Safety-Related
Innovative Nuclear Reactor Technology Elements

– R&D Network –

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TOPICAL REPORT

WORK PACKAGE 2:

INNOVATIVE SAFETY FEATURES

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This report and a great deal of additional information is available on the Internet. After having registered, it can be assessed via the SINTER Network Homepage:

http://www-is.ike.uni-stuttgart.de/sinter/

LIST OF CONTENT

LIST OF ABBREVIATIONS 4

1. INTRODUCTION TO WORK PACKAGE 2 6

2. DRIVERS FOR INNOVATIONS 9
2.1 Utility Requirements 9
2.2 Competitiveness 11
2.3 Licensing Requirements 16
2.4 Socio-political Drivers 18

3. INTERNATIONAL INNOVATION TRENDS 19
3.1 Methodology and Database 19
3.2 The safety objectives for future reactors 21
3.3 The classification and the assessment of the R & D activities 22

4. R&D PROPOSALS & INNOVATION POTENTIALS 24
Task 2.1: Innovative Reactivity Control Techniques 24
Task 2.2: Innovative Decay Heat Removal / Depressurisation Systems 25
Task 2.3: Innovative Measures for Maintenance of Coolant Inventory and Integrity of the Primary Circuit under Severe Accident Conditions 28
Task 2.4: Innovative Approaches on Source Term Reduction and Containment Designs 30
Task 2.5: Innovative Accident Management Measures & Influence of Human Factors 32

5. CONCLUSIONS & RECOMMENDATIONS ON FUTURE R&D ACTIVITIES 34

6.0 APPENDIX 37
6.1 Overview on Reactor Types in the SINTER Database 37
6.2 Database on Innovative Reactors 39
6.3 Innovative Features (e.g. ABWR) 42
6.4 Specific Safety Features: Accident Management (e.g. ABWR) 43
6.5 Specific Safety Features: Human Factors (e.g. ABWR) 44
6.6 Overview on Passive/ Innovative Safety Devices 45
6.7 Exemplary Extract from Database on Passive Safety Systems 55
6.8 Classification of the pursued objectives versus the defence-in-depth 57
6.9 Exemplary Comparative Evaluation of Innovative Systems 64

7. REFERENCES 74

LIST OF ABBREVIATIONS

ADS	Accelerator-Driven Systems
AHWR	Advanced Heavy Water Cooled Reactors
AI	Artificial Intelligence
ALWR	Advanced LWR
BWR	Boiling-Water Reactor
CANDU	Canadian Heavy Water Reactor
CDF	Core Damage Frequencies
CHP	Combined Heat and Power Generation
DBA	Design Basis Accident
DBC	Design Basis Conditions
DEC	Design Extension Conditions
DHR	Decay Heat Removal
D&D	Decontamination and/or Dismantling
ECCS	Emergency Core Cooling Systems
EUR	European Utility Requirements
EURD	European Utility Requirements Document
(LL) FP	(Long-lived) Fission Products
GPR	Gas Phase Reactor
IMF	Inert Matrix Fuel
JSRI	Joint Safety Research Index
LDHR	Loss of DHR function
LOCA	Loss of Coolant Accidents
(L) HLW	(Low) High Level Waste
MA	Minor Actinides
MCR	Main Control Room
MICA	MICHELANGELO Concerted Action
MMI	Man Machine Interface
MSR	Molten Salt Reactor
NERI	Nuclear Energy Research Initiative
NHSS	Nuclear Heat Supply System
NPP	Nuclear Power Plants
NPH	Nuclear Process Heat
NRWG	Nuclear Regulators´ Working Group

O&M	Operation & Maintenance
PBMR	Pebble Bed Modular High Temperature Reactor
PCI	Pellet Cladding Interaction
PCIV	Pre-stressed Cast Iron Vessels
PRHR	Passive DHR System (like AP 600)
PSA	Probabilistic Risk Assessments
PTR	Pressure Tube Reactors
P&T	Partitioning and Transmutation
RCS	Reactor Cooling System
RIA	Reactivity Insertion Accident
RPV	Reactor Pressure Vessel
RRP	Passive/active DHR with RPV-Internal Heat Exchanger
R&D	Research & Development
SA	Safety Authority
SCS	Passive DHR in Secondary Circuit (e.g. of SIR)
SIR	Safe Integral Reactor
SMR	Small and Medium-Sized Reactor
SGTR	Steam Generator Tube Rupture
SIS	Safety Injection System
WENRA	West-European Nuclear Regulators' Association
WP	Work Package

1. Introduction to Work Package 2

Social acceptance of nuclear power is largely influenced by the mechanisms of risk perception /1, 2/ as discussed in Work Package 1. Despite excellent operational behaviour of nuclear power plants in Europe and long practise in operation of LWR by over 6000 reactor years, public opinion still tends to decline from the future use of nuclear energy due to the mismatch in the human sentiment for danger on the one hand and objective safety criteria following the risk formula or established safety and licensing requirements on the other. The safety of nuclear installations as well as the strategies for avoidance and handling of radiotoxic wastes (see WP 3 and 4) have to be adopted to the evolution and mechanisms of risk perception by the public and to the general criteria for sustainable energy supply systems. The nuclear community has not only to react by technological 'mutations' of the safety philosophy and of the safety systems for future plants but to take other sustainability and economic requirements additionally also into account as an integral approach. As far as technically and economically feasible, this will also be important within the frame of system upgrading and modernisation of existing plants.

In this sense Work Package 2 addresses the requirements and potentials for R&D on innovative safety systems and safety concepts for different reactor types or generic safety issues. It focuses on new ideas for the main safety functions and on innovative approaches for an improved defence-in-depth strategy with the following technical objectives:

- increased importance of prevention
- improved control of accident sequences and initiating events
- improved protection systems
- effective accident management measures
- improved mitigation and limitation of consequences (e.g. improvement of the containment efficiency and barrier functions)
- rejection of cliff edge effects
- comprehensive defence (exhaustive PIE analysis for all the significant plant conditions, i.e. power, shut down, maintenance, etc.)
- homogeneous defence
- gradual defence

Innovative means to meet the above mentioned objectives could address:

- ➢ plant architecture / system simplifications
- ➢ functional redundancies implementation with an increased attention to self-acting (passive) safety systems being independent of external power supply
- ➢ long grace periods (plant inertia)
- ➢ inherent forgiving safety characteristics
- ➢ 'transparent safety' for enhanced public acceptance

The R&D approaches take into account the evolutionary experience feedback and actual strategies for improved capability to cope with severe accidents as well as more fundamental innovations. Economic competitiveness, cost / benefit analyses, consequences for the operation, maintenance etc. should be evaluated for new technical solutions, too.

This Work Package covers the following Tasks:

Task 2.1: Innovative Reactivity Control Techniques

Task 2.2: Innovative Decay Heat Removal / Depressurisation Systems

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

Task 2.4: Innovative Approaches on Source Term Reduction and Containment Designs

Task 2.5: Innovative Accident Management Measures / Influence of Human Factors

These tasks follow the technical objectives towards general safety goals or features like:

- nuclear stability
- thermal stability
- mechanical stability
- chemical stability and
- human compatibility / factors / interventions

General technological improvements of systems and components for the related operational functions are also addressed under this chapter even if they are not solely safety-related or motivated as discussed above. A classification system has been elaborated following mainly the defence-in-depth concept but including other items like waste, personnel exposure, maintenance, operational issues etc. In this sense, the classification system tries to combine aspects from the other work packages, too, and can be seen as a first step of an integral assessment that has to be extended with regard to the full set of sustainability criteria. The necessary R&D Tools / Facilities are included and described, as far as their data have been inserted via the questionnaires.

In collaboration with the MICHELANGELO Initiative Concerted Action (MICA), a number of 34 passive systems descriptions have been collected to illustrate the different technical approaches in more detail (see Appendix and SINTER Data Reports on Internet). Although this collection is rather arbitrary, it is interesting to see that 27 address Design Basis Conditions (DBC) and 14 the Severe Accident Scenarios (7) or both (7). 22 systems focus on Decay Heat Removal (DHR) indicating that most attention has been put on thermal hydraulic aspects in the past. The analysis shows that the other safety functions have to be explored in more detail to provide a balanced overall R&D approach on innovative safety systems. Considerable additional information has been provided by the INNOHTR Concerted Action on R&D proposals concerning inherent and passive safety features of HTR.

Another database has been initiated that collects information on advanced, evolutionary and innovative reactor concepts. If more support will be available this database /3/should be accomplished by the designers and supplier industry because it also addresses the specific safety-related innovations. Exemplary, the aspect of Accident Management and Human Factors has been included in more detail for some selected reactor types as progress in this area is judged to be of high importance for enhancing safety. This data is also available on Internet via the SINTER Network Homepage.

It should be mentioned that the SINTER Databank is still in a preliminary status and should be further completed in follow-up projects. Although it can only supply some first results, it demonstrates already the methodology for information handling within R&D Networks as e.g. done when harmonising a multiplicity of HTR-related R&D proposals in a multi-partner environment.

Main recommendations for future R&D on innovative safety systems address:

- Passive safety systems implementation is justified if the performances are fulfilled with the requested reliability and if the economical competitiveness is verified
- The optimisation process towards self-powered function has to be continued.
- Specific combinations of different safety functions should be studied in more detail.
- System selection should be organised on the basis of a Systematic and Standardised Assessment Methodology.
- Computer codes improvement for the Performances Verification should be pursued,
- A Reliability Assessment Methodologies to improve the PSA quality have to be developed.
- Adequate Economic Assessment Methodology have to be developed.
- Passive safety systems development that perform other Safety Functions than DHR should be encouraged.
- Improve robustness: i.e. implement simplicity both for system design and management procedures
- Screen the AP600 and Loviisa Licensing procedures in order to identify specific regulatory Requirements for passive system implementation and management
- There is a need to rethink the IAEA passive safety system classification in order to close the gap between active and passive systems by self-powered safety equipment.

A set of Criteria for selecting innovative reactors and innovative safety concepts has been defined as an integrated approach:

- Market potential
- Competitiveness versus fossil fuel plants
- Innovative potential
- Safety potential
- Simplification
- Easy licensing
- Minimisation of wastes
- Security of long term energy supply
- Public acceptance features
- ALARA design and operation
- Limitation of transportation of fuel and wastes
- Coherency with EUR

Although this Work Package is mainly dealing with safety-related aspects it has been revealed that a broader view is necessary to cope with market needs, sustainability requirements on the one hand and to make use of new technologies, methods and materials on the other.

2. Drivers for Innovations

2.1 Utility Requirements

Background Information

In this chapter, some available information on industrial R&D requirements from utilities and suppliers have been collected from the European Utility Requirements (EUR), the EDF-EUROGRAM Study, the MICHELANGELO Initiative and additional information from the SINTER questionnaire actions. This presentation is complementary to WP 1 and focuses on innovative safety features.

Although the EUR are mainly dealing with existing technologies they provide some hints for further technology and safety improvements in a medium to long-term scope.

Regarding the MICHELANGELO Concerted Action (MICA), the main objective of that project is to identify, justify and describe the R&D needed in the next years in order to continue having a safe and competitive nuclear industry. The set of short/medium term actions consists of a number of specific work packages directed to satisfy short-term European needs. For the medium/long term perspectives, MICA /4/ proposes the development of innovative reactor concepts also exploring innovative solutions in the areas of materials, fuel, and waste management also for evolutionary types. The complementarity of SINTER and MICA resulted in close collaboration and mutual use of information.

The EUROGRAM Study being strongly influenced by European utilities mainly reflects the highlights of the ENS conference /5/ held in Brussels in 1996 upon the subject of 'Research Facilities for the Future of Nuclear Energy'. Contributions came from Research Institutions, Universities and the Nuclear Industry. The conclusions were summarised in a seminar /6/. The R&D needs defined there fall in 4 major categories:

- core and fuels,
- operation and safety,
- plant service life and
- back-end of the fuel cycle.

The EUROGRAM Study concentrates on evolutionary improvement of existing reactors balancing the stakes, issues and threats of the main themes mentioned above.

Other background information was taken from IAEA reports /7/ that covered the global situation.

In the following, specific aspects on

- Improved control of Severe Accidents
- Operator actions
- Design Basis Accidents
- Accident environmental impact

being derived from the EUR and the MICA documents are highlighed as background information for further R&D orientation.

Improved control of Severe Accidents

In order to better control accidents involving core melt, a number of safety policies and requirements have been added to the EUR, where provisions exist for both accident prevention and mitigation

A combination of probabilistic and deterministic approaches apply. Some Severe Accidents are identified and selected on the basis of PSA. However, a Severe Accident sequence shall be considered regardless of the cumulative probability of core melt (CDF). There are in addition a number of deterministic requirements to be complied with in the design process.

Since Severe Accidents are to be considered in the extended design conditions called DEC (Design Extension Conditions) the need for a more precise quantification of the related phenomena is arising. EUR feels that current knowledge about severe accident phenomena is sufficient to design a plant without excessive conservatisms that could endanger plant economics.

Nevertheless, the partners of MICA consider that, although there exist a large amount of experimental data, before using them for accident management strategies, an analysis should be made focused on the uncertainties in late degradation phases. Further on, a balance between the reduction of uncertainties expected and the cost of the proposed experiments should be pursued.

Specific accident management strategies of innovative LWR reactors with passive systems should be considered.

If at the time of freezing the design, significant uncertainties in some Severe Accident phenomenologies remain, the designer shall demonstrate by means of margins or alternative paths that the overall objectives are met.

Operator actions

The role of the operators in EUR is also an evolution in comparison to the average common practice. The concept of ”forgiving” design and of ”grace period” have been introduced in the requirements with a set of differentiated requirements for DBA and for DEC.

In case of DBA and DEC for example no operator action can be credited before 30 minutes.

The operators are not disqualified by this requirements; they are and they will be important, but it is essential to reduce the stress in the first period of the accident to allow them to follow the situation and maintain the situation under their control.

Paying emphasis in these theses, the MICA Initiative investigates in R&D topics related to the plant control and monitoring. The use of diagnosis tools and benign man-machine interface for monitoring and diagnosis of accident sequences, as well as the use of on-line computers for safety and safety-related functions, will allow to make easier the operator role.

The EUR encourages the use of new and advanced technologies and requests that verification and validation by an independent review team shall be made to ensure good use of new technologies and to limit human intervention for testing between outages.

The EUR specifies that human factors should be taken into account in the design phase, and provide some guidance to reduce human error when refers to the analysis of the current state-of-the-art, careful selection and allocation of tasks, and the employ of modern data processing and display technology with automatic checks and alerts to detect errors etc. and support the recovery of the plant from accident sequences if they will occur.

