release taking into account the layers configuration and water existing at melt surface;
- Recriticality.

The experience of different sequences modelling of severe accidents at RP with WWER-1000 shows that the separate considering of each stages of severe accident generally results in the rough and sometimes erroneous evaluations of RP behaviour. The necessity of integral detailed accident modelling from the initial condition up to melt relocation from RPV is obvious.

SCHEMATIC OF THE CORE-CATCHER FOR VVER-1000

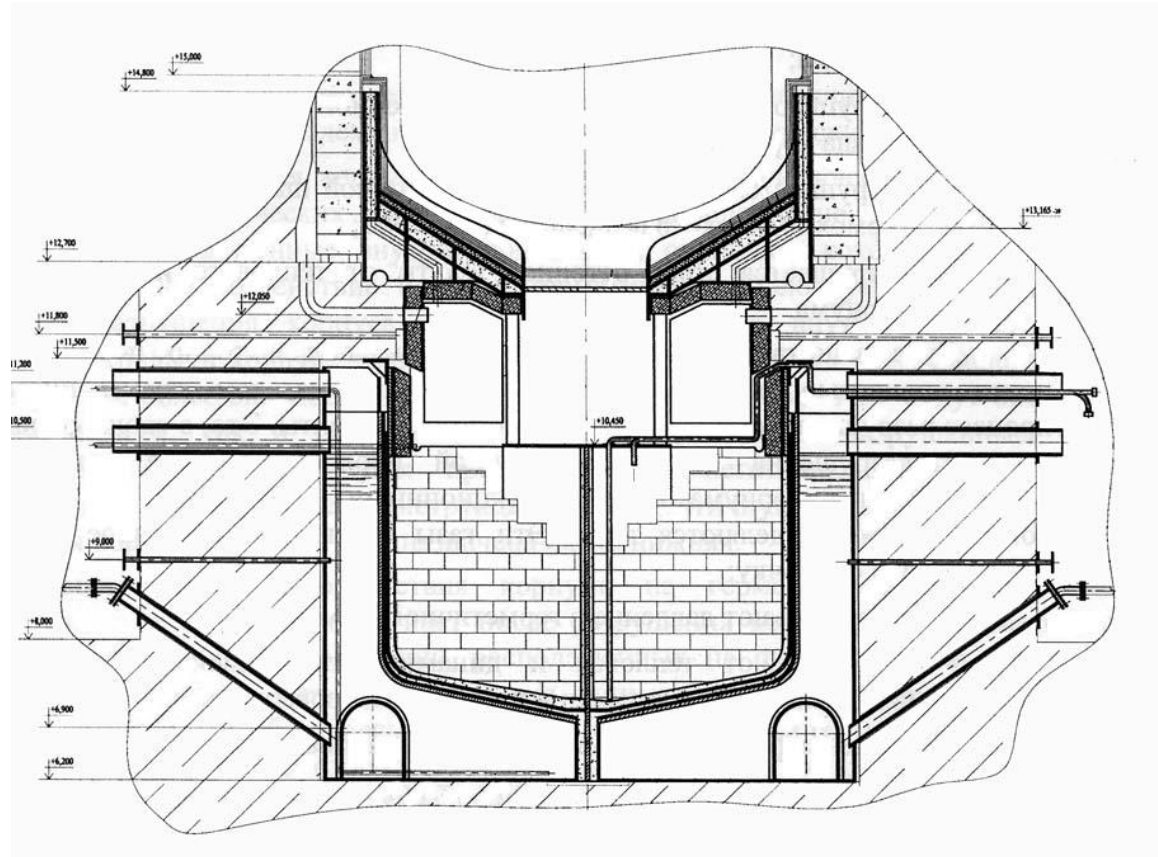


Fig. 1