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TOPICAL REPORT

WORK PACKAGE 2: INNOVATIVE SAFETY FEATURES

TASK 2.3: Innovative Measures for Maintenance of Coolant Inventory and Integrity of the Primary Circuit under Severe Accident Conditions

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TASK 2.3: Innovative Measures for Maintenance of Coolant Inventory and Integrity of the Primary Circuit under Severe Accident Conditions

WP 2.3 Innovative Measures for Maintenance of Coolant Inventory and Integrity of the Primary Circuit under Severe Accident Conditions

1. Introduction

The 'defence in depth' approach forms the basis of safe reactor design for the current nuclear power plants. It is foreseen, that the approach will remain as the central safety principle also for new designs [IAEA 1995]. The primary system forms an essential stage of the multiple barriers required by defence in depth. The safety functions of the primary system are threefold:

1. Failure of the primary system could lead to impairment in the ability to cool the core.
2. The primary system is one of the stages to confine radioactive material
3. In the unlikely event of a severe accident, retaining all of the molten material within the primary system would greatly reduce challenges to the containment integrity.

The current reactors have a large scale loss of coolant accident as one of their design basis accidents. The assumption generally used in the Western Light Water Reactors (LWRs) has been a double ended guillotine break of the largest primary system pipe (the so-called large-break LOCA, LBLOCA). All LWRs in use in the Western countries have been equipped with safety systems capable to cope with a LBLOCA. The safety systems are based on active (high and low pressure injection by pumps) and passive (accumulators) principles. A vast research effort since 60’s has been put to study the thermal hydraulic aspects of loss-of-coolant accidents.

The probabilistic safety assessment (PSA) studies and the severe accident research conducted since the Three Mile Island 2 accident have pointed out that a LBLOCA is very seldom among the risk dominating accident types for the current LWRs. There are alternative accident scenarios that may result to a loss of reactor coolant inventory, against which the current reactors are not as well equipped. The LBLOCA may still remain the reference accident for the design of the emergency core cooling systems.

Severe accidents must be taken into account in design of new plants. A substantial amount of knowledge has been accumulated of the severe accidents physical and chemical phenomenology by research work conducted for example within the EU 4th framework research programme, in USA and in Japan. The research efforts should be put into practical use by transferring the knowledge into new plant designs combining high safety level with economical electricity production.

2. Drivers for innovations

Generally, the defence in depth principle can also be applied to formulate an integrated approach to secure the plant safety. The EU Concerted Action "R&D Priority Needs for the Future Development of Nuclear Industry (MICA)" [Fiorini et al. 1999] has assessed new safety systems based on:

- accident prevention
- protection
- accident mitigation

The nuclear safety must always put the highest priority in accident prevention. Protection covers all design efforts for easier management so that the accident sequence can be successfully terminated. Severe accident mitigation must be seen as the last alternative, needed to ensure that even highly improbable events do not cause large environmental effects.

The new approaches to cope with loss of coolant accidents and primary system integrity have concentrated on:

- Maintaining the coolant inventory within the primary system
- Retention of the core material within the primary system in severe accidents
- Strengthening of the primary system, new type of pressure vessels

2.1 Utility requirements

A plant safety design starts from a set of design basis accidents. The plant safety systems must be able to prevent core damage in all design basis accidents, even if conservative assumptions of their availability are used. Severe accidents are accident sequences that progress to considerable core damage. This could only occur, if the plant safety systems do not fulfil their objectives, or if the accident sequence has not been taken into account in the basic plant design. The latter type of accident sequences are typically very low probability events.

Safety targets for new plants require in any case that severe accident mitigation must considered. A key question for severe accident mitigation is to demonstrate that the core melt will be coolable either within the pressure vessel or in the containment. It is expected, that for new plant designs at least the latter can be achieved with the present day knowledge of severe accidents. In-vessel retention offers some clear advantages, discussed in chapter 3.2.

A common trend in the new plant design is to reduce the burden of the operators in accident situations. The procedures for severe accidents mitigation should be simple and focus on a few high level actions designed to cope with the plant specific spectrum of severe accidents.

Design of the safety systems must ensure a high safety level without producing costs that may affect the plant economy. From the utility point of view, the plant operation, inspection and maintenance are also important parameters that must be taken into account in the systems design.

2.2 Competitiveness

An accident leading to large scale core damage would be an economic disaster for the utility and to the nuclear industry at large, even if it could be safety terminated. The main focus should therefore always be in accident prevention. To fulfil the strict licensing requirements, the plant must also be designed for severe accident mitigation. Both targets should be accomplished without excessive burden to the plant economics.

