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Overview and Lessons Learned following the Major Global Nuclear Accidents

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Only nuclear power that avoids being a threat to health and safety is acceptable to society.

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The results of accident studies of Three Mile Island, Unit 2 (USA, 1979); Chernobyl, Unit 4 (USSR, 1986); and Fukushima Daiichi, Unit 1 – 4 (Japan, 2011) had shown:

- Severe accidents present risks of Nuclear Power for safety, health and socio – economic conditions only;
- Fundamental Safety Principles remain appropriate as a sound basis for nuclear safety when properly implemented.
- Full understanding of Safety Fundamentals and proactive promotion by all stakeholders of their implementation up to the details is necessary for minimizing the risks of severe nuclear accidents in the future.

THERE ARE THE MAIN LESSONS OF THE THREE FAMOUS NUCLEAR ACCIDENTS

Three Mile Island (TMI) Unit 2 (USA, 1979)

- There were no injuries of the plant personnel or the population.
- There was no significant radioactive contamination outside the plant.
- Accident caused a reduction of investments in new NPPs due to a decreased interest from private investors.

Weaknesses were revealed in design of I & C, quality of operating procedures and the realism of the analyses supporting them, personnel training, and feedback of operating experience.

Chernobyl, Unit 4 (USSR, 1986):

- the spread of the accident to the other reactors at the plant was prevented but cost the lives of 30 plant staff and firemen;
- there was widespread radioactive contamination over large parts of Europe, thousands of people had to be relocated;
- regionally, the accident produced excess thyroid cancers and a large psychological impact on the public;
- accident also had significant political resonance.

Significant weaknesses were revealed: in core stability; inadequate design of control rods and instrumentation and controls; absence of full scope confinement; bad quality of operating procedures; insufficient feedback of operating experience and so on.

Lessons Learned

- INSAG issued reports on General Safety Principles and Safety Culture;
- nuclear industry established WANO for review and feedback of NPP operating experience;
- safety regulations and NPP design were upgraded;
- international nuclear safety regime based on the NSC and other international accords was established;
- NSC called for reviewing the safety of existing NPPs to identify and implement improvements;
- international cooperation was strengthened to ensure NPP safety;
- importance of nuclear education and training was acknowledged (WNU, regional nuclear education networks were established)

TMI and Chernobyl

- were initiated by internal events leading to an unusual situation for which the operators were not trained and provided with proper procedures;
- the initiating events were not taken into account in plant design and were initiated by more complicated sequence of events not considered.
- the lack of correct operator actions and weaknesses in the plant design resulted in a severe accident although all safety systems needed to avoid an accident were available and functional.

Fukushima Daiichi:

- the direct cause was a natural cataclysm that destroyed not only a large number of safety systems but also much of the infrastructure that would have been needed for management of the accident situation;
- the accident has demonstrated that extraordinary external events is not the subject to accurate prediction or control. Climate change, the probability of flooding and other extreme weather events is likely to grow over time, challenging engineered structures of all kinds;
- design, construction, and operation of NPPs should make them capable of surviving rare and severe external events without large or early releases of radioactivity to the environment, resulting in long-term land contamination;
- preparation for extreme events have to be a continuing obligation.

TMI, Chernobyl and Fukushima showed (1)

- In the past attention was focused on DBA (postulated events that an NPP was to accommodate by using engineering features designed specifically to respond to those events). It is necessary to pay more attention to events with more severe consequences (the BDBA in the past). Analysis of the so called BDBA should be a part of NPP design;

- It is necessary to establish in NPP design additional engineered features (additional installed and/or mobile equipment that provides energy and cooling water to back – up the essential safety functions, including confinement of radioactive materials) and accident management procedures to prevent or mitigate a severe accident resulting from common cause failures of "regular" safety systems.

TMI, Chernobyl and Fukushima showed (2)

- Broader set of initial events including superposition of events that lead to common cause and multiple failure of safety systems should be considered in design;
- Direct radiation-related health impacts of the mentioned accidents were significantly less than it could be expected.
- Scope of regulatory objectives should be more emphasized on limitation of radioactive releases to the extent practical to avoid (decrease) environmental and societal – economic impacts.

Strengthening DiD concept (1)

- level 3 of DiD should be extended to cover single and also postulated multiple failure events where all of the safety systems would fail and significant fuel damage needs to be prevented by additional safety features;

- The design should provide for handling all accident scenarios that are initiated from single events postulated to occur with higher than specified frequency;

- Additional safety features should be designed to terminate the accident escalation in the event of complete failure of the safety system (reasons for the primary safety system failure could be: mistake made in the safety system design (common cause failure) or hazard impacting large part of the plant (multiple failure).

Strengthening DiD concept (2)

- the main goals at levels 1, 2, and 3 of DiD are high reliability of reactivity control and decay heat removal;
- level 4 has its focus on confinement of radioactive materials, with emphasis on containment integrity. For mitigation of consequences of fuel damage – level 4 of DiD − should be equipped with dedicated means needed to protect the containment integrity, including condition with fuel melt down;
- level 5 is focused in emergency response to be taken after a significant off-site radioactive release.

DiD levels needs to be strong and be defended by systems that have proper redundancy, diversity, physical separation, protection from hazards and adequately qualified equipment.

Strengthening DiD concept (3)

Complementary safety features specifically designed to fulfill safety functions required in postulated severe accident conditions need to be independent from the safety systems, in order to avoid their failure due to the same cause that resulted in the fuel damaged:

- avoid using the same power supply and distribution systems as the normal operating systems and the safety systems;
- use their own systems for cooling their components;
- be controlled with their own I&C system from their own control points;
- have their own storages of supplies (fuel and oil tanks and water supplies) that are needed to ensure their operation.

