IAEA-SM-353/18

BALANCING PASSIVE AND ACTIVE SYSTEMS FOR EVOLUTIONARY WATER COOLED REACTORS

N.S. FIL
OKB Gidropress, Podolsk, Russian Federation

P.J. ALLEN
Atomic Energy of Canada Ltd, Canada

R.E. KIRMSE
GRS, Germany

M. KURIHARA
Mitsubishi Heavy Industries Ltd,
Yokohama 220-8401, Japan

S.J. OH
Korea Electric Power Research Institute,
Taejon, Republic of Korea

R.K. SINHA
Bhabha Atomic Research Centre,
Trombay, Mumbai, India

Abstract

Advanced concepts of the water-cooled reactors are intended to improve safety, economics and public perception of nuclear power. The potential inclusion of new passive means in addition or instead of traditional active systems is being considered by nuclear plant designers to reach these goals. With respect to plant safety, application of the passive means is mainly intended to simplify the safety systems and to improve their reliability, to mitigate the effect of human errors and equipment malfunction. However, some clear drawbacks and the limited experience and testing of passive systems may raise additional questions that have to be addressed in the design process for each advanced reactor. Therefore the plant designer should find a reasonable balance of active and passive means to effectively use their advantages and compensate their drawbacks. Some considerations that have to be taken into account when balancing active/passive means in advanced water-cooled reactors are discussed in this paper.

1. INTRODUCTION

The future of nuclear power depends essentially upon the two interconnected factors: how effectively and how safely it performs. The accumulated experience of nuclear power (around 450 commercial reactors with about 9000 reactor-years of operation at the end of this year) has demonstrated the good indices in both these aspects in comparison with the conventional power technologies. Few accidents have occurred in the history of nuclear energy, and the most serious ones turned out to be the results of the improper human actions or disconnection of those safety systems which have been designed specifically to prevent such accidents. So, many people's scepticism about the use of nuclear energy is not justified considering the causes and consequences of the events that have occurred.

To convince the public about the existing safety level and the competitiveness of nuclear power as well as to consider the increased demand of the public on safety, all organisations involved in nuclear power development and generation continue to give increasing attention to the safety and economics of the current and future nuclear power plants. In particular, great efforts are being devoted to this subject world-wide by designers, utilities and regulatory bodies as applied to advanced water-cooled reactor concepts. Many of these designs employ so-called passive features and means, some well proven by operation of existing reactors and others relatively novel. With respect to plant safety, application of passive systems/components is intended to simplify the safety systems and to improve their reliability, to mitigate the effect of human errors and equipment failures, and to provide increased time margin to enable the operators to cope with design basis accidents, as well as with design extension accidents.

The IAEA Conference on "The Safety of Nuclear Power: Strategies for the Future" [1] included discussions on the safety of future plants, and noted that "the use of passive safety features is a desirable method of achieving simplification and increasing the reliability of the performance of essential safety functions, and should be used wherever appropriate. However, a careful review of potential failure modes of passive components and systems should also be performed to identify possible new failure mechanisms". It was stressed that safety can be achieved by using either passive or active systems or a combination, and that both types of systems should be analysed from the standpoint of reliability and economics.

The application of passive means is connected with some problems which have to be solved by each plant designer. The passive systems have their own advantages and drawbacks in comparison with the active systems both in the area of plant safety and plant economics. Therefore a reasonable balance of traditional systems and new passive means is adopted in many future reactor concepts as the possible way to improve safety and public acceptability of nuclear power, and at the same time to keep nuclear power competitive with conventional power technologies. Some considerations which have to be taken into account when balancing active/passive means in the advanced reactors are discussed in this paper.

2. ACTIVE-PASSIVE CATEGORIZATION

Consideration of the operating nuclear power plants and the advanced concepts shows that safety systems cannot be simply classified only by two terms "active" and "passive". We can often find passive and active means in one safety system or even in its separate components. The traditional emergency core cooling system of the pressurized water reactor could be mentioned as an example of a safety system where the hydro-accumulators (passive element) and high/low pressure injection pumps (active element) are being used.

