

Advanced Nuclear Plant Design Options to Cope with External Events

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ABSTRACT There is a renewed interest in many Member States in the development and application of nuclear power plants (NPPs) with advanced reactors. Decisions on the construction of several NPPs with evolutionary light water reactors have been made (e.g., recently, EPR for Finland and France, AP1000 for China, VVER-1000 for Bulgaria and India, etc.) and more are under consideration. High level of safety and improved economic competitiveness are common goals for advanced NPPs. There are special concerns that safety of these advanced reactors may be challenged by external events following new scenarios and failure modes, different from those well known for the currently operated reactors. This aspect may become even more important in the future in view of possible global deployment of nuclear power plants in a variety of siting conditions, potentially prone to various natural and human induced external events. Therefore, the engineering community identified the need to assess the proposed design configurations in relation to external scenarios at the earliest stages of the design development. It appears that an early design optimization in relation to external events is a necessary requirement to achieve safe and economical advanced nuclear power plants.

INTRODUCTION

The IAEA-TECDOC-936 “Terms for describing new, advanced nuclear power plants” [1] defines an *advanced design* as “a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced designs consist of *evolutionary designs* and designs requiring substantial development efforts”, i.e., *innovative designs*.

Multiple projects of nuclear power plants (NPPs) with evolutionary or innovative nuclear reactors are being developed worldwide [2, 3]. The IAEA activities to foster development of advanced reactor technology are carried out on the advice and with the support of technical working groups (TWGs) that consist of representatives of national programmes and international organizations in these technologies. Upon the advice and with the support of these TWGs, the IAEA provides all interested Member States with balanced and objective information on advances in nuclear plant technology and coordinates international efforts on selected issues of technology development for such reactors [2, 3].

Under the terms of Article III of its Statute, the IAEA is authorized to establish standards of safety for protection against ionizing radiation and to provide for the application of these standards to peaceful nuclear activities. The regulatory related publications by means of which the IAEA establishes safety standards and measures are issued in the IAEA Safety Standards Series: <<http://www-ns.iaea.org/standards/>>. The IAEA has recently produced the updated safety guides and other publications on NPP design and siting regarding external events [4 - 6]. The purpose of these safety guides is to provide recommendations and guidance on design and siting for the protection of nuclear power plants from the effects of human induced and natural external events.

In 2004 - 2006, the Department of Nuclear Energy and the Department of Nuclear Safety and Security of the International Atomic Energy Agency (IAEA) have cooperatively conducted an activity to identify design options for protection from external event impacts in advanced NPPs. The objective of this activity was to bring out the state-of-the-art in design approaches for the protection of NPPs from external event impacts, and to assist the designers of advanced NPPs in defining a consistent strategy of design and siting evaluation in relation to extreme external events. The activity, conducted through a collaboration of the designers of 14 advanced NPPs from Argentina, Canada, Germany, India, Japan, Lithuania, the Republic of Korea, the Russian Federation and the United States of America and several international experts, resulted in a preparation of the report “Advanced Nuclear Plant design Options to Cope with External Events”, published as IAEA-TECDOC-1487 [3] in February 2006¹. This paper presents major findings, conclusions, and recommendations of the abovementioned activity.

SCOPE

No limitations were set on the scope of external events, which, according to the recommendations of [6], may include human induced events, such as aircraft crashes, explosions, release of hazardous gas, etc., and natural events, such as earthquakes, extreme meteorological conditions, floods, landslides, etc.

Likewise, there were no limitations on specific types of evolutionary or innovative reactors within the NPP projects to be addressed, and many designers around the world were invited to participate. As a result, 14 designs of advanced NPPs ranging from evolutionary to innovative were addressed, as shown in Table 1.

A summary of the outputs of this activity is provided in the following sections.

¹ The conclusions and recommendations provided in this report were derived and shaped up, on a consensus basis, by a dedicated IAEA technical meeting held in Vienna on 14-19 November 2004.