2.3 Licensing requirements

The accident sequences considered in the plant safety must cover all types of accidents. The sequences can be classified as:

- anticipated transients,
- postulated accidents, and

- severe accidents.

The Finnish safety analysis guide [YVL 2.2, 1996] for example, gives the following list of initiating events that must be considered:

- leaks from the primary circuit during power operation, change in operational state, refuelling and/or outage
- leak from secondary circuit (PWR)
- leak from primary to secondary circuit (PWR)
- disturbance in the reactor power control or other disturbance, which causes a change in reactivity
- disturbance in primary circuit flow, pressure control or water volume control
- disturbance in steam pressure or steam flow
- disturbance in feedwater flow or feedwater temperature.

The list could be further expanded by such items as pressure vessel thermal shock, high frequency thermal fatigue, water hammer questions, etc.

Severe accidents require a special consideration. As mentioned, severe accidents must be taken into account in all new plant designs. For the designer, this task differs from the conventional design basis accidents. Severe accidents form a wide spectrum sequences initiated by very low probability events. Examples of such events are a very large earthquake or very extreme weather conditions occurring once per million years that would cause simultaneous loss of cooling water, loss of external power and perhaps also loss of containment. It would be impossible to address all of these events or sequences in the plant design. The selection of the severe accidents to be addressed in the new plant design should be a combination of deterministic analyses, engineering judgement, and probabilistic considerations.

Strict demands are put to prevent fission product release into the environment in all accident types, including severe accidents. The target is to increase the plant safety to such a level that evacuation should not be needed. The land contamination and subsequent limits for agricultural products should also be avoided.

2.4 Socio-political drivers

Wider acceptance of nuclear energy by the public can be achieved by ensuring that the plant does not endanger the environment even in case of extreme accidents. It can be argued, that the plants operating today already fulfil the requirement. A problem has been that this fact has not been presented to the public in a way that it can comprehend. The driving force for innovation from the acceptability perspective is to design the plant so that the plant safety can be transparently demonstrated.

3. International innovation trends

3.1 Maintaining the coolant inventory

The main focus should always be accident prevention. A fundamental solution that helps in accident prevention and protection is to have large amount of coolant available in the pressure vessel, primary and secondary system (in case of PWRs).

The conventional solution of current BWRs to regulate the primary system pressure when the reactor vessel is isolated from the turbine condenser is to discharge reactor vessel steam to the suppression pool. A large amount of coolant is lost from the system and has to be replaced. An inadvertent operation of the system is itself a possible accident initiator.

A system suggested to avoid this type of unnecessary loss of coolant is the isolation condenser (IC), proposed for the GE ESBWR and Siemens SWR1000 [Brettschuh & Wagner, 1996] and already utilised in some early BWR designs. The isolation condenser is a passive safety system located in a pool. The steam produced by the reactor in accident situation is conducted to the IC, where it condenses, and from which water is returned to the primary system.

The passive core cooling system proposed for the Westinghouse AP600 provides safety functions of core residual heat removal, safety injection and depressurization. The system uses three passive sources of water: Core make-up tanks, accumulators and in-containment refueling water storage tank. The injection sources are directly connected to nozzles in the reactor vessel so that no injection flow is spilled under large break accidents. The system also includes two identical 100 % passive residual heat removal heat exchangers. The objective of the system is to ensure core decay heat removal if removal through the steam generators is not available. Inside the refueling water storage tank is a passive heat exchanger that is part of the full pressure, closed, natural circulation loop of the RCS. The heat exchanger is activated by air-driven valves that open with loss of power. Natural circulation carries the coolant from the hot leg to the heat exchanger, then down to the cold-leg side of the steam generator.

An alternative to cope with the pipe break type of accident is immersion of the RPV or the entire coolant system in a water pool. The VVER-640 concept [Fedorov et al. 1996] includes a passive emergency cooling system operating in three stages: at the first stage (highest pressure) the core cooling is provided by accumulators. After these are empty, large tanks holding water under atmospheric pressure begin to operate. The tanks are arranged to have a hydrostatic head of 20 m in relation to the core. Finally, a pool formed around the reactor pressure vessel provides residual heat removal by natural circulation. A guard vessel surrounding the entire reactor pressure vessel has been suggested for the VPBER-600 plant [Samoilov et al. 1996].