In several IAEA Technical Committee meetings the general definitions, descriptions and explanations of passive/active systems have been given. According to the IAEA definition, a system should be classified as passive if it consists of only passive components and structures or uses active components in a very limited way to initiate subsequent passive operation. Usually a system should be classified as passive if no external input is needed to perform its safety functions; otherwise a system is considered as active. The above definition of a passive system allows the use of instrumentation and the one-time repositioning of valves if adequate passive power supplies (e.g., batteries) are available.

One may also ascribe the "degree of passivity" to the system depending on the existence and necessity of the moving fluids, moving mechanical parts and external initiating signals; again the "degree of activity" may be ascribed to an active system depending upon the necessity of human actions and external inputs to initiate or to operate the system. Such a classification on the scale from fully passive to fully active may be useful for the system evaluation. For this classification, some items, either the inherent characteristics of the system or needed for the system to perform its function may be indicated (e.g. moving fluid, moving mechanical parts, input signal, etc.). Depending upon the number of the proposed items which are needed, a classification of seven categories was proposed in the framework of an IAEA study [2], shown in table I.

The system which has none of the active items is the system of Category 1 and it has the maximum of passive safety features (such a system could be considered as fully passive). An example of fully passive means would be cooling by radiation directly to the environment. Category 7 describes the features of a fully active safety system that can be characterised by the presence of all the above items;

the fire detection and fighting system may be an example of this category. In the IAEA-TECDOC-626, passive systems are described in 4 categories (A, B, C and D) which are the same as categories 1 to 4 mentioned in the table above. The above 7 categories are generally in agreement with the discussions that have been carried out during the IAEA technical committee meetings in Vasteras (1988) and Julich (1994).

Table I. Degrees of passivity

Cat.	Criteria						Examples
	moving fluid	moving parts	signal inputs	extern. power	human initiation	human interact.	
1	no	no	no	no	no	no	cooling by radiation
2	yes	no	no	no	no	no	cooling by free convection
3	yes	yes	no	no	no	no	check valves, accumulators
4	yes	yes	yes	no	no	no	passive heat removal system
5	yes	yes	yes	yes	no	no	ECCS of current PWRs
6	yes	yes	yes	yes	yes	no	boron injection
7	yes	yes	yes	yes	yes	yes	fire detection and fighting

Passive systems fall into the categories 1 to 4, and categories 5 to 7 are usually called active systems. In categories 2 – 4, the fluid (e.g. air, water) moves without external energy due to thermal-hydraulic conditions, whereas in categories 5 – 7, fluid movements are supported by pumps driven by external energy. In categories 3 and 4 mechanical movement occurs due to imbalances within the system (e.g. static pressure difference) or due to the forces directly exerted by the process (e.g. energy input into the closed reservoir of fluid). In categories 5 – 7, mechanical movement is supported by external energy. The systems in category 4 are initiated by components that rely on electronic, electro-mechanic, hydraulic or pneumatic logic.

3. CONSIDERATIONS TO GOVERN THE BALANCING PASSIVE/ACTIVE MEANS

The above classification does not mean that a more passive system should be automatically considered as more reliable with regard to the fulfilment of the designated safety function. These categories are intended to illustrate the concept of the spectrum from active to passive components. Both passive and active systems/components have advantages and drawbacks; therefore, a case by case evaluation must be made, considering at first the fulfilment of the required safety function with sufficient reliability but also other aspects as e.g. the impact on plant operation, design simplicity and - last not least - costs. The best effect for the plant safety may be achieved with a reasonable combination of active and passive features to assure a certain safety function. Combined usage of active and passive safety means for the advanced reactors may allow to decrease the sensitivity of the safety functions to common cause failure, to increase the plant safety and at the same time to improve its economic performance.