Table 1. NPP designs considered [3]

#	REACTOR	DESIGNER/ COUNTRY	TYPE*
1.	APR 1400	KEPCO/ Republic of Korea	Loop type PWR (E)
2.	EPR Finland	AREVA/ Europe	Loop type PWR (E)
3.	VBER-300 (Floating NPP)	OKBM/ Russian Federation	Loop type PWR (E/I)
4.	VVER-91/99	SPb AEP/ Russian Federation	Loop type PWR (E)
5.	CAREM	CNEA/ Argentina	Integral design PWR (I)
6.	IRIS	International team led by Westinghouse/ USA	Integral design PWR (I)
7.	PHWR-540	Operating reactor/ India	PHWR /CANDU (O)
8.	ACR-700	AECL/ Canada	PHWR /CANDU (E)
9.	AHWR	BARC/ India	Heavy water moderated, boiling light water cooled, pressure tube type (I)
10.	SWR 1000	AREVA/ Europe	BWR (E)
11.	VK-300	NIKIET/ Russian Federation	BWR (E/I)
12.	ABWR-II	Toshiba/ Japan	BWR (E)
13.	BN-800	SPb AEP/ Russian Federation	Sodium cooled fast reactor (E/I)
14.	CHTR	BARC/ India	Pb-Bi cooled, high temperature, with HTGR type prismatic fuel (I)

* E is for evolutionary; I is for innovative; E/I is for evolutionary design with innovative features; O is for operating NPP.

APPROACHES IN DESIGN: POSTULATED EVENTS, LAYOUT, PASSIVE FEATURES, BEYOND DESIGN BASIS EVENTS, AND EMERGENCY PLANNING ISSUES

Postulated External Events

External events postulated in the designs of the advanced NPPs considered are summarized in Table 2. The natural external events, viz. earthquakes, wind, floods are considered, as applicable to a site, for a majority of the NPP designs surveyed. Among the human-induced external events, accidental aircraft crash evaluation and external stationary explosions lead with their consideration in at least nine of the fourteen designs, even though the extent of the event definition (impact of small aircraft vs. large commercial airliner at various crash speeds) vary. In at least one design, internal flooding has been treated as an external event. Some of the external events are specific to a floating NPP alone, while a group of reference external events (as per IAEA-TECDOC-1341 [6]) has not been taken into consideration for any of the fourteen designs, obviously on account of their inapplicability based on site features considered for these reactor designs.

Approaches In Design

On an analysis of the different reactor designs it was noted that the approaches to deal with external events might be classified into two categories:

Structural design and layout based approaches which provide protection to safety related buildings and structures, systems and components against external events;

Design measures that strengthen the plant robustness or redundancy in general, to resist effects of both internal and external events.

Structural Design And Layout Based Approaches

In all the addressed designs, the safety related structures are designed for design basis earthquakes, winds, extreme and severe meteorological conditions and design basis flood in line with national codes.

In addition, in several designs, a major emphasis is noted in the treatment of aircraft impact, and in the attention to achieve robustness of design that could enhance safety under extreme external events beyond the design basis. One approach used in the design is to ensure that buildings and structures have a capability to withstand the specific design basis external events. For example, in EPR Finland design (Fig. 1), the reactor building as well as the surrounding auxiliary buildings housing safety related equipment are structurally strengthened to the extent needed for surviving the impact of a large commercial aircraft. Some design measures, provided to deal with specific external events, call for additional protective features in plant layout and design. In EPR and SWR 1000, for example, aircraft crash protection measures have been implemented through attention being paid to plant layout, low vertical profile of containment, and additional robustness of protective external structures.