Regarding the human-machine interface, the EUR gives an example of how to use these means: by task-related displays of the fluid systems, by presentation of situation-specific, pre-processed condensed information in an appropriate context, and by provision of situation-specific operator aids (e.g. procedures for manual operation, decision aids, detailed information about equipment, periodic test instructions, etc).

The EUR requires a Remote Shutdown Station to bring the plant to cold state in case of unavailability of the MCR. And also a Technical Support Centre for the case of emergency with screen-based monitoring means similar to those of the supervision area of the MCR.

Design Basis Accidents

EUR is innovative also in the approach to DBAs although not being a licensing document. It is essentially a technical specification. Therefore, it should draw from existing common licensing position to add, where necessary, additional requirements from a utility point of view. Unfortunately, in the field of DBA evaluation, the licensing requirements in different countries are very different and a common position cannot be identified in many cases.

Therefore, EUR defines requirements that - while still providing large conservatism margins - are fundamentally based on a more realistic evaluation of the events leading to radioactive releases from the plant.

This is also justified by the fact that large margins for DBAs cannot be justified anymore as providing protection against severe accidents, not explicitly mentioned in the design process. Since EUR addresses severe accidents DBAs shall be analysed for what they are.

For DBAs the Containment System shall be designed to meet the radiological targets specified in the EUR for the selected conditions. The maximum allowable leakage rate from the Primary Containment shall be defined to satisfy this requirement, and the means to monitor and maintain such leak rates shall be provided.

In case of fuel damage - if any - fission product release in the containment, their release to the atmosphere and their diffusion in the environment are to be treated mechanistically. The problem is that some of these phenomena have not been investigated in detail and that the licensing authorities will need time to endorse such an approach.

Accident environmental impact

Given the nature of EUR it is reasonable that environmental impact targets are expressed in terms of targets for releases from the plant. In practice, these release targets have been derived taking into consideration the need of minimising the environmental impact and reducing or eliminating the need of protective actions involving the population, according to the most recent international standards, such as the Basic Safety Standard, issued by IAEA. The release targets in EUR, if met, will allow a plant to comply with these limits even in a very unfavourable site.

Attention is given in EUR also to the reduction of the economic impact associated with land contamination and subsequent limits to the commercialisation of agricultural products.

2.2 Competitiveness

Attending to the cost experience of nuclear power it can be seen that while in some countries nuclear power has become the primary source of economic baseload generation, in other ones some facilities have had to close before the end of their design life due to the lack of economic competitiveness. The competitive margin of nuclear energy has been progresively eroded under pressure from public authorities to reinforce safety, and – as the EUROGRAM states – for increasing the competitiveness new R&D subjects to improve our knowledge of limit-setting phenomena are needed in order to reach a higher fuel performance, a higher components efficiency etc.

Present time, the trend of deregulation of electricity market forces to pay more attention on plant economy. In a deregulated environment, the large capital cost of nuclear compared to alternate energy sources could be a serious obstacle if not compensated with a substantial decrease in generation costs.

The virtual conflict between competitiveness and safety can be dissolved – as shown in many US plants – because high availability and economic operation is strongly coupled with the excellence of plant supervision and maintenance. Many old US plants e.g. are now envisaging considerable life extention. This can produce a long delay for the construction of new NPPs and a 'jump' from the next generation of reactors directly to the over-next.

Most Utilities have been working together to develop Utilities Requirements Documents (URD) for the next generation of NPPs not addressing innovative designs. This deficit should be avoided by including more innovative design solutions and other applications (e.g. CHP) in the future activities on EUR.

One of the major goals of the EUR has been to reduce the capital and operation cost. In this context the major points are:

Simplification and increased margin

Plant designs have to pursue to minimise the number of systems, valves, pumps, etc., consistent with essential functional requirements. An important aspect of simplification is the operation. Thus, an improved man-machine interface, simplified protective logic / actuation systems and system designs which minimise operator demands will lead to higher plant availability.

The increase in the operating margin may increase the initial cost, but it improves the plant availability greatly reducing the chance of shutdown. To improve the operating margins, evolutionary PWR designs are incorporating larger pressurizer volume and steam generator inventory. Making this, it relaxes the operator action time in the event of loss of feedwater transient. Most of the evolutionary plants are being designed with the goal of minimum operator action of 30 minutes.

These simplifications and improved operating margins give economic benefits such as high availability, reduced staffing level, and spare parts reduction.

Regulatory Stability

The requirements necessary to get regulatory approval must be clear and stable. The redesign and plant modifications have to be avoided. The U.S. Nuclear Regulatory Commission has developed rules to further define and improve the licensing process through a "one-step licensing process". Early plant designers and regulatory bodies interaction can lead to reach a better comprehension of the regulatory requirements and how the plant design can meet them.

Technological progress – especially in the field of Information Technology (IT) and AI – should also be used to make licensing procedures more efficient and less time consuming. A 'quasi on-line' licensing using electronic data transfer and expert systems for evaluation in great extent should not be a vision but a real objective in restructuring and harmonising the licensing process on a European base.

Standardisation and series order

One of the most important mechanisms to achieve low costs is designing and constructing a standardised plant. A standardised approach creates efficiencies in engineering, construction, and schedule. With a standardised plant, the bulk of design and engineering activities can be performed once (the first) and the costs amortised over many units. Licensing time and costs will be reduced, and construction techniques will become more refined, reducing both cost and schedule. Operation and maintenance costs will be reduced through reduced operator error and improved maintenance efficiencies.

The French experience is of interest in this connection since its large nuclear programme, based upon standardised units and large series orders, led to competitive nuclear generation costs as compared with fossil fuels. It allows an estimate that the cost of the first unit are about 15-55% higher as compared to the a series unit. The Korean nuclear power programme is characterised by standadisation and technology self-reliance. The major cost reduction were achieved in the NSSS, turbine plant equipment, and design and engineering.

Improved Constructibility, Modularization and multiple unit sites

Incorporating the aspects identified above, the construction duration will be kept to a minimum, which will greatly influence the plant capital cost. In addition to the above items, improvements in construction will also be made when there is a large fraction of the design complete before construction begins. As an example, the URD requires that ninety percent of the design be complete (i.e., 90 percent of design drawings must be 100 percent complete) before plant construction starts.

Another aspect of improved constructibility relates to modularisation, where segments of a plant can be fabricated and assembled in a factory environment and shipped to the site for placement and interconnection. The factory setting provides a better work environment as activities tend to have greater quality control with the potential for greater automation and higher productivity. Modular construction also reduces site congestion and improves construction schedule as module production can take place away from and in parallel with site specific activities.

An additional factor that can influence economic competitiveness is the use of rnultiple unit sites. In addition to the sharing of the site land cost, site licensing costs can also be shared among multiple units. During the construction phase, considerable efficiencies and associated savings can be gained from phased construction and rolling the various craft teams from one unit to the next. Also, by construction repetition, there is craft labour learning that reduces the time to perform a given task and correspondingly reduces both construction labour cost and schedule. Finally, common facilities such as administration and maintenance buildings, warehouses, roads, and guard stations can be shared by multiple units at a common site.

Modularisation of large units into a set of small or medium sized plants is also a way towards safety and availability improvement. This concept is one of the main drivers e.g. for the South African Pebble Bed Modular High Temperature Reactor (PBMR). The use of a significant part of the waste heat is another challenge to improve economics. But the siting in densly populated or industrial environments may need a basic exclusion of major radioactive releases as necessary safety philosophy.

The consideration of safety, operability and constructibility during the phase design

The design can be improved if the PSA is performed in an early design stage and results are incorporated. Formal design reviews performed by experienced operators, and joint constructibility studies performed with construction companies, allow to maximize the benefits of past experience, resulting in cost reduction during future plant construction and operation.

Regarding specific structure, systems and components, the **containment** is an important contributor to the overall competitivity of a NPP design. It should not be forgotten that a difficult balance exists between the need for cost control and the new requirements in terms of safety.

It is of paramount importance that innovative technology takes into account cost factors in an early design stage to favor those R&D lines that are more promising also in terms of economics. In addition, the containment design may significantly affect the overall plant construction schedule and have a consequence on the costs. Thus, containment structures designed to withstand very high pressures (> 7 bar) may imply a big step up in plant costs, since construction techniques that would be required would exceed the current practice. Effective containment cooling and reliable hydrogen mitigation strategies could be another approach to reduce design pressures.

Measures to minimize costs which are part of the design include:

- The use of proven materials (concrete, steels, etc.)
- Detailed planning of construction schedules to avoid interference between the containment construction and that of its content
- Optimization of construction techniques (modularization,…)
- Early formulation of design criteria to allow integration of the design of all systems from the beginning taking into account the need for access and maintenance requirements
- Simplification of design (reduction of the number of penetrations, avoidance of over-specified features)
- Design for long plant lifetime
- Make provisions for decommissioning

For maintainability it is required in URD that the ALWR will be designed for ease of maintenance to reduce operations and maintenance costs, reduce occupational exposure, and to facilitate repair and replacement of equipment.

With regard to safety it is required that the ALWR design will achieve excellence in safety for protection of the public, on-site personnel safety and investment protection. It places primary emphasis on accident prevention as well as significant additional emphasis on mitigation. containment performance during severe accidents will be evaluated to assure that adequate containment margin exists.

The choices that have more direct impact on the economics of the containment are the decision to adopt a steel or a concrete containment, a single or double containment, with or without liner, large or small.

Regarding the containment system, special attention must be paid since there could be instances where increasing safety, even though already satisfactory, may imply an increase of cost. The areas where the potential exists for an increase in costs are those where the containment is called to:

- Withstand a wider range of accidental situations

- Incorporate extra equipment to cope with the additional treats to be taken into account
- Comply with modified (and possibly more complex) licensing and assessment procedures
- Need to develop and test innovative components and systems.

The pressure at which the ability of the containment system to maintain containment integrity and leaktightness is threatened shall be assessed using the method discussed in the EUR, which includes discussion on phenomena to be taken into account to estimate the Severe Accident thermal and pressure loads on Containment.

Concerning the influence of the **human factors** in the costs, an appropriate configuration/optimisation of the Man Machine Interface (MMI) design/layout is very important for reducing operating costs, which is fundamental for making a plant competitive. The EUR mentions it in various chapters:

- *Safety and economic aspects shall be given sufficient consideration in I&C and MMI system design.*

- *The I&C should provide a major contribution to achieving significant cost savings over the plant's life cycle through the achievement of higher plant availability factors and shorter outages.*

- *It shall be possible to control the plant with 2 Operators, and in steady conditions it should be possible to control the plant with only one operator.*

Many of the I&C systems developed by suppliers in the past led utilities to choose between a high capital cost with low operating cost or the reverse. New open international standards and third party products are permitting some suppliers to offer both low initial cost and low operating cost systems. These systems are typically more modular and make better use of standard off-the-shelf industry standard components.

New systems exhibit self-checking attributes and monitoring capabilities that allow the state of equipment to be known immediately. This facility can be used to reduce manual intrusive checking of parts and, in conjunction with redundancy within systems, increases the availability of the system.

Nuclear plants will continue to demand a high degree of standardisation in their I&C systems in order to control both capital and operating costs. The I&C related maintenance cost, outage cost and unavailability cost must be minimised. Indirect cost due to licensing delay caused by a new digital system should also be taken into account.

Regarding the approach for the **severe accidents management**, in a first step the real needs and potentials have to be thoroughly considered. In a second step (and if appropriate), severe accident challenges, some specifics of such accidents need to be included:

- The degree of complexity of Severe Accident sequences is much greater than that of Design Basis Accidents
- Plant behaviour cannot be actually considered deterministically. General phenomena can be anticipated, but detailed evolution is difficult to predict
- In-situ evaluation of plant status is difficult. For example, beyond a minimum level of core degradation, deciding whether the corium is still inside the vessel could prove problematic
- For core degradation progresses there are more uncertainties in the understanding of plant status

It therefore appears reasonable to limit, as far as possible, core degradation through appropriate accident management procedures and deal with challenges to key component integrity (e.g. defend vessel integrity (by in-vessel core retention strategies) or containment structure by effective cooling and ultimate heat sinks).

For utilities, though recognising that mitigation is needed, prevention is emphasised. However, this must be done in a very comprehensive way:

- First, prevention must be controlled. In some cases, prevention results in added (and unnecessary) complexity which, in turn, can increase risk
- Costs incurred must be commensurate with risk reduction. If risk reduction is marginal, investing becomes questionable, and the question to be raised is: would the same (or a smaller) amount of money allow more significant risk reduction if invested to deal with other challenges?
- Some challenges can be adequately dealt with at minimal cost through mitigation. This is the case for hydrogen generation or vessel melt-through for example

For all Severe Accident challenges, many candidate solutions exist (e.g. for hydrogen):

- Inherent protection through an increase of the containment volume
- Containment inerting
- Mitigating devices such as recombiners or igniters
- Removal of the heat from recombination by containment cooling

Decisions must therefore be made on a case-by-case basis, after consideration of:

- The safety significance of the problem
- Potential benefit resulting from implementation of each candidate solution
- Costs incurred

Finally, when dealing with costs, it must be kept in mind that not only investment cost is important, but also operation and maintenance costs.

2.3 Licensing Requirements

In this chapter, a general review of the main streams of regulatory innovations and trends are identified complementary to WP 1. In most cases, reference is made to papers and documents presented by Safety Authorities(SA), but in particular in the identification of the long term trends, the author judgements had to be used.

First of all, it is not easy to identify clear licensing trends currently that can affect the R&D for advanced reactors and the technological innovation from statements of SA. The combination of a clear slow down of the interest for new reactors order and of the traditional prudence of SA in changing the licensing bases is leading to weak signs about the future of licensing bases in the medium-long term.

With a few notable exceptions, the focus of all SA is at the moment the assurance of the highest possible safety levels to the operating plants. Therefore issues, like: life extension, ageing, plant backfitting, safety levels of plants designed against previous standards are of foremost importance together with new emerging issues related to plant decommissioning, waste disposal and closure of the fuel cycle.

However, the need for a licensing framework for advanced plants is shared also by the SA. It is a great opportunity to review what has been done in the past and rationalise it, possibly simplifying it. The real question is the confrontation of the trend for an international harmonisation of the requirements, and therefore the need for compromises, and the responsibility of each SA to assure at the national level the safety of nuclear installations according to the role they have been assigned. In particular in Europe, the ”internationalisation” of the safety requirements is becoming effective both with the agreement of French and German Safety Authorities about the EPR and with the common review of the EUR requirements. With the implementation of a deeper European integration, also safety requirements may be expected to be further harmonised.