DIVERSITY OF SAFETY SYSTEMS

Reactivity control and decay heat removal needs at least two separate safety systems that could be used in a flexible manner, depending on the course of the accident. Decay heat removal safety systems should have as minimum two ultimate heat sink.

Safety systems should be independent and physically separated from each other to the extent reasonably practicable so that at least one of them would remain operable in postulated accident scenario:

- systems operated on electrical power that is supplied from diverse and redundant off-site and on-site power sources through the plant's fixed power distribution system;
- systems operated on electrical power that is supplied from a dedicated power source should be isolated from other distribution system so that it is not lost due to a electrical disturbance;
- systems that do not need external electrical power and could comprise from permanently installed diesel driven pumps, manually operated valves, local control instruments, and their own water supplies and fuel storage tanks;
- passive systems that operate by natural driving forces (gravity, pressure difference) after they have been switched on by a function of a very reliable start device;
- transportable power sources and pumps that could be considered as a back-up for permanently installed equipment.

STRENGTHENING OF POWER SUPPLY

- Reliability of off – site power supply should be upgraded (transmission lines and transformer sub-stations that connect the plant to the Grid);

- Where possible, direct connection lines between NPP and other power generators that are not depending on the availability of the Grid should be implemented.

- Availability of DC power to systems that provide essential information and acceptable work conditions to plant operators should be ensured:
  - I&C systems needed for accident management,
  - communication systems,
  - lighting, in particular of the main control room and of emergency control points and relevant places where operators may have to work or walk through, and
  - filtering of inlet air of the main control room and of emergency control points.

Limitation of Radioactive Releases (1)

Strategy for confining a fuel melt accident should be included in the design of the new NPPs and specific measures must be implemented for "old" NPPs (NPPs designed and constructed according to earliest safety regulations).

To avoid environmental and societal impact of severe accidents, the design target shall be:

- only limited protective measures in area are needed for the public (no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the NPP, limited sheltering, no long term restrictions in food consumption), and
- sufficient time is needed to implement these measures.

Limitation of Radioactive Releases (2)

Issues that have been addressed by dedicated systems or by accident management procedures are:

- core meltdown in high pressure;
- hydrogen management;
- gradual pressure increase inside the containment;
- containment boundary penetration by the molten core;
- re-criticality during progress towards the fuel damage;
- containment by-pass sequences.

Limitation of Radioactive Releases (3)

- **Fuel meltdown in high pressure** has to be practically eliminated by de pressurization of the reactor coolant system (RCS) after it has been concluded that progress to a fuel damage is unavoidable;

- **Hydrogen management** to avoid risks from hydrogen and other flammable gases that could lead to containment failure;

- **Gradual pressure increase inside the containment** could be caused by steam pressure as a consequence of the accumulation of the reactor decay heat energy and accumulation of the non -condensable gases inside the containment (**attention:** *the steam condensation present a risk in relative increase of hydrogen concentration when amount of steam is reduced*).

Limitation of Radioactive Releases (4)

Containment boundary penetration by the molten core needs to be prevented by stabilization of molten corium. Such stabilization is essential for reaching a safe and stable state. The strategies being already used:

- In-vessel retention of molten corium ensured by early flooding of the reactor cavity and heat removal by external cooling of the RPV (the approach has been proven for reactors up to about 2000 MW thermal power. In larger reactors the success of this approach require delay time from reactor shutdown to core meltdown);
- Using of core catcher where the molten corium drops and mixes with special materials ensuring sub - criticality and forming of a solid cover that protects the cavity structures from direct heating and restricts the hydrogen generation;
- Keeping the reactor cavity dry until molten corium relocation onto a flat spreading area, and then pouring water on top of the corium layer that is simultaneously cooled through the floor of the spreading area;
- Early flooding of the reactor cavity or lower drywell prior to any escape of molten corium from the RPV when in-vessel retention is not considered feasible.

Limitation of Radioactive Releases (5)

- **Re-criticality during progress towards the core meltdown** should be considered in the severe accident management strategy for molten core in severe accidents.

- **Containment by-pass sequences** is the result in loss of leak tightness of some containment penetrations or airlocks, a failure to close properly the containment isolation valves in all pipelines that are not needed to be open for decay heat removal, or a break in pipe or heat exchange tube (or steam generator header) that is part of containment boundary.

Protection Against External Hazards

Each potential external hazard should be considered and selected for analysis:

- If it is physically capable of posing a threat to nuclear safety, and
- If the frequency of occurrence of the external hazard is higher chosen reference index.

The factors to be considered when undertaking this analysis:

- NPP layout to minimize impact of external hazards;
- Combinations of external hazards that can occur simultaneously or successively within the time to reach safe stable plant state, including correlated hazards and those combinations which occur randomly;
- Potential consequential events, such as fire or flooding following, for example, a seismic event;
- The impact of external hazards on the systems and components;
- The strength of the buildings and structures exposed to an external hazard.

On – site Emergency Preparedness

- The accessibility, functionality and habitability of the control rooms and of the emergency response centre to be maintained in severe accidents conditions;

- Integrated planning of safety and security is necessary (for example, it is necessary to exclude blocking security gates and doors in black-out or in fire conditions);

- The reliability and functionality of the systems needed for emergency management is necessary also in conditions related to severe external hazards, including:
  - on-site and off-site communication systems and
  - equipment needed for measuring releases, radiation levels and meteorological conditions.