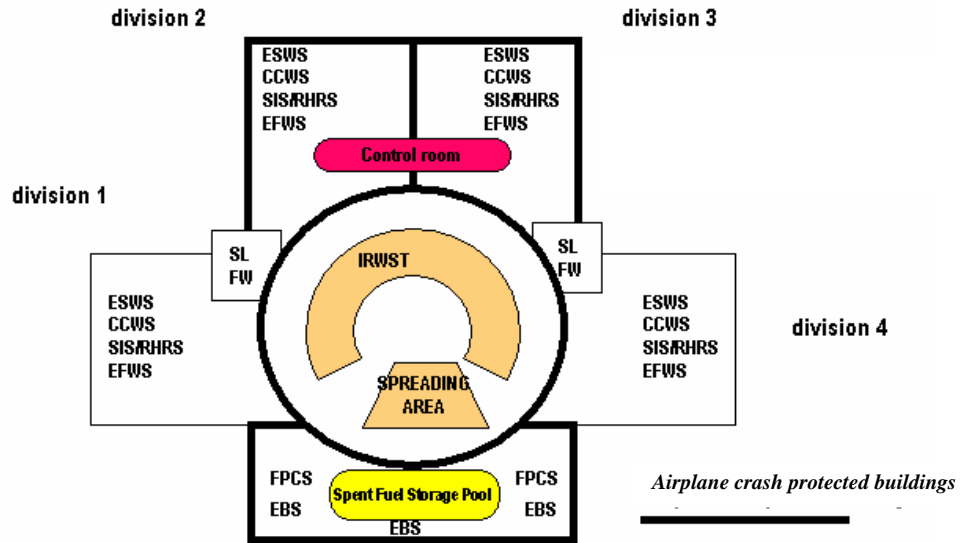
In a large number of the designs, provision of redundancy of safety related systems and their physical separation in plant and building layout is an important element of defence in depth to ensure that in the event of limited damage to a portion of the safety related system, caused by external events, the remaining undamaged portion can still perform the required safety function.

Table 2. Postulation of external events in the design of some advanced NPPs [3]

CATEGORY	EXTERNAL EVENT (EE) GROUP	NPP DESIGNS FOR WHICH THE EE GROUP WAS EXPLICITLY MENTIONED	NUMBER OF NPPS
Natural events considered in several plants	Earthquakes	APR1400, EPR Finland, VBER 300 FNPP ² , VVER 91/99, IRIS, PHWR-540, ACR-700, SWR 1000, VK-300, ABWR-II, BN-800, AHWR, CHTR	13
	Extreme meteorological conditions (temperature, snow, hail, frost, subsurface freezing, drought).	APR1400, EPR Finland, VVER 91/99, IRIS, PHWR-540, SWR 1000, VK-300, ABWR-II, BN-800, AHWR, CHTR	11
	Floods (from tides, tsunamis, seiches, storm surges, precipitation, waterspouts, dam forming and dam failures, snow melt, landslides into water bodies, channel changes, work in the channel).	APR1400, EPR Finland, VVER 91/99, CAREM-25, IRIS, PHWR-540, SWR 1000, VK-300, AHWR, ABWR-II, CHTR	11
	Cyclones (hurricanes, tornadoes and tropical typhoons)	APR1400, VVER 91/99, CAREM-25, IRIS, ACR-700, PHWR-540, VK-300, ABWR-II, BN-800, AHWR, CHTR	11
	Lightning	EPR Finland, CAREM-25, IRIS, ACR-700, PHWR-540, SWR 1000, ABWR-II, AHWR, CHTR	9
	Landslides and avalanches.	SWR 1000, CHTR	2
Human induced events considered in several plants	Aircraft crashes	EPR Finland, VBER 300 FNPP, VVER 91/99, IRIS, PHWR-540, ACR-700, SWR 1000, VK-300, BN-800, AHWR	13
	Explosions (deflagrations and detonations) with or without fire, originated from offsite sources and on-site (but external to safety related buildings), like storage of hazardous materials, transformers, high energy rotating equipment.	EPR Finland, VVER 91/99, CAREM-25, PHWR-540, SWR 1000, VK-300, BN-800 VBER 300 FNPP, AHWR	9
	Electromagnetic interference from off-site (e.g., from communication centres, portable phone antennas) and on-site (e.g., from the activation of high voltage electric switch gears).	EPR Finland, VVER 91/99, IRIS, ACR-700, SWR 1000, BN-800, AHWR, CHTR	8
	Collision of ships and floating debris (ice, logs, etc.) with the water intakes and other hazards with potential influence on cooling water intakes	VBER 300 FNPP, VVER 91/99, VK-300, EPR-Finland, SWR 1000, AHWR	6
	Fire generated from off-site sources (mainly for its potential for smoke and toxic gas production).	EPR Finland, APR1400, VBER 300 FNPP, SWR 1000, PHWR-540	5
Additional external events	Internal flooding	APR1400, VBER-300 FNPP, AHWR	3
	Internal hazard loads	BN-800	1
External events specific to floating NPPs	Breakdown of attachment or rigid mooring bars due to ice lock with further grounding under strong wind and heavy sea; Minor shock against mooring ship (service ships); Ship-to-shore communication pipeline rupture; Floating power unit grounding, including rocky ground natural phenomena during haul (heavy sea, wind, ice)	VBER-300 FNPP	1
External events not considered in any of the NPPs	Release of corrosive gas and liquids from off-site and on-site storage; Abrasive dust and sand storms; Volcanism.		0