The comprehensive effects of the balancing of passive/active safety means on the overall plant safety can be quantified through the use of probabilistic safety assessment methodology, yielding the values of the core damage frequency (CDF) and the large off-site radioactivity release frequency (LRF). Also, the effect of passive features in the system design may be quantified deterministically in terms of the maximum tolerable inaction time (MIT), during which the designated safety function is assured even in the absence of any actions performed by either operator or by active components. A low value of CDF is an indicator of the robustness of design, and investment protection. A low value of LRF is important for environment protection and public acceptance. A high value of MIT deterministically provides a measure of robustness in the plant design for dealing with any unforeseen situations of the equipment failures and operator errors. It should be noted, that today the acceptable or desirable figures for CDF and LRF are directly included in the normative documentation of some countries. For example, according to Russian safety standards, these figures should be less than 10^{-5} and 10^{-7}, respectively; among other factors, this large difference between CDF and LRF results in the relatively wide usage of passive means in the advanced concepts of the Russian plants VVER-1000/V-392 and VVER-640/V-407.

From an academic view point, to find the optimum balance of active and passive means, it will be desirable to minimise CDF and LRF, and maximise MIT, to the extent possible under given constrains (e.g., plant capital and operational cost). However, for the advanced reactor concepts incorporating a number of relatively new design features and accident scenarios to be considered, it is difficult to accurately quantify many of the inputs needed for computation of CDF and LRF. This may result in a rather large uncertainty in the predicted values of these parameters. Therefore, with regard to these criteria an equally dependable conceptual decision about the active/passive features coupling may be achieved, more quickly and economically, on the basis of engineering judgement applied in a qualitative manner.

This approach can be translated in the form of the following considerations:

- application of passive features should reduce the number of components, and yield design simplification, so that the number and complexities of safety actions can be reduced;
- the passive means should be taken, to the extent possible, from similar ones having certain operational experience at power plants or elsewhere, so that the efforts needed to demonstrate the reliability and licensability are not too large;

Passive systems should be applied with high priority whenever such systems can provide one or more of the following benefits:

- elimination of need for the short-term operator actions during accidents being taken into account in the design;
- minimisation of dependence on off-site power, moving parts, and control system actions for normal operation as well as during design basis and beyond design basis accidents;
- reduction in capital, operation and maintenance costs due to design simplification.

Thus, the reasonable balance of the passive and active safety systems in the advanced reactor concepts is based on the detailed consideration of their advantages and disadvantages as applied to their effect on the overall plant safety and total cost. In general, one should point out the most essential advantages of the passive systems/means as follows:

- passive systems do not depend upon external energy supply
- passive features simplify the safety system configuration and reduce the number of equipment
- passive components may be more reliable than the active ones for their designated safety functions, but this should be carefully demonstrated over the expected range of conditions and considering possible degradation mechanisms
- passive systems decrease the possibility of human errors
- passive systems make the plant less sensitive to plant equipment malfunctions and erroneous operator actions.

The main drawbacks of passive safety systems include the lower driving forces and less possibility to alter the course of an accident if something undesirable happens (i.e., less operational flexibility). Due to low driving forces, the operation of these systems may be adversely affected by small variations in thermal-hydraulic conditions. Besides, the current computer codes are not sufficiently validated for the relevant conditions and phenomena (low pressure, low driving heads, effect of noncondensables, boron transport at low velocities, and the like). Therefore, separate effect and integral tests may be required for the code assessment and for demonstrating the safety performance of the passive systems being proposed in the design. The lower driving forces might also lead to quite large equipment, and this factor may reduce the cost savings projected from elimination or downsizing of active components. Besides, larger components may cause additional difficulties in seismic qualification on some plant sites, and this issue should be taken into account when evaluating the core damage and large release frequencies. In many cases, sufficient operating experience of the passive system/component under real plant conditions does not exist; so time-and money-consuming research and development works may be needed individually for each advanced reactor concept.

The design decisions with regard to the balancing active/passive features may also depend upon the functions assigned to the given system. In particular, the system having an important role in the mitigation of severe accident consequences which is located in potentially contaminated area (e.g., the part of the containment cooling system which is located inside the containment) could be designed as passive as reasonably achievable. This is because of the difficulty or even impossibility of access to such areas and because passive components may not require maintenance even during long term operation.