At this point, it is needed to highlight the common initiatives that the National Safety Authorities are performing in the European Union framework:

- The Nuclear Regulators´ Working Group (NRWG) is an advisory expert group to the EC, which mission is strengthening the cooperation in Europe in the field of safety of nuclear installations
- The West-European Nuclear Regulators’ Association (WENRA), whose main objective is to develop a common approach to nuclear safety and regulation.
- The ”Multi-annual Community Plan of Action (2000-2006) for cooperation in the field of safety of nuclear installations”, recently proposed, is based on the growing need to set a general framework to provide measures to strengthen the Community efforts and to promote common safety approaches, targets, criteria and assessment methods consistent with the best European and international safety practices. This Plan of Action will complement those activities concerning the Framework Programmes and the PHARE and TACIS technical assistance programmes . Of particular interest is Article 2 of this Plan of Action which proposes that individual actions shall be selected primarily on the basis of criteria, one of that deals with contributing to harmonisation of safety targets, criteria and assessment methods in the context of development of new power reactor concepts.

The need of standardised European designs for the next generation of LWRs and of common European Utility Requirements for these and other future reactors gives a unique opportunity for further harmonisation. As a result, the major European utilities are producing the EUR taking into account the whole life cycle of the plant from design to decommissioning. The NRWG is instrumental in this process which is essential to achieve standardisation in Europe and to compete on foreign markets: actually regular meetings among the safety bodies of the various countries are organised to discuss these requirements and the conclusions are reported to the NRWG.

The NRWG also is paying attention to new technologies being developed both in existing and future plants (such as I&C) and to measures implemented to prevent severe accidents or mitigate their consequences. It has been shown that very significant progress has been achieved in the harmonisation of safety approaches and in the common understanding of safety related phenomena, but that such progress is not always reflected in the regulatory requirements.

Here is a list of relevant work areas identified by the NRWG, which could play a role in the development of advanced nuclear reactor designs.

- Feedback of operating experience: in particular to assess the generic safety significance of incidents.
- Risk analysis with emphasis on risk based methods: the approach is to give the preference to monitoring those components whose failure could lead to a severe accident.
- Operational safety fundamentals and the development of safety culture.

- Off-site releases of Design-basis Accidents: the objective is to reduce the considerable differences between the different models (particularly in the areas of safety margins and uncertainties) in use and agree on a number of common models and acceptance criteria.
- Severe accidents: it is recommended to review the work being carried out by the Euratom framework programmes, European utilities, OECD/NEA, IAEA and USNRC and to identify ways to come to a consensus among regulators.
- Codes and standards: this activity could have an important role in the future as TSOs are collaborating at the European level, especially for future evolutionary LWRs.
- New technologies: licensing issues related to safety critical software are still a big challenge. Future work on site characteristics (siting) also could become important if a new generation of plants is built.

2.4 Socio-political Drivers

In Work Package 1 the main impeding factors for acceptance of nuclear power have been illustrated as well as some essential criteria towards sustainable developments (see /1, 2/). A pro-active response in the safety philosophy seems to be necessary to overcome public concerns. The following table refers to some mechanisms in risk perception to answer the question whether they can be addressed by technological innovation, at all.

Qualitative Risk Characteristics	Potential Response
Possibility for avoidance	Independent barriers, self-acting safety systems
Potential for control	Accident Management Measures (Fire Brigade)
Social control	Transparent’ technology and surveillance
Degree of familiarising / knowledge	Neutral competent information
Scientific / technical maturity	open information on the technological progress
Fatal vs. limited damage	Restriction of max. releases
Delayed vs. prompt damage	Larger grace periods
Catastrophic vs. continuous damage	Transmutation of waste into short-lived material
Extreme catastrophes	Deterministic exclusion by design
Possibility for fleeing	slow accident progression
Sentiment for danger	open information on all abnormal situations
Reversibility / irreversibility	Restricted max. release
Alternate possibilities	Neutral comparisons, sustainability criteria
Distance to the source of danger	Siting, underground construction
Distribution of benefit	Lower local electricity cost near to NPP
Artificial vs. natural risk	Use of natural laws for accident control

These few examples show that the trends for advanced and innovative designs as well as the EUR are on the right orientation for coping with these anticipated parameters and that recent licensing requirements requesting restriction of maximum releases and inclusion of core melt accidents in the design as well as the need for a cooperative communication can be correlated logically.

The technological innovation potential for addressing these factors are not being discussed in an open way mainly because of the 'risk' perceived by the nuclear community itself with regard to potential negative consequences for older designs.

The distribution of the benefits to the whole community while concentrating the risk on the neighbourhood of the power stations is in disagreement to the assessment of social justice. The price for fuel is often lower near to the refineries. Why should the surrounding municipalities of NPPs not benefit by lower electricity cost?

Technologies are always judged as a socio-technical system within the social context of their development, control and application as well as their incorporation in political decision processes and the credibility of control.

The actual acceptance problems do not represent a general objection against innovations and are also not specific for certain countries. In some variation, they are existing in all highly industrialised societies with some variation of the general scheme and mechanisms. Federalism, decentralisation and low national identification may influence the difference of interest between those who develop and apply a technology and those who feel threatened by it. Mass media generate enhanced attention and especially offer a public forum for criticism and politicisation of conflicts with regard to specific technologies.

The risk / technology controversy is not a temporary pathologic effect but a characteristic of modern societies (see /1/). It is very important to handle this conflict in a positive way and to develop - as a 'social innovation' - a culture of communication and dispute in conjunction with technological innovations that respond to the mechanisms and needs of acceptability.

3. International Innovation Trends

3.1 Methodology and Database

A large number of reactor concepts of different types (PWR, BWR, HWR, HTR, LMR, MSR etc.) following different design principles and safety approaches have been developed up to now. Permanent reviews of the progress have been presented at several major conferences and workshops /8, 9, 10, 11, 12/ and especially via international organisations like OECD NEA and IAEA providing documents that summarise the technology and design features /13, 14/ as well as the terminology with respect to the different development stages of new concepts /15/ in the range between SMR and large NPP.

The following categories of reactor types are mainly determined by specific different Decay Heat removal (DHR) strategies /16/:

- Evolutionary PWR (EPR, System 80+, APWR etc)
  ⇒ active DHR with enlarged coolant reservoirs
- Passive PWR (AP 600, EPP, MS 600 etc.)
  ⇒ natural convection cooling, passive injection and cooling systems,
  large water reservoirs, pit-flooding, Gravity Driven Cooling Systems (GDS)
- Innovative PWR (PIUS, NILUS, ISIS etc.)
  ⇒ natural convection cooling, passive injection and cooling systems, integrated designs,
  large water reservoirs, pit-flooding, Gravity Driven Cooling Systems (GDS)
- Evolutionary BWR (ABWR, BWR 90 etc.)
  ⇒ active DHR with enlarged coolant reservoirs, depressurisation pools
- Passive BWR (SWR 1000, SBWR, ESBWR etc.)
  ⇒ passive safety systems, passive DHR and depressurisation ,
  Gravity Driven Cooling Systems (GDS)
- Advanced Heavy Water-Cooled Reactors (CANDU 9, CANDU 6, AHWR etc.)
  ⇒ Passive Moderator (Calandria) Cooling systems
- Passive Pressure Tube Reactors (CANDU 3, PTLWR etc.)
  ⇒ DHR by natural convection cooling of each pressure tube in the calandria,
  exclusion of core melt by temperature / corrosion resistant fuel elements
- High Temperature Gas-Cooled Reactors (HTGR)
  ⇒ Modular designs, large heat capacities, temperature resistant fuel and structures,
  DHR via RPV surface
- Liquid-Metal-Cooled Reactors (LMR)
  ⇒ natural convection cooling, DHR via the RPV surface and natural convection
- Homogenous Reactors
  ⇒ Minimisation of core inventory, elimination of the decay heat source

It can be seen that there is a common trend towards passive safety systems /17/, transparent safety concepts and improved accident management provisions including core melt scenarios.

To distinguish the different safety features systematically, a yet non-exhaustive collection of data from different advanced, evolutionary and innovative reactor concepts has been established as an ACCESS 97 database (see Appendix 6.1). It is not yet interactive for data insertion like the other databases due to the limited resources within this Concerted Action. It could therefore not yet be complemented and revised by original data of the designers and supplier industry. Nevertheless, it covers different systems and allows to address specific safety-related features. It would be very beneficial, if such interactive databases will be used in future also by international organisations like IAEA or OECD NEA instead of paper-written reports when routinely establishing surveys on new reactor concepts. Table 6.2 illustrates an example (ABWR) with the general data of the concept including some information on the status of the project etc. Other additional data can be extracted from the SINTER site:

- Innovative Features (Table 6.3),
- Accident Management (Table 6.4),
- Human Factors (Table 6.5).

This has to be extended to other features of interest if more manpower for accomplishment of the database will be available in a follow-up programme. But a first step has been undertaken to demonstrate the advantages of a database available on Internet against paper-written reports and to provide a structure being different from the existing literature concerning the impetus on innovative features.

Further information on passive safety systems could be established in collaboration with the MICA project. Table 6.6 provides an overview on the different concepts and their correlation to the different safety functions. More detailed information can be taken from the SINTER database as shown in Appendix 6.7. for one example. Some of the passive safety systems – as idicated in the tables - have been chosen by the MICA partners for evaluation of their potentials.

Another source of information has been the 'Joint Safety Research Index (JSRI)'. Due to close collaboration between SINTER and JSRI it was possible to include the information on 448 European R&D projects into the SINTER Network database and to get early access to the project descriptions that also refer to a considerable number of R&D on innovative safety systems besides R&D being more focused on safety research in the Severe Accident domain.

To integrate all this information and trends, an attempt has been undertaken in the SINTER Network to establish a classification system that would allow a correlation of requirements stemming from licensing and utility needs as well as from international trends and sustainability / economic aspects. At least on a semi-quantitative base, the consistency with the future R&D needs can be checked for each innovative concept giving some indication for the priority for further development. This classification approach is highlighted in the following subchapters.

3.2 The safety objectives for future reactors

Concerning the safety for future reactors several references /18/, /19/, /20/, /21/, /22/, /23/, /24/ etc. presenting recommendations and R&D guidelines can be summarised as follows :

- improvement of the operation, the reliability and the availability of the plants;
- improvement of the plants safety to reduce the radiological impact during normal operation and that expected following abnormal events.

To organise an R&D programme on innovative systems and technologies it is essential to translate these generic recommendations into technical objectives useful as well for the designers as for the organisations involved in the R&D effort. Still following the same references, these objectives are mainly the following :

- an increased effort for the plant **simplification** and the implementation of **functional redundancies** with an increased attention for the **passive systems**[a]**;**

[a] The AP600 prospectus on the economy of implemented materials is a good example of the "quantification" of the simplification.

- the adoption of the **defence-in-depth** principle with an increased effort for the **prevention**[b], the improvement of the **forgiving character** of the reactor[c]**,** the reduction of the **core melt frequency**[d]**,** the improvement of the **containment efficiency** and the rejection of the **cliff edge effects**[e]**.**

To structure the necessary R&D efforts, the SINTER Partners fixed three complementary objectives which must be considered as generic guidelines :

- **a comprehensive (exhaustive) defence**. Since the preliminary design, an effort must be made to prevent all the plausible initiating events including those that can lead to the core degradation. On the other side the demonstration that the severe accident conditions can be managed and that the reduction of the consequences is effective must be made.

- **an homogeneous defence** to avoid great differences among the contributions of the different event families, and/or the plant status, to the core melt frequency.

- **a gradual defence** to avoid short sequences that can lead to important releases. The objective is a design with inherent characteristics and automatic implementation of the safety systems considering the possibility for intermediate operator intervention in order to restore the sequence management.

In parallel, the above recommendations generate **constraints** that must be taken into account to reduce the risk for unfruitful researches which results would be inapplicable. The common French - German safety authority (GPR - RSK) expressed explicitly the choice for an **evolutionary approach**; the goal is to point out the **importance of the experience feedback** and the need for taking it into account. Other constraints are imposed by the **economic competitiveness**. Moreover, the adoption of the defence-in-depth leads to take into account the **severe accidents** that generate design objectives. Finally the need for a "**transparent safety**" is a constraint because technical solutions must satisfy criteria that are not necessarily technical[f][g].

3.3 The classification and the assessment of the R & D activities

The classification of the R&D activities for the innovative technologies has been an essential step of the SINTER programme. This classification allows to situate the R&D effort within the context of the above recommendations.

The "general goals" of this classification can be summarised as follows :

- **to have a widespread view about all the safety concerns**
- **to organise the information exchanges on similar topics**

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[b] i.e.: Reduction of the frequency or suppression of initiating events, and/or reduction of the potential consequences of the accidental sequences.

[c] i.e.: Grace delay increase, thinking about the evolution of the accidental sequences in case of human error, etc.

[d] This reduction is the result of the prevention effort, as well as the implementation of an increased number of lines of defence.

[e] The safety analysis of highly hypothetical scenarios is used to verify that there is no plausible event/sequence to which, for a small reduction of the occurrence probability, would correspond a brutal increase of the consequences (cliff edge effects). The events/sequences which do not respect this rule are either excluded by the design or treated, to reduce their consequences or their occurrence probability.

[f] The IAEA definition is relatively "vague" : *Transparent safety is obvious or easily understandable safety and normally follows from inherent safety characteristics and from simple, straighforward design concept. ...*

[g]

- **an easier identification of the possible duplications**
- **an easier identification of the possible lacks**
- **stimulation of R&D on relevant safety-related issues**

Beyond such "administrative" goals, the classification scheme can be used to organise the discussions about the interests and the priorities of the programmes, either for those underway as well as for those that are proposed for the future. This step can be considered as preamble for a common assessment.

This assessment of the interests and the priorities can only be made using a common grid of technical objectives. The goal is the achievement of a common understanding about the technical meaning of requirements.

To do this, a series of safety "key points" had been integrated :

- Initiating events : internal, external
- Plant states : shut down, power
- Safety related functions : reactivity control, heat removal, FP confinement
- defence-in-depth : prevention, control, protection, management, mitigation.

These key points are linked each others. The two complementary steps : "**design integrating safety**" and the "**plant assessment** from safety point of view", are organised structuring these items.

The **initiating events** are "applied" to the **plant states** to identify the "plant conditions[h]" that are effectively evaluated toward the safety objectives. The goal is the verification that the **safety functions** are correctly achieved answering, at the same time, the **defence-in-depth** principle content.

Table 6.8 in the appendix presents a proposal for a functional development based on the defence-in-depth levels. The recommendations presented above are translated into functional objectives. These objectives are applicable to all the plants types and they implicitly cover all the safety functions.