Another common approach used in several designs relates to provision of redundancy and physical (layout) separation of systems fulfilling safety functions. In several designs, with either outer containment (VVER 91/99, PHWR-540, EPR Finland, AHWR) or a reactor/ auxiliary building (or compartment) surrounding the inner containment (IRIS, CAREM, SWR 1000, VBER-300), the outer structure provides the protection to inner containment against direct damage caused by impact or blast loads. The ACR-700, AHWR and PHWR-540 designs provide for two physically separate, mutually independent trains of safety and plant protection systems, with an auxiliary control room being available in case the main control room becomes unavailable.

² FNPP is the acronym used to denote a floating, i.e., barge-mounted NPP



Emergency feedwater system (EFWS)
 Component cooling water system (CCWS)
 Emergency boration system (EBS)
 Valve compartments (SL/FW)

Essential service water system (ESWS)
 Safety injection system (SIS)
 Fuel pool cooling system (FPCS)

Fig. 1. Layout of EPR Finland showing features for protection against aircraft impact [3].

Some generic design approaches of advanced NPPs to deal with external events, other than those conventionally adopted for most current generation reactors, are summarized in Table 3.

Several types of future advanced NPPs are expected to have a wider spectrum of applications and designs (floating NPPs, desalination plants, combined electricity and district heating plants, very high temperature reactors, reactors with very long core lifetime, etc.). Many of these designs may adopt new design approaches to address specific external events. For example, for a reactor coupled with a hydrogen generating plant in close proximity, a major consideration could be events originating in the hydrogen generating plant.

Table 3. Structural design and layout approaches that facilitate protection against impact of external missiles [3]

#	GENERIC DESIGN APPROACHES	NPPs (BASED ON QUESTIONNAIRES)	NUMBER OF NPPs
1.	Primary containment located within either a secondary containment or an external structure or building capable of withstanding postulated external impacts	APR1400, EPR Finland, VVER 91/99, CAREM-25, IRIS, PHWR-540, AHWR, SWR 1000, VK-300, CHTR	10
2.	Redundant physically separated safety trains with single containment capable of withstanding postulated external impacts	EPR Finland, APR1400, VBER 300 FNPP, VVER 91/99, ACR-700, AHWR, SWR 1000, ABWR-II, BN-800, CHTR, VK-300	11
3.	Physical and electrical separation of safety related equipment and cables.	APR1400, EPR Finland, VVER 91/99, PHWR-540, ACR-700, AHWR, ABWR-II, SWR 1000, BN-800, VK-300	10
4.	Structural design of structures against extended missile loading, e.g., aircraft impact	APR1400, EPR Finland, VBER 300 FNPP, SWR 1000, BN-800, VK-300	6
5.	Structural decoupling of inner structures with external containment to reduce the loads on these structures and safety related equipment arising out of external impact	EPR Finland, SWR 1000, PHWR-540, AHWR, VK-300	5
6.	Special measures to prevent poisonous gases intake into habitable areas and/or providing for a passive habitability system.	EPR Finland, IRIS, AHWR, SWR 1000	4
7.	Low vertical profile of reactor building to reduce possibility of aircraft impact.	IRIS, CHTR	2
8.	Safety significant equipment and systems such as diesel generator and spent fuel storage building located within protected structures	APR-1400, EPR Finland, SWR 1000	3
9.	Common base slab of auxiliary and containment buildings for enhanced seismic resistance	APR1400, EPR Finland	2