An extreme of the concept is a design in which the primary system is almost completely immersed in a water pool. That kind of an alternative has been developed for the ABB Atom PIUS reactor. The reactor core is located at very low elevation within the primary system (an within the surrounding reactor pool). From the core the coolant circulates through a riser pipe, leaves the reactor vessel and continues to steam generators. The cold leg piping enters the vessel at the same level as the hot leg (on top). As a passive safety system, the PIUS reactor has a pipe opening below the core inlet plenum towards the surrounding reactor pool. The pipe encloses a set of tube bundles, the so-called lower density lock. The upper part of the lower density lock is normally filled with hot primary loop water and serves as a buffer volume to prevent ingress of pool water into the primary loop. There is another density lock at the upper location in the pool. The two always open density locks provide a natural circulation path through the core. During the normal operation the speed of the coolant pumps is controlled so that a pressure balance across the lower density lock is maintained. This keeps the natural circulation inactive. In case of an accident the pressure balance is lost and a natural circulation loop is established providing the reactor shutdown and core cooling.

3.2 Retention of the core material within the primary system in severe accidents

3.2.1 Retention by reactor pressure vessel external cooling

Retention of the molten core within the reactor pressure vessel (RPV) by external cooling of the vessel might provide a viable solution to mitigate severe accident consequences at least for low powered reactors. The concept has been extensively studied for the Loviisa VVER-440 plant [Kymäläinen et al. 1997], and the principle has been accepted by the Finnish regulator, STUK. The concept has been proposed and is being evaluated also for larger reactors, SWR-1000 for example. Melt retention outside of the primary system is discussed in the SINTER Work Package WP 2.4.

A systematic study of the in-vessel retention by vessel external cooling has been summarised in [Okkonen et al., 1994]. The report concludes that the feasibility of the external cooling is highly plant specific. Important physical phenomena affecting the coolability are:

1. Formation of the melt pool in the RPV. The RPV lower head must sustain the initial melt attack to guarantee melt retention. Potential causes for vessel lower head failure are ablation due to melt jet impingement, steam explosions and lower head penetrations. The effect of these phenomena is specific for an accident scenario (pressure, amount of coolant in lower head) and reactor design (penetration material, location of weldings).

2. Melt pool convection. The thermal behaviour of melt pool is governed by natural convection in a volumetrically heated liquid. A solid crust creates isothermal boundary conditions for the pool. Most of the pool forms a stable thermally stratified region, in which temperature increases in the upwards direction. Melt flows downwards in a cold boundary layer along the cooled walls. The pool natural convection results in a very non-uniform heat flux along the pool boundaries. Most of the heat will be removed from the pool upper surface.

3. Material interactions. Density differences may lead to segregation of the melt pool to metallic and oxidic layers. The lighter metal layer will float on top. Due to the high thermal conductivity of the metal layer may focus a large fraction of the heat removed from the oxidic pool sideways threatening the vessel wall.

4. Heat radiation. Most of the heat generated within the pool is radiated from the upper surface to the vessel internals and to the RPV wall in upper locations. This is beneficial for the ex-vessel cooling requirements, because the heat removal can be distributed on a larger surface area. A corollary is, that to remove the radiated heat from the external surface the vessel must be submerged up to the hot leg connections.

5. External coolant behaviour. In-vessel melt retention is not possible without efficient cooling of the vessel external surface. A sustained heat transfer crisis on the vessel surface would lead to vessel heatup and ultimately to vessel failure. The critical heat flux is lowest for a downward oriented surface. The melt pool convection produces highest heat flux in the upward direction whereas the heat flux downwards is modest. This helps to achieve the required conditions on the vessel external surface. Design of the RPV thermal insulation is also important for the ex-vessel heat removal. The insulation must allow

good contact between the coolant and the vessel wall, and paths for steam removal must be secured.

6. Vessel structural integrity. If the ex-vessel cooling is efficient, a portion of the vessel wall remains at low temperature and is capable of supporting the vessel and corium weight. Depressurization helps to reduce the vessel loading. High thermal gradients will exist through the vessel wall, the effect of which has not yet been fully investigated.

7. Long-term phenomena. The core debris may reside in the molten state in the RPV lower plenum for a long time (days). The most important phenomena to be considered are the heatup of the upper pressure vessel structures, the hot leg pipes, and for PWRs the pressuriser surge line and the steam generator tubes.