Further developments can be envisaged to identify a list of functional objectives applicable to a given type of plant as well as to a given safety function. This is done detailing the content of each previous objective also including other areas to achieve a more integral approach towards sustainability. For a full consideration of waste and operational issues etc., the classification would have to be further extended.

This matrix can be taken as a "reference frame"; it can be used either to deduce the R&D themes classification as well as for the assessment of the completeness of the R&D programmes. The eventual lacks ("holes") and/or the excess ("surplus") can be easily identified. Finally, a systematic classification of the R&D activities versus these functional objectives can lead to meet the "formal goals" defined above, too.

It is interesting to stress that an analogous table can be used to assess and to compare, still from safety point of view, different innovative systems (see tables 6.2 and 6.6). As an

[h] These plant conditions are duly categorised and the "envelope plant conditions" are identified for the practical assessment effort.

example, the appendix 6.9 shows the assessment of innovative decay heat removal systems concerning their applicability to development for 900MWel PWR plants. The assessments show that a balancing between different favourable, indifferent or even unfavourable features cannot be avoided and that more detailed R&D seems to be necessary in those areas where a clear judgement cannot be made without improved knowledge.

It was not considered to apply this classification to all the innovative safety systems within the SINTER Network because this would have been beyond the scope of a Concerted Action. However, the main goal was reached by establishing and offering the methodology for more detailed analysis in other projects as e.g. done in the MICA project.

Finally, it can be pointed out that similar approach can be adopted for the other main goals of the innovative programme, namely: the fuel cycle, waste issue and competitiveness.

4. R&D Proposals & Innovation Potentials

Task 2.1: Innovative Reactivity Control Techniques

Reactivity accidents can be initiators for core destruction as has been experienced in the Chernobyl accident. The problem of control of reactivity can be classified into three main categories:

- slow kinetics depending mainly on fuel depletion
- rapid kinetics depending on temperature / power imbalance / two-phase phenomena etc.
- emergency shut down in crisis situation with massive absorber insertion

Concerning the compensation of over-reactivity at the beginning of the fuel cycle different strategies are realised in PWR and BWR by either using boration of the primary coolant or burnable poisons in combination with mechanical absorbers. Both approaches have specific problems either concerning deboration accidents and corrosion or relatively low temperature resistance of the mechanical absorbers in core heat-up accidents. Thus, investigations on boron-free cores as well as temperature resistant absorber clusters and alternate burnable poisons such as erbium or poisoning of the cladding should be continued.

Other solutions for reactivity compensation have to be seen in on-line refuelling techniques (e.g. CANDU, HTR, AGR, Homogenous Reactors) or in adjusting the breeding ratio in a way that long operational cycles can be achieved. The poisoning by fission products is not so strong in fast spectra due to the 1/v behaviour of cross sections. This may also be beneficial for stretching of cycles and burn-up increase. Another future option would be the continuous removal of fission products as discussed for Molten Salt or Gas-Phase Reactors in combination with on-line refuelling of (non-proliferative) fertile material or actinide burning. Such approaches show a better neutron economy and would consequently be more coherent with efforts towards transmutation of long-lived waste.

Plutonium or Minor Actinide Burning induce additional requirements to the dynamics of the core and the control / shut-down system due to the hardening of the neutron spectrum and the associated reduction of absorber efficiencies. Cold hazards in shut-down conditions have to be explored in more detail.

New types of fuel (inert matrix fuel (IMF), CERMET, CERCER, Coated Particle Fuel, SiC-cladded fuel etc) have also to be assessed with regard to their feed-back on reactivity control and effective negative temperature coefficients of fuel and moderator.

It is important to keep in mind that reactivity incidents have to be avoided not only in the reactor but in the whole fuel cycle beginning with fuel manufacture (see Tokaimura Accident 1999) and ending in the final repository of spent fuel. Special attention should be put on the relatively small critical masses of some minor actinides.

Task 2.2: Innovative Decay Heat Removal / Depressurisation Systems

Only about 90% of the energy released from the fission reaction is used directly for power generation, whereas nearly 10% are stored in the radioactive fission products (f.p.). This part of energy represents the so-called decay heat on the one hand and the heat produced by the discharged waste on the other. For large LWR the decay heat power is in the range of 100 MW just after shutdown and still at a level of 5O MW 10 min later. It falls to more than 10 MW after 12 hours and keeps about 1 MW even after 3 months.

The reliable removal of this energy is essential for all nuclear reactors that accumulate large amounts of f.p. in the core. This fact could in principle only be overcome by reactor concepts that permanently 'dilute' the f.p. concentration as foreseen in some homogenous reactors like Molten Salt Reactors (MSR) or Gas Phase Reactors (GPR) that might offer a long-term option for reactors with reduced requirements on Decay Heat Removal (DHR) and having inherent safety features, small fissile inventories, ideal neutron economy and minimum amounts of long-lived waste.

Although the reliability of active DHR systems of current reactors have reached a very high degree by diversity and redundancies there is a clear trend towards passive - or better said - ‘self-powered’ DHR systems. Those systems make direct use of the surplus of energy produced by decay heat and 'organise' the heat removal process in a way that it does not need additional external energy for pumps, blowers and control.

Most innovative DHR systems rely on natural convection, heat radiation, evaporation/ condensation, dynamic and two-phase phenomena representing in part only small driving forces like buoyancy on the one hand or showing very strong heat transfer capabilities like condensation effects on the other. These phenomena and specific systems (e.g. steam-jet pumps) must be calculated precisely over the whole operational range including low-power scenarios during start-up and shutdown as well as in combination with other active systems to avoid disturbances affecting the function as well as instabilities especially when weak and strong driving forces are coupled.

The reliability assessment of symptom oriented, self-initiated and self-powered (passive) safety systems needs specific probabilistic methods differing significantly from active systems as they may be e.g. more sensitive to interference with operational or diverse safety systems, different accident scenarios, deviations in material properties and difficulties in testing their function. In summary, there is a consensus on the need for

- more precise 3D modelling capabilities (CFD codes),
- their validation by highly instrumented experiments and
- the establishment of specific PSA methods for passive safety systems.

In principle, the whole DHR chain from the fuel element via the RPV wall through the containment to the ultimate heat sink has to be assessed and improved towards self-autonomy (i.e. independent from external power supply and control systems).

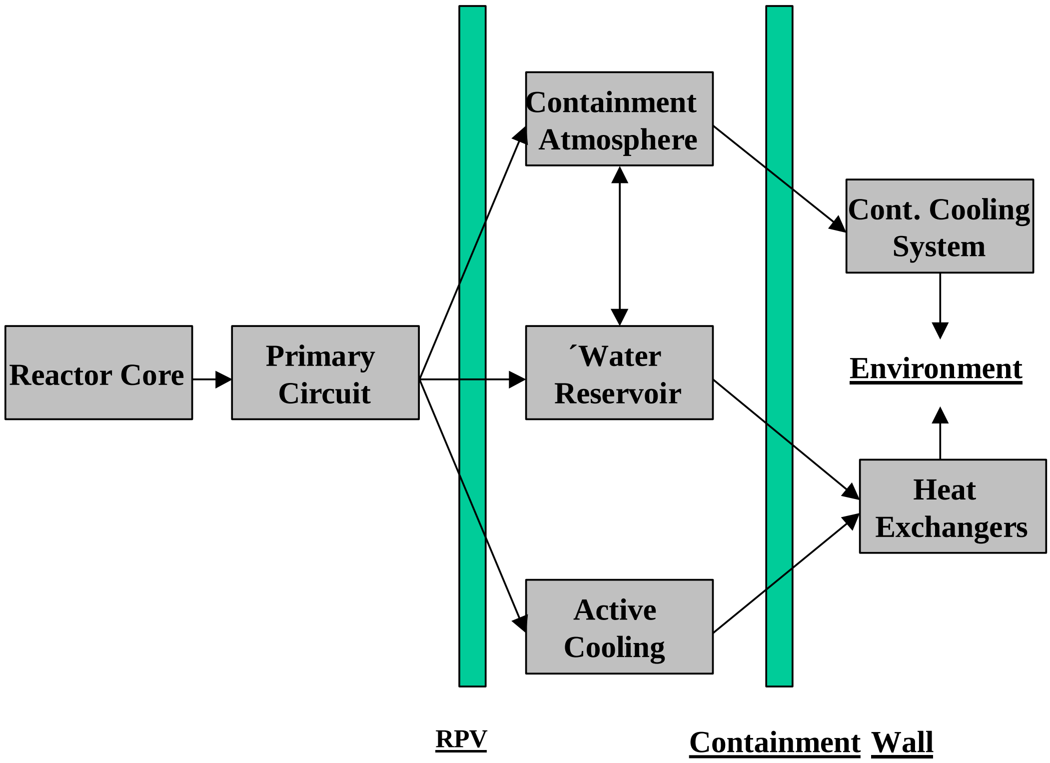


Figure 2: The Decay Heat Removal Chain

Advanced designs fulfil the EUR request not to need operator interventions before 72 h. These grace periods are depending on the limited heat capacities of the ultimate heat sinks, e.g. water reservoirs that have to be refilled after a given time. Only very few reactor concepts like modular HTGR and small LMR are even independent of such actions as they dissipate the decay heat by air coolers on underground structures. The same reflections have to be undertaken for internal or external core catchers to prevent their malfunction and destruction in the long run.

Beside the strategy to significantly lower the core damage frequencies (CDF) by enhanced use of passive safety systems, there is also the possibility of modifications of core and fuel geometry to avoid core melt only by the dissipation of the decay heat via the RPV surface even under the assumption of LOCA as illustrated in figure 3.
This can be done by increasing the surface to volume ratio, by omitting overheating central zones (ring core), increasing the thermal conductivity of the fuel elements (matrix fuel instead of pin arrays), temperature and corrosion resistant materials or modular disintegration of the core (e.g. pressure tube reactors). With these parameters it is very likely that core melt accidents including related incidents like steam explosion an hydrogen release can be completely ruled out by design not only for SMRs but also for large power sizes.

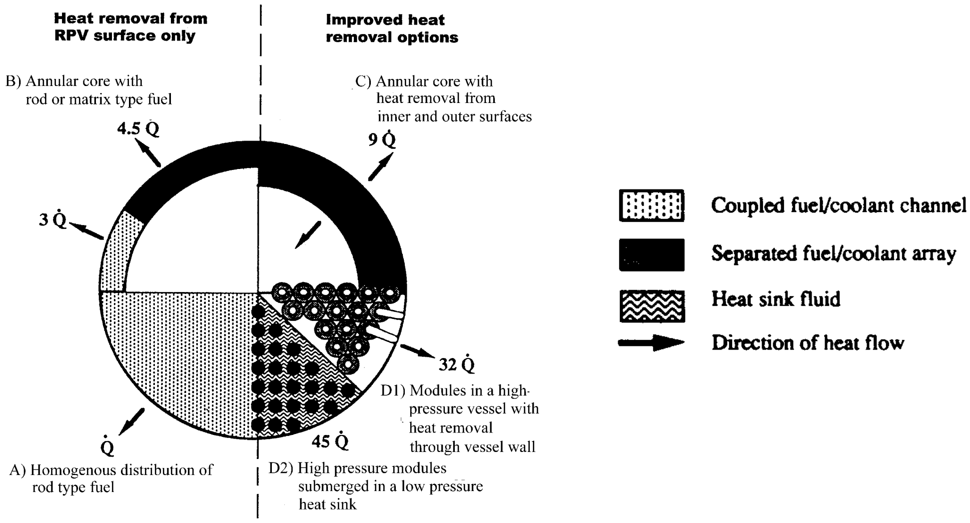


Figure 3: Core Design Options to Avoid Core Melt /25/

The developments of passive DHR systems in the last decades have provided remarkable progress. Their power has been significantly enhanced still showing some reserves by design optimisation. Passive LWR - both PWR and BWR - have already surpassed the 1000 MWe limit (e.g. ESBWR approaching 1400 MWe). They have already got 'adult' and should no more only and still be seen in the light of SMRs. The same trend is to be observed for modular HTR where ring core configurations allow to enhance the power by a factor of three compared to early designs.

LMRs show specific DHR features due to the high heat conductivity, large heat capacity and excellent natural convection behaviour of the liquid-metal coolant. In addition, there are complementary means to dissipate the decay heat via the RPV and steam generator vessel surfaces. Inert coolants like lead or lead-based alloys might help to simplify the whole safety concept of LMRs.

It has been discovered within the SINTER Network that the IAEA classification for passive systems might have created a large gap and psychological barriers between active and passive safety systems as e.g. rotating devices are not considered. A new class of **self-powered safety systems** taking the energy for their operation from the accident environment (overpressure, steam, hydrogen, temperature gradients etc.) could be a good compromise in combining the benefits of active and passive systems. An example is given in figure 4 for a depressurisation system. The discharged steam drives a turbo pump that allows to feed coolant into the RPV during the activation of the depressurisation valves. The system does not need external power or energy storage and accelerates the depressurisation by injecting cold coolant.

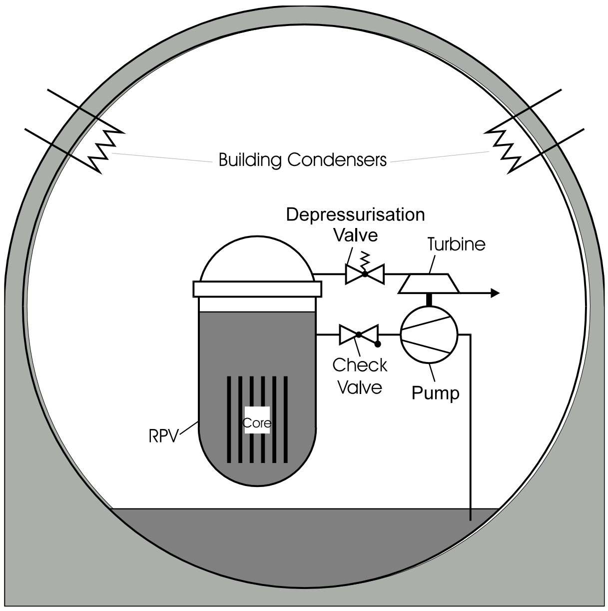


Figure 4. Self-powered Feed and Bleed System

Figure 4 also illustrates an **inherent combination of safety functions** (Depressurisation, Feed & Bleed) that could help to avoid accident sequences like Three Miles Island. Such a system would also take away a lot of responsibility from the shoulders of the operator deciding on the initiation of a depressurisation to avoid e.g. high-pressure RPV failures in core melt scenarios.