4. BALANCE OF PASSIVE/ACTIVE MEANS IN THE ADVANCED CONCEPTS

Safety features desired in future plants have been summarised by INSAG-5 in "The Safety of Nuclear Power" [3]. It notes that the Basic Safety Principles of INSAG-3 [4] remain valid and should become mandatory, and that beyond the safety principles of INSAG-3, but in extension of them, are further opportunities for improvement of safety on which new plant designs should begin to draw. They include several design approaches such as avoiding complexity, reducing dependence on early operator action, among others, and include specifically giving consideration in the design process to passive safety features. INSAG-5 further notes that though it may seem evident that passive systems are always safer, that may not be so in all cases. There may be safety disadvantages that would outweigh the gain. The superiority of the choice should be shown by demonstration or analysis.

Both novel and more or less proven passive systems and features are proposed in many advanced water-cooled reactor designs [5]. Some designs have only added a few passive components to the traditional systems. Some other designs make wide use of the passive systems/components to ensure or to back up a number of safety functions, including the basic ones: reactivity control, fuel cooling and confinement of radioactive substances. Many advanced water-cooled reactor concepts have implemented or considered different passive means to ensure these functions. In particular such functions as the containment heat removal, hydrogen management, core debris cool down and prevention of base-mat melt-through are probably among the most appropriate areas for passive systems usage. For example, the EPR concept with large power while preferring mainly active means for the prevention of core melt accidents also makes significant use of passive systems and components to ensure the confinement of radioactivity after such an accident. A brief review of the design decisions (implemented or being considered) to enhance the basic safety functions in the advanced reactor concepts is given below in this chapter.

4.1. Reactivity control

Traditional gravity-driven (in PWR and PHWR) or gas-pressure driven (in BWR) control rods is the main system to ensure reactor scram in currently operating reactors and in the advanced concepts. The traditional control rods system of PWRs is generally not effective enough to bring the reactor to a cold shutdown state. Therefore the reactivity control function is supported by chemical and volume control system and by emergency core cooling system injecting the highly borated water to the reactor. Although very good reliability records exist for scram excitation, some failures of the gravity-driven control rod insertion have been recognised. The failures occurred for different reasons such as loose parts in the primary circuit, broken fingers of rod clusters, deformation of guide tubes, deposition of impurities, fabrication defects, etc. In most cases, the effects of those failures were a reduction of insertion speed or an incomplete insertion. Besides, some failure modes have been considered which could prevent the reactor scram altogether, and therefore the designers need to analyse Anticipated Transient Without Scram events.

Taking into account the above deficiencies, some advanced concepts have implemented additional passive means to enhance the reactivity control function. The Russian advanced reactor concepts WWER-1000/W-392 and WWER-640/W-407 have an increased number of gravity-driven scram rods to maintain shutdown margin even in the absence of boron supply during the reactor cool down. Also, for the WWER-1000/W-392, a special rapid boron supply system has been designed and tested as a diverse system to the gravity-driven scram system for this reactor. A concentrated boron solution tank is connected to the suction and discharge pipes of each main coolant pump. The valves in the connecting pipes will automatically open if there is a demand for reactor trip but the reactor power after some time is higher than its value after scram. The concentrated boron solution is supplied to the reactor due to pressure difference between discharge and suction of the main coolant pump (pump head); even in case of loss of power the pump head during coastdown is sufficient to push out all the boron solution from the tank. The operability of the system has been confirmed by extensive experimental investigation using a scaled model.

All CANDU plants built in the last 20 years have a rapid gadolinium nitrate injection system that can shut the reactor down as quickly as the shutdown rod system. This injection system uses high-pressure helium to inject a gadolinium solution into the low pressure moderator. Instrumentation separate from the rod system and other safety systems but with equal capability to the rod system is used to open quick-acting, fail-open valves between the helium gas and the gadolinium solution.

A rapid emergency boration system is also implemented in the Sizewell B PWR for diverse reactor shutdown. It consists of four tanks of boric solution (3 m^3 of 7000 ppm concentration of boron in each tank), connected to each cold leg. The inertia of the main coolant pumps is sufficient for the system to fulfil its function. Functional tests were carried out, including mixing tests in case of the system failing on one of the four loops, and the results were used in the safety analysis.