Design Measures That Strengthen The Plant Robustness In General, To Resist Both Internal And External Events

A desirable goal for the safety characteristics of an innovative reactor is that its primary defence against serious accidents is achieved through its design features preventing the occurrence of such accidents. Active safety systems or prompt operator actions are then not required to prevent significant fuel failure and fission product release. The plant can be designed such that its passive features provide adequate protection despite operational errors or equipment failure. Such robustness in design contributes to a significant reduction in the conditional probability of severe accident scenarios arising out of initiating events of internal and external origin. The function of confinement of any radioactivity released in the containment is also made more reliable by adopting robust, redundant, and sometimes, passive design features.

The current generation nuclear power reactors have several safety features to enable the plant to meet all the safety objectives under a variety of postulated initiating events and several combinations thereof. An important criterion for setting up a goal for safety, either implicitly or explicitly, has been the probability of large release of radioactivity outside the plant or site boundary as a consequence of any credible accident scenario. Even in designs, where probabilistic safety targets are not explicitly expressed, the selection of combination of postulated initiating events indirectly relates to probability of occurrence of large release. Many of the innovative reactor designs aim to minimize this probability by introducing additional robustness (often as a consequence of larger design margins) and by introduction of passive safety features, which do not require dependence on external sources of power or operator actions to perform their stipulated functions.

Passive And Inherent Safety Features Used In Some Designs Of Advanced Reactors

Several specific passive safety features are being adopted in the designs of evolutionary and innovative NPPs. Many of these features are common to the different advanced NPP designs addressed. On the basis of information gathered from the questionnaires, a non-exhaustive list of design approaches and enabling technologies, specifically used in these NPP designs has been prepared and provided in [3]. Some highlights of it are given in Tables 4 and 5.

Table 4. Heat sinks remaining available with the loss of external coolant supply [3]

SAFETY FUNCTION	SPECIFIC DESIGN APPROACHES OR ENABLING TECHNOLOGIES	NAMES OF RELEVANT NPP DESIGNS
Post shut-down decay heat removal	Availability of large heat sink either within containment or in thermal communication with the containment (e.g., large pool of water, ambient atmosphere) for decay heat removal.	APR1400, CAREM-25, SWR 1000, ABWR-II, AHWR, IRIS, VK-300, ACR-700
Emergency condition core (ECC) heat removal	Availability of large pool of water within containment acting as a source for passive ECC injection.	EPR Finland, PHWR-540, AHWR, CAREM-25, IRIS, ABWR-II, SWR 1000, VK-300, APR1400, ACR-700

Table 5. Passive systems, which do not require any signals to get actuated or to perform safety functions even with non-availability of all sources of power, coolant and other supplies external to protected buildings [3]