In summary, it can be stated that the enhanced use of self-powered, passive DHR systems is a common trend for all advanced reactor types. Although different designs of passive DHR systems and components have been proposed and tested, the innovation potential is not yet fully explored. Codes are capable to calculate the overall behaviour but have to be improved with regard to three dimensional effects, low power scenarios and the phenomena occurring in the large pools absorbing the heat or in the presence of non-condensable gases. Scaling effects may become more important when full scale experiments are missing. Best estimate codes must replace conservative evaluation models for getting full benefit of the passive features on a realistic base. The availability of necessary thermal hydraulic test facilities is strongly dependent on the continuity of further R&D programmes in this field /26/, /27/ especially due to the fact that near-commercial reactor projects with innovative safety features (except SWR 1000) are not pursued by the European supplier industry with much effort.

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

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. The primary system forms an essential stage of the multiple barriers required by defence-in-depth. Considering accident prevention, failure of the primary system could lead to impairment in the ability to cool the core. The primary system is also one of the stages to confine radioactive material. 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. It could also be a significant step towards an optimisation of the principal of independent multiple barriers.

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) strengthening of the primary system, and
3) retention of the core material within the primary system in severe accidents.

The preventive approaches to maintain the coolant inventory is to avoid unnecessary coolant loss during safety related actions, primary system depressurisation for example, and to strengthen and simplify the primary system to decrease a pipe break probability. The accident management solutions include passive core cooling systems integrated with the primary circuit and immersion of parts of the primary system (Pit Flooding) within a coolant pool around the RPV as another approach. The systems can be and have been studied with other passive emergency core cooling systems. A progress has been made during the EU 4th framework programme and a number of thermal hydraulic facilities are available at the moment. On the other hand, it must be emphasised that back-fitting of existing plants could take considerable benefit from these developments as e.g. demonstrated with the Loviisa PWR in Finland.

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.). Reliability estimates for the systems to be used in connection with PSA formalism must be obtained. Improved calculational tools (CFD) must be developed and validated for these purposes.

In-vessel melt retention by vessel external cooling has also been investigated in several 4^{th} framework projects /28/. It has been showed to be a viable severe accident mitigation strategy for some small and medium sized reactors even without special internal structures in the bottom head of the RPV (AP 600, Loviisa). For larger reactors it will be necessary to develop specific internal crucibles and to offer additional passive cooling (Dual Strategy) for quenching the core melt.

The physical mechanisms of the melt pool thermal hydraulics and the pressure vessel external wall heat transfer are quite well understood. Additional experiments are underway (e.g. for SWR 1000). 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 heat-up 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. For BWR the situation might be different with regard to the multiplicity of standpipes for the absorber rods enlarging the heat transfer area, the smaller wall thickness due to the lower operating pressure and the potential for quick depressurisation.

Special emphasis should also be taken to the aspect of steam explosion. A segmentation of the lower plenum as is the case with the absorber rod guide structures of BWR might be beneficial to avoid a propagation of steam explosions. This influence should be investigated in more detail. The decommissioning of the relevant test facilities at ISPRA is judged as a major draw-back for this kind of research in Europe.

The choice of the steel vessel pre-determines the whole reactor concept of LWR and some modular reactors (e.g. HTR) in a fundamental way. Due to restrictions in the maximum diameter by manufacture and transport capabilities, integral reactor designs are not feasible for larger power sizes. It is strongly recommended to include alternate RPV types like form-welding and Pre-stressed Cast-Iron Vessels (PCIV) into future R&D programmes. Integral reactor designs could provide economic benefits due to compactness and safety advantages due to large coolant reservoirs and nearly no irradiation load on the vessel wall. RPV concepts that can exclude spontaneous burst by design as e.g. multi-filament pre-stressed vessels are also worthwhile for more detailed studies within a more rigorous safety approach to exclude high-pressure sequences.

Task 2.4: Innovative Approaches on Source Term Reduction and Containment Designs

Attention to the Containment in case of severe accident scenarios with Fission Product (FP) release into the containment is a central issue in the development of new reactor designs. The application of a defence-in-depth approach, extended to the consideration of core melt accidents, against which the Containment system is the only fundamental and last barrier, needs a revisiting of the strategy on how to prevent an uncontrolled release of FP to the environment also in these situations.

The requirements for a 'Relocation-free Nuclear Technology' are illustrated in Figure 3. It can be seen that rather low release rates about 10^{-5} of total FP inventory would be necessary to keep the consequences of an accident within the specified limits not causing a severe impact to the environment outside the plant fence. This objective can be reached by different strategies:

- Multi-barrier safety concept with defence-in-depth (emphasis on containment function, independent barriers)
- Exclusion of core melt by passive safety features (emphasis on fuel and passive DHR)
- Permanent removal of FP in homogenous reactors (e.g. Molten Salt or Gas Phase Reactors, low FP inventories)

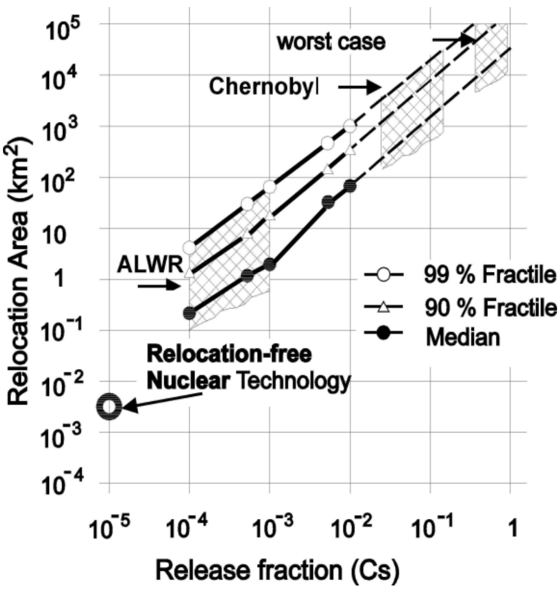


Figure 3: Requirements for 'Relocation-free Nuclear Technology

Under this background, design innovations for the Containment system have been required by potential future owners, indicated by the Safety Authorities and already implemented in practically all new designs. However there are still areas in which potential for improvements exists and the report includes some indications for the medium and long term research. The 3 main areas for exploring new solutions or exploit a R&D program are the following:

- Improvement of the containment function, assuring in an expanded set of conditions an almost perfect leaktightness of a building surrounding the source of FP releases
- To prevent the release of FP from the fuel, even in the most extreme situations, making the classic containment building practically not needed any more as in the case of HTGR type reactors
- Reassess more realistically the Source Term in quantitative and qualitative manners to focus the design of the features which will prevent its release to the environment

Innovation is required to further reduce the consequences of extreme events, the fear of which have caused a rejection of the nuclear energy by the public in some cases. Therefore the concept of an improved conceptual design of the containment system is the possible answer, once it has been recognized that the preventive measures cannot bring to the solution of the issue.

Utility requirements on this issue are based on the double rail of improving safety margins and using proven technology, i.e. the concept of a containment building which is able to contain essentially all the FP released from the fuel even in extreme environmental conditions and loading caused by a severe accident is the basis. Utilities are also very interested in assuring the safety without large credit to correct operator actions in the short term after an accident. Demonstration of FP containment for at least 12 hours based only of passive features and intrinsic characteristic of the containment system is required in some cases, while in others a complete passive containment system is required with at least 72 hours of autonomy.

The major technical features required by the utilities are:

- Large and robust containment structure or pressure suppression containment (like BWRs)
- Double containment with an annulus filtered ventilation system
- Large reactor cavity for retention and cooling of core debris
- A reactor cavity flooding system
- A large cold water inventory inside the containment (IRWST in some PWR's).

Many efforts have been devoted to demonstrate a containment that can maintains its leak tightness in every condition in which it must perform its function. According to figure 3, the allowable leakrate is extremely small and the design and in-service demonstration of such performances requires a number of specific features. At the same time the need for a realistic assessment of the Source Term is recognized, both for the Design Extension Conditions (DEC), including Severe Accidents, and also for the classical DBAs.

The Containment is also an important component because it plays a role in the economic evaluation of the design and it contributes to the overall competitiveness of a design. Its importance on this regard, however, is limited to a few percent of the plant total direct overnight cost. Containment indirect costs are, however, greater. In particular containment design may significantly affect the overall plant construction schedule and have a consequence on the costs. For example Containment structures designed to withstand very high pressures (> 7 barr) may imply a big step up in plant costs, since construction techniques that would be required would exceed the current practice. A complete demonstration of the assumed performances of the proposed systems will require an R&D support.

The scenario shows both traditional and more innovative (AP600, EPR) containment concepts finding their way. In the source term calculation, for instance for AP600, credit is taken for deposition mechanisms specific of the AP600 passive containment, the EUR requirements themselves, show innovative approaches being currently adopted. As it was pointed out previously, the determination of the requested performance of the Containment, for instance in terms of leak rate, depends on the source term and on its calculated impact on the environment. In particular the French and German requirements for EPR are basically in line with these utility requirements.

Recommendations on R&D can be derived from the discussions developed in the previous sections. It shall be repeated that there are two lines of development. The first one is related to strengthen the containment as a structural leak-tight building to make it more resistant and more reliable, and the second one in identifying new features or new designs to prevent in different ways the release of fission products into the environment.

The function of the containment as a barrier against external events may perhaps be improved and updated in the light of possible new challenges to be considered (e.g. earthquakes, new types of aircraft), but this aspect may be of a lesser priority in terms of R&D.

The issue of prompt, reliable and effective containment isolation is one area of further development because it is still a complex system, that requires sensing devices based on number of parameters and parameter combinations, a number of actuators with the necessary supporting systems.

The entire area of severe accident mitigation shall be further explored, in conjunction with the specific phenomenological research. It seems important also to focus on effective containment cooling measures to reduce the driving forces for leakage and the time periods with pressurised containment. As steam and hydrogen more or less represent pure energy, they should also be used to drive cooling devices more effective than natural convection-based systems and to make them more invulnerable to stratification effects and accumulation of non-condensable gases. Combinations of cooling and hydrogen removal systems could offer innovative tools to mitigate severe accidents and to avoid overheating of catalytic recombiners.

With the reduction of the uncertainties margins, components can be made less expensive. The source term, that together with the pressure and temperature conditions, is the major contributor for the definition of the component, is the best candidate for the reduction of the uncertainties and development of innovative cooling systems as described above.

Task 2.5: Innovative Accident Management Measures & Influence of Human Factors

In the majority of initiating events at operating NPPs, including the TMI-2 and Chernobyl-4 accidents, the human factor has been shown to have been decisive, both in causing the events as well as in the actions taken to control them. In addition to its impact on safety, an adequate design of the man-machine interface, significantly affects plant availability and cost reduction, a factor of greater importance when it comes to achieving competitive designs. Both of the above mentioned aspects lead to the conclusion that the human factor should be duly considered during the design of future reactors or innovative measures taken into account for back-fitting at existing plants.

Development has been oriented in three directions:

1. to enhance knowledge of the phenomenology and the effectiveness of Accident Management Studies,
2. design of special devices for intervention,
3. to develop new tools and instrumentation and control devices to improve the capabilities of the operator when it comes to evaluating progression of the accident and plant status.

During the 3rd and 4th Framework Programmes, an extensive research programme was established to support the mentioned development already taking innovative safety features and mitigation measures into consideration. Parallel to this development, regulators and utilities have been working on the establishment of a common approach to the requirements for the assessment of the plant to cope with Severe Accidents. The GPR/RSK position, the EPR and the EUR are the most important efforts in this harmonisation process.

In all of these exercises, precise requirements are established for future design in order to improve human factors, and more specifically to control what is designated as *Design Extension Conditions* in the EUR.

Innovative reactor concepts make greater use of passive safety features and implement systems for improved accident management measures by design (e.g. containment cooling, in-vessel core-retention devices, depressurisation systems, self-acting decay heat removal / coolant injection etc.).

From the overview provided on different R&D programmes and reactor designs , it can be concluded that the human factor and Accident Management have been taken as priority objectives in fission programme development. As a result of these programmes, sound bases support innovative design features and Accident Management procedure implementation.

Nevertheless, these bases need to be consolidated in practical design and procedures for specific implementation in existing and future reactors. Consequently, it is recommended that the following actions concerning future research programmes be taken:

- Exploit the existing information from test results to transfer knowledge to practical design features improvement
- Develop or improve practical tools to allow the operator to easily follow the progression of an accident and evaluate on–line the effectiveness of Accident Management Strategies
- Establish expert judgements on the limitations and possibilities of continuing to implement certain strategies by solving existing uncertainties or whether it is more convenient to try alternative strategies
- Improve the European data base on human errors in plants in operation to translate the operating experience to the improvement of safety and availability
- Continue with the experiments in those areas identified to allow for design of transparent and effective countermeasures when reasonable expectation exists that they will provide a better understanding of the phenomenology and demonstrate the effectiveness of the mitigation action
- Continue the harmonisation process started in Europe with EUR development.
- Reach an agreement on the best approach to cope with severe accident scenarios in new designs. From research programme, develop technical design features to be implemented in future reactors.
- Make use of available energy (steam, hydrogen, pressure differences etc.) to operate self-powered safety systems
- Combine safety functions to avoid inconsistent countermeasures (e.g. feed & bleed)
- Take passive and ‘self-acting’ safety features into account for minimising the need for intervention and for increasing the grace periods.

5. Conclusions & Recommendations on Future R&D Activities

Despite excellent operational behaviour of nuclear power plants in Europe and long practise in operation of LWR by over 6000 reactor years, public opinion still tends to decline from the future use of nuclear energy mainly due to the already illustrated mismatch of the intuitive human sentiment for danger on the one hand and objective safety criteria following the probabilistic risk formula or established safety and licensing requirements, on the other. Catastrophic accident scenarios being associated with Design Extension Conditions (DEC) beyond the 'classical' Design Basis Accidents (DBA) govern public and political debates creating fundamental objection against nuclear energy.

The deterministic limitation of maximum releases of radioactivity, independent barriers, transparent accident management measures and an exclusion of any early containment failure appear as principal preconditions for regaining public acceptance. The intuitive benefit of passive safety systems may be seen in the fact that an 'artificial' danger from NPP may be easier accepted when controlled by 'natural' physical laws. This approach is not new but has been intensified after the TMI and Chernobyl accidents by a multiplicity of 'inherent safe' or passive reactor designs mainly in the Small and Medium-Sized Reactor (SMR) domain thus representing already a profound fundament of knowledge and offering a 'kit' of safety-relevant innovations being worth to be re-assessed against future safety requirements. Despite their excellent safety features, SMR could not be introduced to the market as they are not judged to be competitive to large units and to other energy supply systems. This position has to be revised in the light of the commercial Pebble Bed Modular Reactor (PBMR) project in South Africa.