3.2.2 Retention by internal cooling

In-vessel retention with internal water injection has been studied by [Maryama et al 1999] based on the cooling mechanism proposed by [Henry and Dube 1994]. It would be difficult to cool the melt in the pressure vessel lower plenum by an overlying water pool alone. The gap cooling mechanism assumes that a gap is formed between the core debris and the pressure vessel due to the pressure vessel creep. Is water is available, it can penetrate the gap and remove enough decay heat from the debris outer surface to cool the melt without break-up of the pressure vessel. Several experimental studies for this gap cooling mechanism are currently being conducted [Henry 1996], Table 5.3. The experiments have shown evidence of the gap cooling mechanism. The knowledge from the small scale experiments should be extended to plant scale, however. The critical part is to prove the network of gaps can guarantee cooling on the entire lower head surface. Local hot spots without cooling would rapidly develop into vessel failure even if most of the vessel surface would remain well cooled. The in-vessel cooling requires continuous water supply on top of the melt pool. To guarantee this, depressurization of the primary system may be necessary.

3.2.3 In-Vessel Corium Retention Devices

In-vessel core catchers can be constructed in future reactors to mitigate core-vessel interactions. An in-vessel core catcher located in the lower plenum would guarantee coolant access below the melt pool, avoiding some of the considerations needed for the gap cooling mechanism. The device would also help to suppress high energy steam explosions in the lower plenum. The design requirements for the in-vessel core retention devices include:

1. the device should not impede the reactor normal operation or maintenance,
2. the device must withstand the initial relocation of the melt,
3. the device must prevent a global melt-coolant interaction,
4. decay heat must be removed,

It is envisaged that objective 2 can be achieved by proper choice of materials. A possibility to meet the requirement 3 is to divide a global melt pour into smaller ones by channelling the in-vessel retention device into severe substructures. Most of the decay heat of the melt pool residing in the core catcher is removed through the pool surface. To reach the objective 4, a continuous coolant supply is needed to submerge the in-vessel core catcher.

4. R&D proposals and availability of necessary R&D facilities

Possibilities to maintain the coolant inventory within the primary circuit is studied together with other novel primary system cooling solutions. Passive safety devices have been systematically evaluated within the EU Concerted Action "R&D Priority Needs for the Future Development of Nuclear Industry (MICA)" [Fiorini et al. 1999]. The MICA study lists as most important advantages of passive systems that,

- they are not vulnerable to external failures,
- they are less object to human errors of omission,
- they can be designed for less need of operator intervention, and
- usually permit greater simplification.

The main disadvantages are:

- weaker driving forces,
- more difficulty to restore normal operation,
- more time needed to restore normal operation,
- bulkier equipment, and
- inherent limits restricting the size of the reactor

Based on this, it is argued that it would be worthwhile to investigate also self-powered and self-starting systems that take their energy from the conditions crated by the accident. Such systems may be more effective than complete passive systems and less vulnerable against adverse effects like stratification, and presence of non-condensable gases.

The MICA working group has evaluated some new designs with the objective to maintain the coolant inventory. *A Flashing tank* proposed by CEA is an integral part of the primary system piping. The principle is to cool down vapour flowing from the hot leg by a heat exchanger and feed it back to the reactor core on the cold leg side. *The Passive Injection and Depressurization System (PIDS)* designed by Ansaldo performs depressurization by mixing cold borated water with the reactor coolant system steam and inducing steam condensation. A tank filled with cold borated water will be connected to the pressurizer steam space. Injection will be inherently actuated on low coolant inventory without any active components or operator actions. *The borated water injection system* suggested by FZJ combines the depressurization system with coolant injection by using energy from the steam depressurization as the driving force for the injection. Injection will be performed by a steam driven pump.

Some of the new passive systems can be used both for primary system depressurization and for residual heat removal. Description of the latter can also be found on the SINTER Work Package 2.2, Innovative Decay Heat Removal Systems [http://www-is.ike.uni-stuttgart.de/sinter/].

In-vessel melt retention by vessel external cooling has been studied by in a number of projects during the 1990's. The focus of the facilities has been on thermal hydraulic studies of the melt pool behaviour and heat transfer on the pressure vessel external surface. The main source of prototypic materials behaviour has been the OECD Rasplav project conducted by the Kurchatov Institute, Moscow. New projects have been established to investigate the in-vessel retention by the gap cooling mechanism in Korea and Japan [Maryama et al. 1999, Suh et al. 1999].