SAFETY FUNCTION	SPECIFIC DESIGN APPROACHES OR ENABLING TECHNOLOGIES	RELEVANT NPP DESIGNS.
Shut down / power regulation	Passive Pressure Pulse Transmitters (PPPT) used to activate control rod drives (CRD) with scram system	SWR 1000
	Use of steam over-pressure to drive a valve that passively effects reactor shut down.	AHWR
	Use of high (liquid heavy metal) coolant temperature to passively effect shut-off rod drop	CHTR
	Passive power regulation with feedback from coolant outlet temperature	CHTR
Full power core heat removal	Natural circulation for heat removal under normal power condition	CAREM-25, AHWR, VK-300, CHTR, VBER-300 FNPP
Post shutdown decay heat removal	Use of passive valves actuated by steam over-pressure to valve-in natural circulation based decay heat removal system.	AHWR
	Natural circulation capability in the reactor coolant system to cope with transients due to loss of forced flow	ACR -700 SWR 1000
	Natural circulation driven decay heat removal	IRIS, CHTR, VK-300
Emergency condition heat removal	Use of high coolant temperature to passively effect heat removal through vessel wall	CHTR
	Passive emergency core cooling system (ECCS) coolant injection	APR1400, AHWR, VBER-300 FNPP
	Passive core flooding in the event of LOCA	SWR 1000, VK-300
	Emergency condensers for heat removal from the reactor pressure vessel (RPV)	SWR 1000, VK-300
	Passive containment cooling system	ABWR-II
	Passive core water make-up from containment	IRIS

Reliability Of Passive Safety Features

Passive systems should, by definition, be able to carry out their mission with minimum or no reliance on external sources of energy and should operate only on the basis of fundamental natural physical laws, such as gravity. Passive systems may play a significant role to reduce the conditional probabilities of occurrence of severe accident scenarios following extreme external events, which could jeopardise operator initiated and plant protection system initiated interventions. To evaluate these conditional probabilities, and to establish the contribution of passive systems in the development of accident scenarios, it is important to have an assessment of reliability of passive systems. An approach to carry out such an assessment, mainly based on [7], is outlined in the following paragraphs.

It may be stipulated that a passive system may fail to fulfil its mission because of a consequence of the following two failures:

Component failure: Classical failure of a component or components (passive or active) of the passive system;

Phenomenological failure: Deviation from expected behaviour due to physical phenomena, e.g., related to thermal hydraulics or due to different boundary or initial conditions.

The reliability of components of a passive system can be evaluated by means of well-proven classical methods. However, aspects like lack of data on some phenomena, missing operating experience over the wide range of conditions, and the smaller driving forces make the reliability evaluation of passive system phenomena a challenging one.

For evaluating the failure probability of passive systems, the methodology may move from the classical methods used for Probabilistic Risk Analysis (PRA) and consider, in addition to real components (valves, pumps, instrumentation, etc), virtual components, that represent the natural mechanism upon which the system operation is based (natural circulation, gravity, internal stored energy, etc.). The contribution of real components can be easily assessed by resorting to the reliability databases available, whereas for evaluating the virtual component contribution (process condition related) it is necessary to develop a procedure that allows such assessment despite the lack of failure data. An example of such methodology for evaluation of passive system reliability is shown in the Fig. 2.

Design Approaches To Address Beyond Design Basis Accidents

Beyond design basis accidents (BDBAs) are defined as accident conditions which are more severe than a design basis accident (DBA). Within this category of accidents, the following two classifications exist:

Beyond design basis accidents without significant core degradation;

Severe accidents – which are accident conditions more severe than a DBA and involve significant core degradation.

The more common approaches to address BDBAs, followed in the fourteen designs addressed, have been summarized in Table 6.