The information available from literature /29, 30, 31, 32, 33/ etc. and R&D programmes /34, 35, 36 etc./ on the most important safety functions such as Reactivity Control Techniques, Innovative Decay Heat Removal & De-pressurisation Systems, Integrity of the Primary Circuit, Maintenance of Coolant Inventory, Innovative Approaches on Source Term Reduction and Containment Designs, Accident Management Measures / Influence of Human Factors have been collected and evaluated /37, 38, 39, 40, 41/. In addition, a yet non-exhaustive database /42/ on passive safety systems for different reactor lines (mainly PWR & BWR) has been set up in cooperation with the partners of the industrial MICHELANGELO Initiative. Furthermore, a prototypical database was designed to collect the innovative features of different reactor concepts /3/. This background information allowed for identification of main innovation trends and validation needs:

- an increased effort for the plant simplification (transparent safety & cost reduction)
- the implementation of functional redundancies
- attention for passive or self-powered safety systems
- specific PSA methodologies for passive safety systems
- inherent combinations of consistent safety functions
- provisions for effective accident management measures
- the reinforcement of the 'Defence-in-Depth Principle' with an increased effort on the
    - prevention and mitigation of accidents,
    - improvement of the forgiving character of the reactor ,
    - reduction of the core melt frequency combined with in- & ex-vessel core catchers,
    - enhanced retention of fission products in the fuel,

- improvement of the containment efficiency and
- rejection of ‘cliff edge’ effects leading to unacceptable consequences or early releases.

The development of passive safety systems in the past was very much concentrated on thermal hydraulic aspects for Decay Heat Removal (DHR) and governed by a dualism between passive and active designs. However, future R&D programmes on passive safety systems should be extended to all main safety functions (reactivity control, DHR from NHSS and containment, integrity of primary circuit, integrity of containment etc.) in DBA and DEC scenarios and focused on a symbiosis of passive and active safety functions. **Main recommendations** address:

- Consistent Accident Management Approaches to Limit Maximum Releases of Radiotoxicity (e.g. ex-vessel / in-vessel core retention, avoidance of core melt (HTR, LMR, PTR), minimal inventories (Homogenous Reactors), innovative containment designs, i.e. source term, ultimate heat sink, cooling instead of venting, pressure suppression)
- Conversion of Know-how on Phenomena into New Systems (e.g. in-vessel core retention devices, pit-flooding, avoidance / mitigation of steam & H_2 explosions)
- Self-Powered Safety Systems (Use of available energy instead of external energy supply)
- Inherent Combinations of Passive Safety Functions (e.g. Containment Cooling & Emergency Core Cooling, Feed & Bleed, Containment Cooling & Hydrogen Removal)
- New Core and Vessel Configurations (e.g. annular cores, temperature resistant fuel/structures, pre-stressed pressure vessels, pressure tube reactors, integrated designs)
- Development of Methods / Codes for Innovative Safety Systems (e.g. best estimate codes to reduce conservatism, Computational Fluid Dynamic Codes validation)
- Addressing the Broad Spectrum of Safety Functions (e.g. neutronic, thermal, chemical, mechanical stability)

There is a real need to re-discuss the IAEA classification on passive systems as they create a large gap between active and passive safety systems that should be closed by self-activated’ and ‘self-powered systems’ being driven by the impressive surplus of energy available from the decay heat e.g. in the form of steam, H_2 and pressure differences. Such devices should also allow for proven technology like turbo-pumps, turbo-compressors, turbo-generators etc. even if they rely on rotating mechanical elements. Innovative technologies like e.g. magnetic bearings can exclude wear and blockage with high reliability. Thus there is no need only to concentrate on static passive components in combination with e.g. buoyancy-driven movement of fluids. The advantage of simplicity of static components has to be balanced against the increased efficiency of self-powered systems which could be nearly as effective as active systems but would not rely on external power supply. Combinations of safety functions could inherently link necessary actions e.g. using steam released by depressurisation valves (bleed) to inject coolant (feed) by turbo or steam jet pumps for rapid depressurisation.

The reliable removal of the decay heat is essential for all nuclear reactors that ‘accumulate’ large amounts of fission products (FP) in the core. This fact could in principle only be overcome by reactor concepts that permanently 'dilute' the FP concentration as foreseen in some homogenous reactors like Molten Salt Reactors (MSR) or Gas Phase Reactors (GPR) that might offer a long-term option for reactors with reduced requirements on DHR, inherent safety features, small fissile inventories, ideal neutron economy and minimum amounts of long-lived waste by in-situ burning of actinides.

Beside the strategy to significantly lower the core damage frequencies (CDF) by enhanced use of passive safety systems, there is also the possibility of modifications of core and fuel geometries to avoid core melt only by the dissipation of the decay heat via the RPV surface even under the assumption of LOCA. This can be done by increasing the surface to volume ratio, by omitting overheating central zones (ring core), increasing the heat conductivity of the fuel elements (matrix fuel instead of pin arrays), temperature and corrosion resistant materials or modular disintegration of the core (e.g. pressure tube reactors).

The principles and parameters for avoiding core melt accidents in LOCA conditions can be summarised as follows:

- Low Power Density / Low Power
- Low Peaking Factors
- Large Heat Capacities and Coolant Volumes
- Large Surfaces for Heat Transfer
- High Temperature / Corrosion Resistance (of fuel and core structures)
- High Thermal Conductivity of the Fuel and Fuel Assembly
- High Temperature Gradients (short distance for heat transfer)
- High Boiling Temperatures of the Coolant (in case of liquids)
- Low Excess Reactivity to exclude Re-criticality (on-load refuelling, reactivity compensation by breeding ratio ~ 1)

With an adaptation and optimisation of these parameters it is very likely that core melt accidents including related incidents like steam explosion an hydrogen release can be completely ruled out by design not only for SMRs but also for large power sizes. Other RPV types (pre-stressed pressure vessels, form-welding, pressure tube core) could offer additional potential for DHR or for integrated designs and large coolant volumes if larger RPV diameters are possible. This would also eliminate a great deal of piping and associated LOCA scenarios.

It seems to be important to include the whole DHR chain into consideration from the core to the ultimate heat sink outside the containment. Together with measures for rapid depressurisation, this might have strong implications on the containment design (pressure suppression type) and containment cooling measures for lowering the containment pressure being the driving force for leakage to the environment.

The developments of passive DHR systems in the last decades have provided remarkable progress. Their power has been significantly enhanced still showing some reserves by design optimisation. Passive LWR - both PWR and BWR - have already surpassed the 1000 MWe limit (e.g. ESBWR approaching 1400 MWe). They have already got 'adult' and should no more still be seen in the light of SMRs, only. Finally, passive safety systems should support accident management and allow for higher plant availability, significant simplification and cost reduction.

Back-fitting of passive systems in existing plants is another option that should get more attention as they may provide a more rigorous approach with regard to diversity and resistance against station black-out. Such systems are partially rather inexpensive (e.g. passive initiators, steam jet pumps) and can be used for a variety of safety functions. Even in-vessel core retention may be possible for some medium sized plants as an effective accident management strategy.

System selection or comparison of innovative safety systems should be done on the basis of a set of criteria that combine safety aspects and other operational issues as proposed in the appendix. More detailed information on safety-related innovations can be taken from the data being available on the SINTER Network database on Internet.

6.0 APPENDIX

6.1 Overview on Reactor Types in the SINTER Database

Report on Innovative Reactors
Overview

ABWR (General Information) Innovative Features Accident Management Human Factors	Advanced Boiling Water Reactor	L-BWR
ALMR (General Information) Innovative Features Accident Management Human Factors		FRL
AP 600 (General Information) Innovative Features Accident Management Human Factors	Advanced Passive Reactor	L-PWR
APWR 130 (General Information) Innovative Features Accident Management Human Factors		L-PWR
CANDU-3 (General Information) Innovative Features Accident Management Human Factors		HWR
CAREM (General Information) Innovative Features Accident Management Human Factors		L-PWR
EP 1000 (General Information) Innovative Features Accident Management Human Factors	European Passive PWR	L-PWR
EPR (General Information) Innovative Features Accident Management Human Factors	European Passive Reactor	L-PWR

ESBWR (General Information) Innovative Features Accident Management Human Factors		L-BWR
HRT-Modul (General Information) Innovative Features Accident Management Human Factors		GCR
HTR-10 (General Information) Innovative Features Accident Management Human Factors		GCR
HTR-30 (General Information) Innovative Features Accident Management Human Factors		GCR
IRIS (General Information) Innovative Features Accident Management Human Factors		L-PWR
ISER (General Information) Innovative Features Accident Management Human Factors		L-PWR
ISIS (General Information) Innovative Features Accident Management Human Factors		L-PWR
MHTGR (General Information) Innovative Features Accident Management Human Factors		GCR
PBMR (General Information) Innovative Features Accident Management Human Factors		GCR
PIUS (General Information) Innovative Features Accident Management Human Factors		L-PWR
PIUS-BWR (General Information) Innovative Features		L-BWR

Accident Management Human Factors		
SBWR 200 (General Information) Innovative Features Accident Management Human Factors		L-BWR
SBWR-600 (General Information) Innovative Features Accident Management Human Factors	Simplified Boiling Water Reactor	L-BWR
SIR-300 (General Information) Innovative Features Accident Management Human Factors		L-PWR
SWR (General Information) Innovative Features Accident Management Human Factors	Siede Wasser Reaktor	L-BWR
SWR 600 (General Information) Innovative Features Accident Management Human Factors	SiedeWasser Reaktor	L-BWR
System 80+ (General Information) Innovative Features Accident Management Human Factors		L-BWR
VP VER -600 (General Information) Innovative Features Accident Management Human Factors		L-PWR
VVER-1000 (General Information) Innovative Features Accident Management Human Factors		L-PWR
VVER-500 (General Information) Innovative Features Accident Management Human Factors		L-PWR

6.2 Database on Innovative Reactors

Exemplary General Information on Innovative Reactors (e.g. ABWR)
(taken from the SINTER Database)

Acronym	**ABWR**
Full Reactor Name	**Advanced Boiling Water Reactor**
Reactor Type	**LW Boiling Water Reactor**
Comments on Reactor	**In Service in Japan, Kashiwazaki-Kariwa 6 & 7.**
Reactor Designer 1	**General Electric / North and Central America / United States of America /**
Reactor Designer 2	**Toshiba / Far East / Japan /**
Reactor's Purpose	**Prototype Design , Commercial**
Rev 2	**Development Phase Operational (Commercial)**

Countries Participating in Project's Development (up to five Countries)

Zone I (North and Central America Country)	**United States of America**
Zone II (Far East Country)	**Japan**

<u>Reactor's Basic Data</u>

Number of Blocks (Moduls)	**1.0**
Electrical Power(MWe)	**1356.0**
Cooling Circuits Not Applicable:	**Internal Recirculation Pumps**
Thermal Power(MWTh)	**3926.0**
Average Power Density(kW/l)	**50.6**
Fuel	**UO2**
Cold Cooling Fluid Temperature, ºC	**216.0**
Moderator	**Light Water**
Hot Cooling Fluid Temperature, ºC	**288.0**
Coolant	**Light Water**
Primary System Pressure, MPa	**7.2**

<u>Reactivity Control and Shut Down Features</u>

Number of Reactivity Control Systems	**3.0**
Depressurization	**yes**
Reactor Shut Down Mechanisms	**Electrical , Hydraulic, Quick Boron Poisoning**

<u>Residual Heat Removal System Characteristics</u>

Residual Heat Removal System	**Active**
RHR Autonomy (Days)	**7**
RHR System Capacity	**3 x 50 %**

Containment Features

Designs :	
Design: S/D	**Double**
Inner (Primary) Containment	
Inner Containment Construction:	**Reinforced Concrete with Suppression Pool**
Containment Liner:	**Lined**
Inerted Containment:	**Inerting Un-Specified**
Fitered Vent:	**Yes, Rupture Disc**
Comments on Inner Containment:	
Outer (Secondary) Containment	
Outer Containment Construction:	**Non Pressure-Resistant Building**
Comments on Outer Containment:	

Additional Information on Specific Safety Features

Reactivity Control Systems and Means

Reactivity Control Techniques	**Intrinsical Reactor's Design Properties**
Reactivity Control Ways	**Negative Temperature Coefficient**
Comments	

Reactivity Control Techniques	**Intrinsical Reactor's Design Properties**
Reactivity Control Ways	**Void Fraction Control**
Comments	

Reactivity Control Techniques	**Control Rods**
Reactivity Control Ways	**B4C-Boron Carbide**
Comments	

Reactivity Control Techniques	**Burnable Poisons**
Reactivity Control Ways	**Non Extractable:Gadolinium / Fuel Elements**
Comments	**At Cycle's Beginning**

Reactivity Control Techniques	**Soluble Poisons Dilution**
Reactivity Control Ways	
Comments Not Necessary	

6.3 Innovative Features (e.g. ABWR)

Innovative Reactors

Innovative Features

Innovative Reactors

Acronym	ABWR
Full Reactor Name	Advanced Boiling Water Reactor

Innovative Features or Aims Included in Reactor's Design

Innov.Fields	Economics: Reactor's/Plant's Efficiency	**Innovative Feature 1**	Improved Component's Reliability
Innov.Fields	Safety	**Innovative Feature 2**	Prevention of Core Melting
Innov.Fields	Economics: Reactor's/Plant's Efficiency	**Innovvative Feature 3**	Lower Safety-related Components Number

6.4 Specific Safety Features: Accident Management (e.g. ABWR)

Innovative Reactors

Accident Management

Innovative Reaktors

Acronym	ABWR	
Full Reactor Name	Advanced Boiling Water Reactor	

Accident Management Considerations in Project

Accident Management Measures Registered for

Types of Accidents Considered	Containment Failure	Considered Probabilistically
	Loss of Coolant	Considered Deterministically
	Station Black-Out	Considered Probabilistically
	Core Melt	Considered Probabilistically
	Hydrogen Explossion	Considered in Design
	Reactivity Excursion	Intrinsically Prevented
Data Adquisition & Management Systems	Central Data Adq.& Mgt.System	On-Line Digital Data Adquisition System
	Best Estimates Predictions (software)	Required in Basic Design Phase
	On-Line Off-Site Data Transmission	Not Required in Basic Design Phase
Emergency Planning	Plant Emergency Planning	Considered in Design
	Off-Site Emergency Planning	Considered in Design
External Events Considerations	Extreme Wind Conditions	Contemplated as per Civil Design Code
	Air-Craft Crash	Considered Probabilistically
	External Explossion	Considered in Design
	Sabotage	Not Contemplated in Design
Operator's Actions	Operator's Action Foreseen	DBA and Extended Conditions
	Operator's Action Foreseen	Operator's Action Not Required for 8 h
Accident Definition (Deter/Prob)	Deterministic	Only for DBA
	Probabilistic	Only for Extended Conditions
Source Terms	DBA	Deterministic Source Terms
	Design Extended Conditions	Best Estimate Source Terms
	Containment Failure	Best Estimate Source Terms