4.2. Fuel cooling

The safety function "fuel cooling during transients and accidents" is ensured by provision of sufficient coolant inventory, by coolant injection, by sufficient heat transfer, by circulation of the coolant, and by provision of an ultimate heat sink. Depending on the type of transient or accident, a subset of these functions or all of them may be required. Various passive safety grade and safety relevant systems/components are proposed for future reactor concepts to fulfil these functions.

It is a feature of many advanced concepts that the water for replenishment of primary coolant inventory is entirely stored inside the containment. This ensures protection against external events and reduces the risk of loss of coolant accidents with containment bypass. Additional features implemented in some new designs to improve the replenishment of primary coolant inventory function include:

- pressurizer relief via the relief tank to the water storage tank;
- removal of heat from the primary circuit to the water storage tank via heat exchangers located in the water storage tank;
- water storage tank combined with the containment sump;
- water storage tank located at higher elevation than the reactor core for gravity-driven injection;
- storage of a portion of water at high elevation under the full primary pressure for coolant injection at high pressure.

Most of the new concepts suggest a combination of different passive and active means to ensure the function "coolant injection". Passive injection systems at high primary pressure are new in comparison to systems in operating reactors. AP-600 is an example of a design where this function is provided by core make-up tanks (CMT). Pneumatic isolation valves in the injection lines open automatically if one of the initiation setpoints (e.g. low primary pressure, low pressurizer level) is reached. These valves are fail-safe since they will open even if AC power fails. As long as the reactor coolant system (RCS) is still filled with liquid, cold water from the CMT flows to the RCS by natural recirculation. After the coolant starts to boil, steam enters CMT, the natural recirculation is terminated and injection to the RCS continues due to gravitation. To assure continued injection by medium and low pressure injection systems before the CMTs are empty, stepwise depressurization of the RCS is initiated if the liquid level in the CMT falls below defined setpoints.

Passive accumulator injection at medium primary pressure is applied in current pressurized water reactors as well as in the advanced concepts. Improvements of efficiency have been suggested for the future reactors on the basis of experience, such as optimised initial pressure, water/gas ratio, flow resistance in the injection line. Also, the abolition of the isolation valves in the injection lines is being considered in some new designs to increase the system reliability. The tendency in some advanced designs in comparison with the existing plants is to widen the primary pressure range for passive injection and to make it more controllable. The American AP-600, Russian W-392 and W-407, Mitsubishi APWR and Indian AHWR designs could be mentioned as examples of this tendency. In particular, Mitsubishi APWR designs make use of an advanced accumulator system to ensure the safety functions of core cooling. It has the function of both the accumulator tank and the low-pressure injection pump of conventional plants. So, the low-pressure injection pumps are eliminated and the safety injection system configuration is simplified.

Passive low pressure injection is foreseen in some new concept to replace or to back up the traditional pump injection being used for the operating plants. To ensure passive injection, the traditional water storage tank can be installed at higher level than the reactor core or special low pressure injection tanks at high elevation can be provided. Since the water level is at containment atmosphere, injection by gravity can only take place after complete de-pressurization of the reactor coolant system. This is accomplished e.g. by the last step of the de-pressurization sequence in the AP-600 design or by the special de-pressurisation system in the WWER-640/W-407 design; this system starts passively when the primary pressure decreases below 6 bar

The function “provision of sufficient heat transfer” in the advanced concepts is ensured in the same fashion as in currently operated reactors. This function is assured as long as sufficient water is supplied to the fuel rods. Sufficient water in the core is provided by the systems ensuring injection of the coolant as described above. Heat transport in reactor designs using mainly passive means is ensured during accidents by natural circulation between the core as heat source and heat sink (e.g. steam generators as in the Russian WWER-1000/W-392 design or heat exchangers in the water storage tank as in AP-600 design); the natural circulation may exist in single phase, two-phase and boiler-condenser modes. Some advanced designs make use of relatively new natural circulation paths, e.g. natural circulation after LOCA between sump and core via the sump screen and broken pipe in AP-600 or between the core, the flooded pool around the reactor and the spent fuel pool via the depressurization pipes and further connection pipes in WWER-640/W-407 design. The Indian AHWR uses natural circulation driven core heat removal during normal operation and hot shut down, making the core heat removal capability immune to the station black-out event.