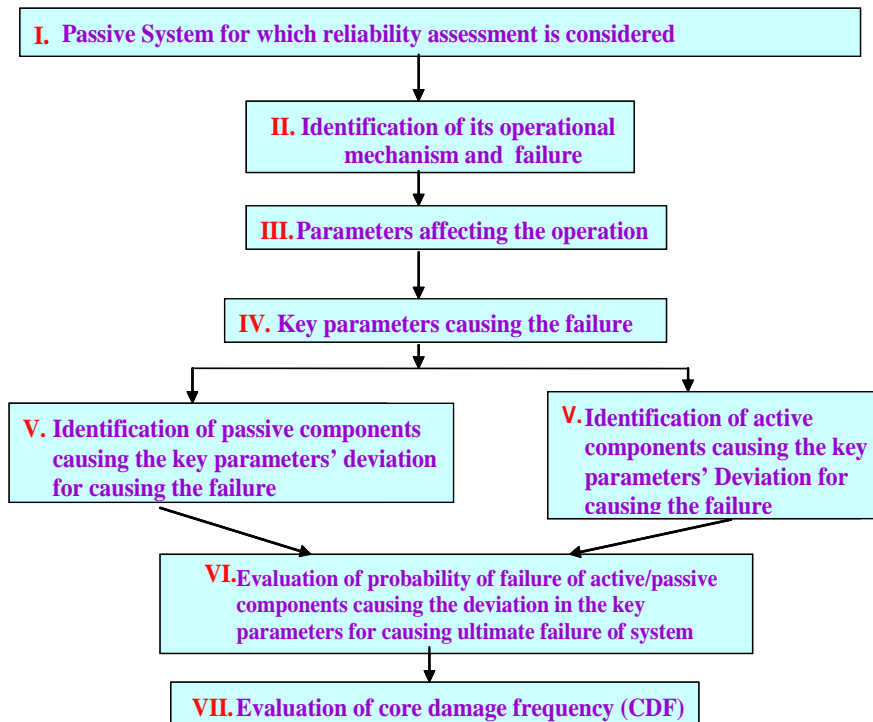


Fig. 2. Passive system reliability evaluation methodology APSRA (BARC, India [3]).

Table 6. Design approaches to address beyond design basis accidents [3]

SAFETY FUNCTION	SPECIFIC DESIGN APPROACHES OR ENABLING TECHNOLOGIES	RELEVANT NPP DESIGNS.
Prevention of fuel failure	Fast acting diverse shutdown systems	APR1400, AHWR, IRIS, PHWR-540, ACR-700, SWR 1000
	Multiple redundant passive ECCS trains	AHWR, VK-300
Prevention of pressure boundary failure	Cold moderator surrounding the fuel channels, which can serve as heat sink; water filled reactor vault	PHWR-540, AHWR, ACR -700
	Flooding of reactor cavity following LOCA and external reactor vessel cooling system	SWR 1000, APR1400, IRIS, AHWR
Avoidance of high pressure core melt ejection	RPV depressurization by highly redundant and diverse safety relief valves (SRV) / automatic depressurization system (ADS) to avoid high pressure core melt sequences	EPR Finland, ABWR-II, SWR 1000, IRIS
	Low pressure calandria or reactor vessel	AHWR, PHWR-540, ACR-700, CHTR
	Use of reactor vessel bottom cooling system to confine the melt inside the vessel (In-Vessel Retention - IRV)	VBER-300 FNPP, IRIS
Hydrogen mitigation (for water cooled reactors)	Hydrogen mitigation after core melt by passive autocatalytic recombiners	ABWR-II, IRIS, APR1400, ACR-700, EPR Finland, VK-300
	Containment inerted by nitrogen to avoid hydrogen-oxygen reactions	IRIS, ABWR-II, SWR 1000
Maintaining containment integrity	Emergency containment spray back-up system	APR1400, VVER 91/99
	Containment heat removal systems	EPR Finland, IRIS, ACR-700, AHWR, SWR 1000, ABWR-II, VK-300
	Containment is designed for hydrogen generation of 100% zirconium oxidation	SWR 1000, VK-300
Control of releases outside containment	Limiting radioactive releases by containment isolation and filtering of potential leakages	EPR Finland, PHWR-540, ACR-700, SWR 1000, AHWR, VBER- 300 FNPP, ABWR-II
	Secondary containment, with purging arrangement to maintain negative pressure in annular space between primary & secondary containments	PHWR-540, AHWR, VK-300, SWR 1000, EPR Finland
	Passive containment isolation system	AHWR, SWR 1000

Emergency Planning Issues For Advanced Reactors

Most of the NPPs with innovative reactors aim to eliminate the need for intervention in public domain (outside the plant boundary) through the use of enhanced passive safety features in their design. Many of these designs also aim to take advantage of the advanced safety characteristics to seek exemption from maintaining a large exclusion distance around the nuclear power plants.