6.5 Specific Safety Features: Human Factors (e.g. ABWR)

Innovative Reactors

Accident Management

Innovative Reaktors

Acronym	ABWR
Full Reactor Name	Advanced Boiling Water Reactor

Accident Management Considerations in Project

Accident Management Measures Registered for

Types of Accidents Considered	Containment Failure	Considered Probabilistically
	Loss of Coolant	Considered Deterministically
	Station Black-Out	Considered Probabilistically
	Core Melt	Considered Probabilistically
	Hydrogen Explossion	Considered in Design
	Reactivity Excursion	Intrinsically Prevented
Data Adquisition & Managenment Systems	Central Data Adq.& Mgt.System	On-Line Digital Data Adquisition System
	Best Estimates Predictions (software)	Required in Basic Design Phase
	On-Line Off-Site Data Transmission	Not Required in Basic Design Phase
Emergency Planning	Plant Emergency Planning	Considered in Design
	Off-Site Emergency Planning	Considered in Design
External Events Considerations	Extreme Wind Conditions	Contemplated as per Civil Design Code
	Air-Craft Crash	Considered Probabilistically
	External Explossion	Considered in Design
	Sabotage	Not Contemplated in Design
Operator's Actions	Operator's Action Foreseen	DBA and Extended Conditions
	Operator's Action Foreseen	Operator's Action Not Required for 8 h
Accident Definition (Deter/Prob)	Deterministic	Only for DBA
	Probabilistic	Only for Extended Conditions
Source Terms	DBA	Deterministic Source Terms
	Design Extended Conditions	Best Estimate Source Terms
	Containment Failure	Best Estimate Source Terms

6.6 Overview on Passive/ Innovative Safety Devices

Passive Safety Devices: Design Basis Conditions and Complex Sequences

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
1.1. Fission Products Retention							
• Containment spray system							
• F.P. sparging							
• Containment tightness control	32	Containment isolation of main steam line	Basic design	C,D	None	None	Passive actuation
• Leakage recovery							
1.2 Reactivity Control							
• Absorber injection system	1	Lithium Expansion Module (LEM) Lithium Injection Module (LIM)	Conceptual design	B	Drawbacks correction or minimization	LEM action is inherently reversible. LIM effect is not reversible	Degree of passivity, potential reliability (to be analysed in detail) and fast response
	3	Reactor Shutdown System	Basic design	C,D	None	None	Tank size and design pressure reduction. Prevents nitrogen to enter in RPV
• Control rods insertion	4	Control Rod Enhanced Expansion Devices (CREED)	Detailed design	C,D	None	Risk for inadvertent insertion	High reliability
	3	Reactor Shutdown System	Basic design	C,D	None	None	Tank size and design pressure reduction. Prevents nitrogen to enter in RPV

Passive Safety Devices: Design Basis Conditions and Complex Sequences (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
1.3 Decay Heat Removal **1.3-1 Primary side**							
• Water injection	2	Core Make-up Tank (CMT)	Detailed design	C	Not identified	Not identified	Simple, easy inspection and maintenance
	33	Passive Depressurization System	Conceptual design	Not applicabl e.	Device development, design and test	Not identified	Covers the whole pressure range. Avoids high pressure scenarios and extends the grace periods
	34	Core Reflood Tanks(CRT) and Accumulators of EP1000	Basic design	C	None	None	Low cost, simple, easy maintenance and redness monitoring.
	5	Core Flooding Pool	Basic design	B, C	None	None	Diverse passive water injection
• Water circulation and heat removal	6	Direct Reactor Cooling (DRC)	Detailed design	C,D	None	Efficiency and size	Natural convection DHR
	7	Flashing Tank	Conceptual design	C	None	Not yet identified	

Overview of Existing Passive Safety Devices: Design Basis Conditions and Complex Sequences (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
• *Water circulation and heat removal*	8	RP2/BOPHR	Conceptual design	C,D	None	Extension of the primary circuit	Accident management simplification. Active system backup and diversification
	9	RRP/BOPHR	Conceptual design	B,C	None	Increase of pressure vessel size	Accident management simplification. Active system backup and diversification
	10	Secondary Condensing System – Isolation Condenser (SCS-IC)	Conceptual design	C	None	Not yet identified	Passive Heat Removal
	11	Passive Residual Heat Removal (PRHR)	Detailed design	C	None	Extension of primary system	Simpler than active system, easy testing and maintenance
	12	Emergency Condenser	Detailed design	B	None	None	Completely passive
	13	Isolation Condenser System (ICS)	Detailed design	D	None	High reactor pressure rate reduction due to no pressure control. Needs to vent non condensables for proper functioning.	Cools the core without loosing water inventory. Avoids safety relief valves opening

Passive Safety Devices: Design Basis Conditions and Complex Sequences (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
1.3-2 Secondary Side							
• Feedwater							
• Water circulation and heat removal	14	Decay Heat Removal Through the Vault (DHRTV)	Detailed design	B	None	Loss of reactor investment in case of the inter vessel flooding	Spatial segregation. No penetration on the reactor roof
	7	Flashing Tank	Conceptual design	C	None	Not yet identified	
	15	Steam Injector (SI)	Conceptual design	C	None	Lack of information on basic phenomena . Complicated start-up and restart-up. Performance degradation. Non-condensable gases. Lack of available convincing devices.	Use of steam as an energy source. Low cost. Easy maintenance.
	10	Secondary Condensing System – Isolation Condenser (SCS-IC)	Conceptual design	C	None	Not yet identified	Passive Heat Removal
	16	Thermal Valve	Conceptual design	C	Other Pilot Valve locations are under evaluation	Not yet identified	No valve in the high pressure loop. Reduces the heat exchanger thermal loads
	13	Isolation Condenser System (ICS)	Detailed design	D	None	High SG pressure rate reduction due to no pressure control. Needs to vent non condensables for proper functioning	Cools the core without loosing water inventory. Avoids safety relief valves opening
• Air circulation and heat removal	17	Reactor Vessel Air Cooling System (RVACS)	Conceptual design	B	Layout , sizing and components performances optimization	Applicable only to small/medium plant size	Higher reliability: always in ‘ready standby”. Operates indefinitely without any support system

Passive Safety Devices: Design Basis Conditions and Complex Sequences (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
1.3-3 ***Primary pressure control***	7	Flashing Tank	Conceptual design	C	None	Not yet identified	
	18	Safety Relief Valve System	Basic design	C, D	None	None	Additional installation of the Passive Pressure Pulse Transmitter for passive actuation of depressurization.
	19	Passive Injection and Depressurization System (PIDS)	Conceptual design	B	Layout, sizing and components performances optimization	Adds pipes and components to the primary system	Depressurizes while adding mass to the reactor coolant system.
	33	Passive Depressurization System	Conceptual design	Not applicabl e.	Device development, design and test	Not identified	Covers the whole pressure range. Avoids high pressure scenarios and extends the grace periods
1.3-4 Containment							
• Intermediate heat sink	20	Passive Containment Cooling System (PCCS) for PWR type containment	Detailed design	C	Not identified	Not applicable to double containment design	Simple. Easy test, inspection and maintenance.
	21	Containment Cooling Condenser (CCC)	Basic design	B	None	None	Completely passive
	22	Passive Containment Cooling System (PCCS) for BWR type containment	Detailed design	B	None	Containment pressure is controlled but not reduced. Not EUR requirements compliant	Always in ”ready standby”. Long period of operation without any support system.

Passive Safety Devices: Design Basis Conditions and Complex Sequences (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
Intermediate heat sink	23	Passive Containment Cooling System (PCCS) for PWR type dual concrete containment	Basic design	B	External heat exchanger optimization in terms of size, cost and performances	Sensitivity to seismic loads and aircraft crash	Operates indefinitely without any support system. Always in "ready standby". The only available passive system for large double concrete containment.
• External coolant circulation							
1.4 Other	30	Passive Pressure Pulse Transmitter(PPPT)	Basic design	C	Execution of reliability tests with a whole system	Not identified	No need of electric power supply, external media or actuation via I&C signal.

Passive Safety Devices: Severe Accident Conditions

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
2.1 Fission Products Retention							
• Containment spray system							
• F.P. sparging	25	Passive Drywell Flooding and Exterior RPV Cooling	Basic design	C, D	None	None	Molten core remains inside RPV
• Containment tightness control	24	Dual In-Vessel Retention (DIVER)	Conceptual design	C	Other core-catcher geometry/design	Accident management has to be carefully analyzed	
	32	Containment isolation of main steam line	Basic design	C,D	None	None	Passive actuation
• Leakage recovery							
2.2 Recriticality Control	24	Dual In-Vessel Retention (DIVER)	Conceptual design	C	Other core-catcher geometry/design	Accident management has to be carefully analyzed	
______	31	BWR Internals and Structures	Conceptual design	A	None	Lack of demonstration tests	No need of active systems.
2.3 Debris confinement and cooling							
• Core debris configuration	31	BWR Internals and Structures	Conceptual design	A	None	Lack of demonstration tests	No need of active systems.
• Debris cooling system	24	Dual In-Vessel Retention (DIVER)	Conceptual design	C	Other core-catcher geometry/design	Accident management has to be carefully analyzed	
	25	Passive Drywell Flooding and Exterior RPV Cooling	Basic design	C, D	None	None	Molten core remains inside RPV
• Feedwater	24	Dual In-Vessel Retention (DIVER)	Conceptual design	C	Other core-catcher geometry/design	Accident management has to be carefully analyzed	

Passive Safety Devices: Severe Accident Conditions (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
2.4 Long Term Containment Heat Removal							
• Intermediate heat sink	14	Decay Heat Removal Through the Vault (DHRTV)	Detailed design	B	None	Loss of reactor investment in case of the inter vessel flooding	Spatial segregation. No penetration on the reactor roof
	6	Direct Reactor Cooling (DRC)	Detailed design	C,D	None	Efficiency and size	Natural convection DHR
	20	Passive Containment Cooling System (PCCS) for PWR type containment	Detailed design	C	Not identified	Not applicable to double containment design	Simple. Easy test, inspection and maintenance.
	21	Containment Cooling Condenser (CCC)	Basic design	B	None	None	Completely passive
	26	Natural Convection driven Cooler and Recombiner (NCCR)	Conceptual design	B	Device development, design and test.	Not identified	Allows to cool the containment atmosphere and to remove the hydrogen and the recombination reaction heat
	27	Turbo-Compressor Recombiner (TCR)	Conceptual design	Not applicabl e	Device development, design and test.	Not identified	Allows to cool the containment atmosphere effectively, to remove the hydrogen and the recombination reaction heat and to avoid containment atmosphere stratification.

Passive Safety Devices: Severe Accident Conditions (continued)

Safety Functions	Syst. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
• Intermediate heat sink	23	Passive Containment Cooling System (PCCS) for PWR type dual concrete containment	Basic design	B	External heat exchanger optimization in terms of size, cost and performances	Sensitivity to seismic loads and aircraft crash	Operates indefinitely without any support system. Always in "ready standby". The only available passive system for large double concrete containment.
• External coolant circulation							
• Ultimate heat sink	24	Dual In-Vessel Retention (DIVER)	Conceptual design	C	Other core-catcher geometry/design	Accident management has to be carefully analyzed	
	17	Reactor Vessel Air Cooling System (RVACS)	Conceptual design	B	Layout , sizing and components performances optimization	Applicable only to small/medium plant size	Higher reliability: always in "ready standby". Operates indefinitely without any support system.

Passive Safety Devices: Severe Accident Conditions (continued)

Safety Functions	Sy st. N°	System Identification	System Status	Passivity Degree	Needs for Improvement & Simplification	Drawbacks	Main Advantages
2.5 Combustible Gas Control	26	Natural Convection driven Cooler and Recombiner (NCCR)	Conceptual design	B	Device development, design and test.	Not identified	Allows to cool the containment atmosphere and to remove the hydrogen and the recombination reaction heat
	27	Turbo-Compressor Recombiner (TCR)	Conceptual design	B	Device development, design and test.	Not identified	Allows to cool the containment atmosphere effectively, to remove the hydrogen and the recombination reaction heat and to avoid containment atmosphere stratification.
	28	Passive Recombiner	Conceptual design	B	Increased recombination reaction rates by modified substrates and cooling measures to avoid substrates overheating	Not identified	No need of energy supply. Self-starting.
	29	Removal Devices	Conceptual design	B	The behavior of semi-permeable membranes is to be studied under the specific conditions	Any surplus of injected oxygen has to be excluded	No need of any energy supply and oxygen. Self-starting. Avoids any release via filters.
2.6 Containment Pressure Control							
• Filtered vent containment							
• Pressure suppression system							

6.7 Exemplary Extract from Database on Passive Safety Systems

Passive System 12

Device/system name : Emergency Condenser ***Designer/Supplier*** : Siemens

Main Safety Functions to be realised

Fission Product Retention ☐ *Reactivity control* ☐ ***Heat removal*** ☒

Corresponding Safety sub-function *to be realised* :

- **Primary side: Water circulation and heat removal**

Short description :

The emergency condenser system consists of four separate sub-systems which together provide a rated heat transfer capacity of 4 x 56 MW at 71 bar reactor pressure. Each emergency condenser subsystem consists of a steam line leading from an RPV nozzle, and a condensate return line back to the RPV, which is equipped with a siphon. The emergency condensers are connected to the RPV with no isolating element, and are activated only by a drop in the RPV level. The emergency condenser is not in operation during plant operation, as the heat exchanger tubes are filled with cold condensate owing to their location in relation to the normal RPV level, such that heat transfer is not possible. The heat exchanger tubes only fill up with steam (which condenses) after the water level in the reactor falls. The condensate returns to the RPV by gravity flow.