Some new proposals have been identified by the MICA group [Fiorini et al. 1999]. The CEA developed *DIVER, Dual In-Vessel Retention* system proposes an in-vessel core catcher, an in-vessel injection water storage tank, and a second larger water storage tank. The idea is to delay melt relocation to the RPV lower plenum by melt retention within the in-vessel core catcher cooled by the in-vessel injection. The core melt may eventually relocate into the lower plenum. At this time the power density would be so low that the decay heat can be removed by external vessel flooding. The Siemens *Passive Drywell Flooding and Exterior RPV Cooling* system floods the BWR lower drywell from a gravity driven flooding pool. The steam produced is condensed at the containment cooling condensers, which transfer the heat outside of the containment.

Available facilities have been collected in Tables 4.1 - 4.3.

4.1 Maintaining of primary system coolant inventory

Facility name	Operated by	Purpose
PANDA	PSI, Switzerland	Passive decay heat removal from the primary circuit (Performance of an Isolation Condenser)
NOKO	FZJ, Germany	Passive decay heat removal from the primary circuit (Performance of an Emergency Condenser)
PACTEL	VTT; Finland	Performance of an integral Core Make-up Tank

4.2 In-Vessel melt retention by external cooling

Facility name	Operated by	Purpose
Rasplav	Kurchatov Institute, Russia	Investigate heat load from melt pool to the RPV lower head. Prototypic materials
COPO2	Fortum Engineering, Finland	Investigate heat load from melt pool to the RPV lower head. Water as simulant
BALI	CEA, France	Investigate heat load from melt pool to the RPV lower head. Water as simulant
SULTAN	CEA, France	Investigate heat transfer from RPV to external coolant
ULPU	Univ. of Santa Barbara, USA	Investigate heat transfer from RPV to external coolant
CYBL	Sandia National Laboratories, USA	Investigate heat transfer from RPV to external coolant
ACOPO	Univ. of Santa Barbara, USA	Investigate heat load from melt pool to the RPV lower head.

4.3 In-Vessel melt retention by internal cooling

Facility name	Operated by	Purpose
ALPHA	JAERI, Japan	Debris-RPV gap formation and heat transfer
LAVA	KAERI, Korea	Debris-RPV gap formation and heat transfer
FOREVER	RIT, Sweden	RPV deformation and gap cooling
FAI Experiments	FAI, USA	Debris-RPV gap formation and heat transfer

5. Recommendation on future R&D activities

Approaches to cope with primary system integrity during design basis and beyond design basis accidents have concentrated on

1) maintaining the coolant inventory within the primary system,
2) retention of the core material within the primary system in severe accidents, and
3) strengthening of the primary system.

The main focus should be in preventive and protective solutions. New systems can be developed that can help to avoid unnecessary coolant loss during safety related actions, primary system depressurization for example. These include passive core cooling systems integrated with the primary circuit and immersion of parts of the primary system within a coolant pool as an extreme example. The safety research needs concerning these approaches are common with other passive safety systems. The systems usually operate under small driving forces. Functioning of the systems under all conceivable operating conditions must be investigated, taking into account mechanisms that may degrade their efficiency (natural circulation if non-condensable gases are present, efficiency of heat exchangers if aerosols collect on their surface etc.). Self-powered and self-starting systems can be an interesting alternative that avoid some of the problems connected with passive systems and at the same time keep the requirements of external power sources at minimum. Reliability estimates of the passive systems must be obtained so that these can be easily integrated with the PSA formalism. Improved calculation tools (CFD) must be developed and validated for these purposes.

In-vessel melt retention by vessel external cooling has been showed to be a viable severe accident mitigation strategy for some small and medium sized reactors. The physical mechanisms of the melt pool thermal hydraulics and the pressure vessel external wall heat transfer are quite well understood. Some features, like the effect of melt segregation into oxidic and metallic layers and material effects need still further investigation. The long term behaviour and ultimate coolability of the melt residing in the pressure vessel lower plenum should still be studied. The situation is different for larger reactors in the class of 1000 MW or more electrical power. The heat transfer capability of the pressure vessel outer surface is the critical parameter for these reactors with larger decay heat production. A sustained heat transfer crisis on the vessel surface would lead to vessel heatup and ultimately to vessel failure. Heat transfer characteristics up to the critical heat flux should be studied for relevant geometries. Penetrations in the vessel bottom complicate the situation. Structural mechanics assessments of the penetration behaviour should be performed to ensure the bottom integrity.

Strengthening and simplifying the primary system should result in lower failure probability of pressure components. The improvements should be systematically considered so that they do not cause excessive additional costs. A balanced safety level should be ensured for all pressure components, not only the primary system. The PSA techniques can provide a cost benefit estimate for the additional efforts.

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