Seven out of the fourteen designs addressed specifically consider the strengthening of safety features in these designs a sufficient basis for contemplating either ‘nil’ or significantly reduced need for intervention in public domain under BDBA conditions.

Enhanced Safety Objectives For Advanced NPPs

There was a consensus at an IAEA technical meeting of 14-19 November 2004 that the design of future advanced reactors should progressively be based upon an integrated approach taking into account both internal and external events together, using technology independent quantitative probabilistic safety criteria as a basis [3]. Evolution of quantitative probabilistic safety criteria is a prerequisite for such approach.

The current nuclear energy systems are designed to meet stringent safety criteria, as laid down in various international and national regulatory codes, guides and other documents, e.g., [8]. The risk to the general public, and the environment, from the operation of these NPPs has been demonstrated to be far less than that from any other comparable industrial activity. Nevertheless, an anticipated several fold increase in the global fleet of nuclear energy systems as required to meet large energy needs in densely inhabited regions, should potentially call for, as a minimum, one of the following enhanced safety related goals, also considered to be of special importance to public acceptability [3]:

- The core damage frequency (CDF) should be reduced, at least in inverse proportion to the number of reactors in operation (this is related to the risk of latent fatalities);
- The large release frequency (LRF) should be reduced to such an insignificant level that implementation of emergency measures in public domain is not needed, and it is possible, in principle, to site the NPPs in close vicinity of population centres (this is related to the risk of prompt fatalities).

Reflecting the aforementioned considerations, INSAG-12 [9] spells out the objective for future plants as the practical elimination of accident sequences that could lead to large early radioactive releases, whereas severe accidents that could imply late containment failure would be considered in the design process with realistic assumptions and best estimate analyses so that their consequences would necessitate only protective measures limited in space and in time.

CONCLUSION

Accident prevention is the main driving force for advanced NPP designs. Several design innovations are aimed towards bringing down conditional core damage frequencies (CCDF) to an extent that make the plant less vulnerable to extreme external event based and malevolent event based accident scenarios. Typical design approaches that, among others, could contribute to achieve such robustness in design are:

- Capability to limit reactor power through inherent neutronic characteristics in the event of any failure of normal shutdown systems, and/ or provision of a passive shutdown system not requiring any trip signal, power source, or operator action to effect a shutdown of the reactor if the safety critical plant parameters tend to exceed the design limits;
- Availability of a sufficiently large heat sink within the containment to indefinitely (or for a long grace period) remove core heat corresponding to abovementioned event;
- Availability of very reliable passive heat transfer mechanisms for the transfer of core heat to this heat sink;
- Measures to ensure deterministically the immunity of abovementioned functions from external events and malevolent human actions.

It is often observed that engineering features that make plants safe for internal events also make the plant safer under external events. However, any new features should be checked for additional or peculiar vulnerabilities under external event scenarios.

In view of their potential advantages in terms of independence from other systems and operator actions, passive systems may play a very significant role to reduce the conditional probabilities of occurrence of severe accident scenarios following the extreme external events, which could jeopardise operator initiated and plant protection system initiated interventions. A reliable safety assessment of NPPs with innovative reactors requires well-developed assessment procedures for the reliability of passive systems.

It was observed that innovative design measures need to be supported and encouraged by a rational technical and non-prescriptive basis to define a severe accident (core melt need not be postulated to occur). The rational technical basis could be derived from realistic scenarios applicable to the specific plant design. This implies that it could be necessary to carry out best estimate calculation of source term in order to take full advantage of new reactor designs.

External events should be considered together with internal events in an integrated approach in design, yielding cost effective solutions that meet quantitative probabilistic safety criteria for the plant, as well as deterministic success criteria for the systems, structures and components important to safety. Rules for combination of events and combination of loads could come out of this approach, which is yet to be developed. However, provisions of existing safety standards and national practices, including those relating to the treatment of external events, could be a starting point [4 - 6, 8].

External events should be considered at the early stages of the reactor design (e.g., plant layout, containment design, etc.). If external event considerations are added at later stages, they may lead to major modifications or even unacceptable safety levels.

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