The function “ultimate heat sink” for accident conditions in the advanced concepts is mainly ensured either by the water stored in tanks (located inside or outside the containment) or by heat transfer directly to the surrounding atmosphere (via special heat exchanger or via containment shell). In the first case, the heat sink may be limited in time, and human actions are required to restore it. For this type of the ultimate heat sink, the passive containment cooling water storage tank in the AP-600, which is needed especially for accidents in the design extension area, or the water tanks for passive containment cooling and for passive decay heat removal in W-407 and AHWR designs are examples. An example of the unlimited heat sink is the use of air heat exchangers in WWER-1000/W-392 design located outside the containment.

Another aspect of heat sinks that is sometimes made passive is the feedwater to the boilers. In CANDU, for example, there is gravity feed from an elevated tank into the boilers. High capacity valves can be opened in the steam system to depressurize the boilers and allow gravity flow for makeup.

4.3. Confinement of radioactive substances

This safety function is ensured by protecting and maintaining the integrity of the potential radioactivity release barriers (fuel, reactor system boundary and containment). These barriers are passive components as themselves; in addition, several passive means are proposed in new reactor concepts for the protection of these barriers. Most of these means are derived from design backfitting programs of existing plants, others are relatively novel. As far as the fuel and the pressure boundary are concerned, most of the considerations are the same as for the existing plants. New applications are mainly in the area of containment protection.

Essential reduction of radioactive releases intended for the advanced plants implies a significant reduction of the probability of core degradation up to core melt and - concerning the last level of defence-in-depth - a significant reduction of potential sources for radioactive releases in core melt scenarios. Severe accidents are considered already at the design stage of new concepts, so that the associated maximum conceivable release would necessitate only very limited off-site protective measures in area and time. The advanced concepts imply substantial improvement of the containment functions with respect to the radioactivity confinement in case of a core melt accident, and passive systems play an important role to achieve this objective.

Containment over-pressurisation may be avoided by passive containment cooling (e.g. this is proposed in AP-600, AHWR and W-407 designs) or by spray systems with preferably passive components inside the containment. Such design requirements are derived from the conditions inside the containment resulting from active systems failures. It also has to be considered that maintenance of the systems inside the containment may be impossible because the containment is not accessible during the long term phase of an accident. Filtered venting systems (like those at some existing plants) are also being considered in some concepts (e.g. WWER-1000/W-392) to prevent containment over-pressurisation. These systems are to be designed to follow the current long-term requirements in this area (e.g. filtered venting should not increase the risk of losing the containment function, filtered venting is not required in the short term of a core melt accident up to 24 hours, etc.). Some designs (e.g. AHWR) are being developed to incorporate passive means for isolation of the containment, using a water seal that gets established when a particular value of containment pressure is reached.

Special systems and components are being considered in many advanced concepts to solve the hydrogen-related problems during severe accident scenarios which are being considered in many advanced concepts. As a requirement, the containment volume should be designed large and strong enough to withstand a global deflagration of the maximum amount of hydrogen that can be contained in the containment atmosphere and also should resist a representative rapid local deflagration. Additional provisions are taken with respect to local detonation and to deflagration-to-detonation transition (DDT) sequences that might jeopardise the containment or its internal structures. A proper design of internal structures, catalytic devices for passive recombination of hydrogen, inerting of the containment atmosphere and other measures are taken to avoid dangerous concentrations of combustible gases (e.g. see GPR/RSK recommendations of 1993).

Penetration of the containment base-mat by molten corium must be avoided because this could result in a significant release and contamination of underground water and sub-soil. Passive core melt catching devices or specific spreading areas are suggested for this task in different advanced designs. Specific attention has to be paid for long term heat removal from the containment. For example in the

EPR concept, pipes are applied to connect the spreading compartment with in-containment water storage tank; these pipes are plugged by a fusible material. The plugs would be melted by contact with the corium, thus allowing the water to cool the corium in spreading compartment from the top.

5. CONCLUSIONS

The utilisation of passive systems in a reasonable combination with or instead of traditional active systems is being considered as an important measure to enhance the safety in many concepts of the next generation plants. Passive means have always been applied to reactor designs, and their wider usage in the advanced concepts is an available engineering option, not a safety objective by itself. Consequently no preference in general should be given for the use of either active or passive systems, and an individual evaluation is needed for each advanced design. The main criterion for the design decision is that the proposed system fulfils the required function to the appropriate reliability taking into account the existing constrains (e.g., for the plant economics).

The right balance of active and passive systems can be found only for each advanced concept separately, but the basic criteria for decision-making are the same for the most of the concepts. These criteria are mainly based on the weighing of passive and active system's advantages and disadvantages with regard to the designated functions, overall plant safety and cost. Some specific aspects should be reviewed when balancing passive/active means, such as:

- principle of defence-in-depth (e.g. multi-barrier concept), requirements of redundancy,
- diversification, single failure criteria, common cause failure modes;
- new accident scenarios such as inadvertent operation or interactions of systems;
- inspectability, recurrent testing, in-service testing close to operational mode;
- sensitivity to human errors and equipment malfunction;
- need of research and development work to demonstrate system operability.

There are some aspects in this area which are very plant specific, e.g. the validation of passive systems for plant conditions, integration of passive features in the overall safety systems, in-service inspection of passive components, etc. These problems have to be addressed by each plant designer to propose the optimal combination of active and passive systems and components. Nevertheless, one can conclude that passive systems/components have clear potential advantages in some applications. This conclusion is particularly true for beyond-design-basis accidents, and the passive means (systems) are being designed in many advanced reactors for severe accident mitigation. The design basis for these passive means (systems) is to be established with account for probabilistic safety criteria.

The IAEA, with international co-operation to elaborate global trends, has documented broad objectives for the development of advanced nuclear plants [6]. With regard to enhancing safety, its TECDOC-682 states that the plant design should seek to take the maximum, feasible advantage of inherent safety characteristics, and efforts should be made to utilise passive safety systems to the extent that they can be shown to be as reliable and cost effective as active systems for the same function.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Mr. V. Berkovich (AEP, Russia), Mr. J. Cleveland (IAEA), Mr.R. Lyon (IAEA) and Mr. A. Podshibiakin (OKB GP, Russia) for very fruitful discussions and comments on the paper. The assistance and support of Mr. A. Anand (BARC, India), Mr. Y. Choi (KEPRI, Korea), Mr. V. Fedorov (OKB GP, Russia), Mr. W. Frisch (GRS, Germany), Mr. K. Matsushita (NUPEC, Japan), Mr. E. Price (AECL, Canada) and Mr. M. Vidard (EDF, France) are greatly appreciated as well.

REFERENCES

[1] "The Safety of Nuclear Power: Strategy for the Future", Proceedings of an International Conference organised by the IAEA, Vienna, September 1991, (IAEA, Vienna, 1992).

[2] B.Th. EENDEBAK et al.: "Inherent and Passive Safety Features in the Design of NPPs", Int. Conf. on Design and Safety of Adv. Nucl. Plants, Vol. IV, Session 37-4, October 25-29, 1992, Tokyo.

[3] International Nuclear Safety Advisory Group, "The Safety of Nuclear Power", Safety Series No. 75-INSAG-5, (IAEA, Vienna 1992).

[4] International Nuclear Safety Advisory Group, "Basic Safety Principles for Nuclear Power Plants", Safety Series No. 75-INSAG-3, (IAEA, Vienna 1988).

[5] "Status of advanced water cooled reactor designs 1996", IAEA-TECDOC-968 (IAEA,Vienna, 1997).

[6] "Objectives for the development of advanced nuclear power plants", IAEA-TECDOC-682 (IAEA, Vienna, 1993).