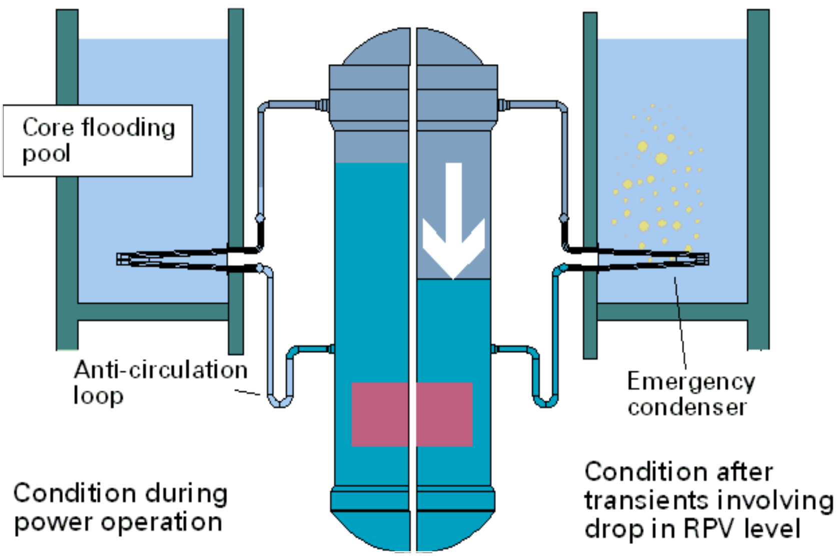
Operational Range covered :

Normal Plant Operation

Design basis incidents ☒ *Design basis accidents* ☒

Design Extension Conditions - Complex sequences ☒ *Design Extension Conditions - Severe accidents*

Sketch with the behaviour principles :



Current Development Device/System Status :

Detailed design ☒ *Basic design* ☐ *Conceptual design* ☐

Passivity Degree *(cf. IAEA definitions)* :**B**

Main ***advantages*** *versus corresponding active devices/systems* :

The emergency condensers function as completely passive devices for residual heat removal from the RPV to the core flooding pool.

Main ***drawbacks*** *versus corresponding active devices/systems* :

Open Issues *for the device/system qualification* :

Identified ***needs for Improvements and Simplification*** :

Candidates for ***MICA Assessment : Yes*** ☒*; Not* ☐

Potential Application in the ***Short/Medium Term*** *:* ***Yes*** ☒ *; Not* ☐

Potential Application to ***Existing Facilities and Designs*** *: Yes* ☐ *;* ***Not*** ☒

Potential Application to the ***New Reactor Concepts*** *: :* ***Yes*** ☒ *; Not* ☐

Lower estimated Cost versus corresponding active devices/systems : Yes ☒ ; Not ☐

6.8 Classification of the pursued objectives versus the defence-in-depth

Table 6.8.1

Safety Related Innovative Items : *Classification for the pursued objectives versus the defence-in-depth*		
		Comments
1st level : PREVENTION conservative design, quality assurance, safety culture		
⇨ **Elaborate a simplified design** • Elaborate a simplified neutronic design • Elaborate a simplified thermohydraulic design • Elaborate a simplified thermomecanic design		
⇨ **Satisfy the design rules** • Elaborate a design consistent with all the plausible situations. • Qualify the materials (mechanical, electrical, etc.)		
⇨ **Simplify the reactor operations and the maintenance procedures for normal conditions** (human factor for operation and shut down) • Improve the quality of the information (operational data) • Improve the man-machine interface • Simplify and automatize the procedures for the operation • Simplify and automatize the procedures for the inspection • Simplify and automatize the procedures for the maintenance and preventive repair		
⇨ **Integrate the principles of the defence-in-depth : balanced, gradual and extended defence** • Take care to the balanced character of the implemented defence • Take care to the gradual character of the implemented defence • Take care to the extensive character of the implemented defence		
⇨ **Minimize the personnel exposure during normal operation** • Minimize the contact dose • Limit the length of circuits which carry activated fluid • Minimize the maintenance times for normal conditions		

Table 6.8.1

Safety Related Innovative Items : Classification for the pursued objectives versus the defence-in-depth		
		Comments
1st level :PREVENTION (continued) conservative design, quality assurance, safety culture (follows)		
⇨ **Minimize radioactive waste during normal operation** • Simplify the chemistry of the primary circuit • Reduce the self -generation of radioactive waste • Reduce the corrosion phenomenon • Ensure the good materials behaviour under irradiation		
⇨ **Minimize the frequency for the Postulated Initiating Events** (PIE - abnormal situations; during normal operation and shut down) :		Postulated Initiating Events (PIE) list is established for each concept.
⇨ **Minimize the potential for Common Modes** (Initiators) • Separate and diversify the systems • Minimize the potential for flooding • Minimize the potential for fires • Qualify the material for the earthquake		
⇨ **Minimize the inherent potential consequences for the PIE** (operation and shut down) :		PIE list must be established.
⇨ **Avoid by design (prevent) the sequences that can lead to unacceptable consequences and early releases. Reject the risk for the cliff edge effect** • Avoid by design the reactivity excursions • Avoid by design the core melting concomitant to the loss of the containment (bypass). • Avoid by design the risks for the steam explosions		

Table 6.8.2

Safety Related Innovative Items : Classification for the pursued objectives versus the defence-in-depth		
		Comments
★ **2nd level :CONTROL** control of abnormal operations and detection of failures		
⇨ **Detect the Postulated Initiating Events** (PIE – operation and shut down) :		PIE list must be established.
⇨ **Minimize the uncertainties about the plant conditions** • Implement an adequate instrumentation (for automatic and manual devices) • Implement a design that simplify the abnormal sequences		
⇨ **Simplify the plant inherent behaviour under abnormal conditions** (operation and shut down)		PIE list must be established.
⇨ **Elaborate a forgiving design** • Ensure appropriate physical margins • Ensure appropriate grace period • Limit the intervention of safeguard functions (unnecessary safety systems actions)		
⇨ **Take into account aggravating situations** (coherently with the PIE category) • Take into account the corrective functions unavailability for maintenance • Take into account the PIE with cumulative system failures		
⇨ **Simplify the reactor operations and maintenance procedures under abnormal conditions** (human factor for operation and shut down) • Improve the quality of the information (operation data) • Simplify and automatize the procedures for the plant oper. under abnormal cond. • Simplify and automatize the procedures for the plant inspection, maint. and repair		
⇨ **Minimise the personnel exposure under abnormal conditions** (oper. and shut down) • Strengthen the first barrier • Strengthen the second barrier • Reduce the time for the intervention under abnormal conditions		

Table 6.8.2

Safety Related Innovative Items : Classification for the pursued objectives versus the defence-in-depth		
		Comments
★ **2nd level :CONTROL (continued)** control of abnormal operations and detection of failures		
⇨ **Minimize the radioactive waste under abnormal conditions** (oper. and shut down) • Strengthen the first barrier • Strengthen the second barrier • Strengthen the third barrier		

Table 6.8.3

Safety Related Innovative Items : Classification for the pursued objectives versus the defence-in-depth		
		Comments
★ **3rd level : PROTECTION** safety systems and protection systems		
⇨ **Minimize the uncertainties about the plant conditions under accidental conditions** (operation and shut down) • Implement an adequate instrumentation (for automatic and manual devices) • Implement a design that simplify the accidental sequences		
⇨ **Simplify the reactor management under accidental conditions** (oper. and shut down)		PIE must be established.
⇨ **Take into account aggravating situations** (coherently with the PIE category) • Take into account the safeguard functions unavailability for maintenance • Take into account the PIE with cumulative safeguard system failures (multiple failure situations) • Take into account the loss of the redundant systems (complementary situations)		
⇨ **Minimize the potential for Common Modes** (mutual agressions, internal or external hazards) • Separate and diversify the safety systems		
⇨ **Simplify the accidental intervention procedures under accidental conditions** (human factor for operation and shut down) • Ensure an adequate information (abnormal situation) • Simplify and automatize the procedures for the accident management • Simplify and automatize the procedures for the plant inspection, and repair		
⇨ **Reduce the core melt frequency** • Improve the availability of the safeguard systems • Implement an adequate functional redundancy for the important safety functions		
⇨ **Minimize the offsite accidental release** (without core melt) • Conceive the plant in order to guarantee no necessity for protective measures		

Table 6.8.4

Safety Related Innovative Items : Classification for the pursued objectives versus the defence-in-depth		
		Comments
★ **4th level : MAJOR ACCIDENT MANAGEMENT** accident management including the confinement protection		
⇨ **Take into account the severe accident configurations** • Ensure the safety function accomplishment under severe accident conditions • Protect the material against the potential hazards (steam explosion, H2 deflag., etc.)		
⇨ **Minimize the uncertainties about the plant conditions under severe accidental conditions** (operation and shut down) • Implement an adequate instrumentation • Elaborate a design that simplifies the inherent plant accidental scenarii		
⇨ **Simplify the reactor operations procedures under severe accident conditions** • Improve the grace delay		
⇨ **Minimize the offsite accidental release** (low pressure core melt situations) • Conceive in order to need only very limited protective measures in area and in time		
⇨ **Avoid by design (prevent) the sequences that can leads to unacceptable consequences and early releases. Reject the risk for the cliff edge effect.** **(For recall → must be realized at the prevention level.)** • Avoid by design the reactivity excursions • Avoid by design the core melting concomitant to the loss of the contain. (bypass). • Avoid by design the risks for the steam explosions		

Table 6.8.5

Safety Related Innovative Items : *Classification for the pursued objectives versus the defence-in-depth*		
		Comments
★ **5th level : CONSEQUENCES MITIGATION** offsite emergency response		
⇨ **Delay the offsite release** ⇨ **Minimize the offsite radioactive release**		

6.9 Exemplary Comparative Evaluation of Innovative Systems

FUTURE PWR DECAY HEAT REMOVAL (DHR) FUNCTION

- Comparative Evaluation among Different DHR Systems -

For illustration of the evaluation approach, different Decay Heat Removal (DHR) Systems have exemplarity been compared:

1. Implementation of a Passive Decay Heat Removal (PRHR) system,
2. DHR heat exchangers installed within the primary vessel (RRP) system or a
3. DHR by secondary circuit (SCS) like SIR of a future standard PWR [7].

These evaluations are based on assessments made by CEA to judge the applicability of advanced or innovative systems that are mainly discussed for small or medium-sized reactors (SMR) also for larger PWR of the 900 MW class.

The contributions linked to the systems implementation in larger reactors are indicated by :

favourable (⇧),
unfavourable (⇩),
indifferent (⇨)

judgements. This is of course only a rough assessment how the system copes to the requirements but it could be further developed for quantitative statements.

Table 6.9.0: DHR System Options to be Compared

OPTION	System	Comments
1	PRHR	Passive Decay Heat Removal system implemented on the primary circuit of the AP600 concept. Studies have been performed at the CEA to implement similar system on a 900 MW PWR.
2	RRP	Passive/active Decay Heat Removal system. Heat exchangers installed within the primary vessel Studies have been performed at the CEA to design the system for a 900 MW PWR.
3	SCS	Passive Decay Heat Removal system implemented on the secondary circuit of the SIR concept. Studies have been performed at the CEA to implement similar system on a 900 MW PWR.

Table 6.9.1
FUTURE PWR DECAY HEAT REMOVAL (DHR) FUNCTION
- COMPARATIVE EVALUATION AMONG DIFFERENT DHR SYSTEMS-

Implementation of a PRHR system; or a RRP system; or a SCS system for the Decay Heat removal of a future standard PWR.

Identification of the **favourable (⇧), unfavourable (⇩), indifferent (⇨)** contributions linked to the systems implementation

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
1st level : PREVENTION conservative design, quality assurance, safety culture				
⇨ Elaborate a simplified design				
• Elaborate a simplified neutronic design				
• Elaborate a simplified thermohydraulic design				
* *Simplify the vessel internals*	⇨	⇩	⇨	RRP - Increased complexity within the vessel
* *Simplify the thermohydraulic for the normal DHR*	⇧	⇧	⇧	
* *Simplify the thermohydraulic for the safeguard DHR*	⇩⇧	⇧	⇧	PRHR ⇩ Steam generator thermally isolated RRP - The DHR function efficiency is still guaranted with low primary water inventory
* *Separe the normal operating DHR function from the safeguard DHR*	⇧	⇧	⇧	Systems for normal and/or safeguard DHR ?
* *Increase the range covered by normal DHR systems (forced conv., natural conv.)*	⇧	⇧	⇧	(→must be defined after accurate design)
* *Reduce the number of components per system*	⇧	⇧	⇧	
* *Standardize the components among normal operating DHR and safeguard DHR*	⇧	⇧	⇧	
• Elaborate a simplified thermomecanic design				
* *Simplify the vessel internals*	⇨	⇩	⇨	RRP - Increased complexity within the vessel
* *Reduce the number of systems connected to the primary circuit*	⇩	⇧	⇧	PRHR implemented as an extension of the P.C
* *Reduce the impact of transients*	⇩⇧?	⇧	⇩⇧	PRHR(⇧?), SCS ⇧ with thermal valve
* *Minimise the thermomechanical loads (pressure versus geometry, ΔP)*	⇩	⇧	⇧	The risk for overcooling in case of complete system intervention must be evaluated
* *Reduce the number of components per system*	⇧	⇧	⇧	
⇨ Satisfy the design rules				
• Elaborate a design consistent with all the plausible situations.				
* *Take into account the Passive Single Failure criterion for the short term*	⇩	⇧⇩	⇧	PRHR - Primary LOCA; RRP ⇩ in case of internal heat exchangers (IHX) tubes rupture
• Qualify the materials (mechanical, electrical, etc.)				
* *Qualify the materials for the planned function (performances)*	⇧	⇧	⇧	
* *Qualify the materials versus the requested reliability*	⇧	⇧	⇧	
* *Qualify the materials versus the requested availability*	⇧	⇧	⇧	
* *Qualify the materials for the espected environmental conditions*	⇧	⇧	⇧	
* *Plan the possibility for representative tests*	⇧	⇧	⇧	
* *Standardize the components among systems (improve the feedback experience)*	⇧	⇩	⇧	RRP - Ad hoc in vessel exchangers
⇨ Simplify the reactor operations and the maintenance procedures for normal conditions (human factor for operation and shut down)				
• Improve the quality of the information (operational data)				
* *Implement adequate control on systems behaviour and status*	⇧	⇩?	⇧	RRP - Difficulties for IHX instrumentation? (anyhow reduced needs)
• Improve the man-machine interface	⇧	⇧	⇧	Systems easy to operate
• Simplify and automatize the procedures for the operation	⇧	⇧	⇧	Systems easy to operate
• Simplify and automatize the procedures for the inspection	⇧	⇩	⇧	RRP - Difficulties for IHX inspection
• Simplify and automatize the procedures for the maintenance and preventive repair	⇧	⇩	⇧	RRP - Difficulties for IHX maintenance and repair

Table 6.9.1

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR.
Identification of the contribution linked to the implementation of each system
Favourable ⇧; unfavourable ⇩; indifferent ⇨

SYSTEMS	PRHR	RRP	SCS	Comments
1st level :PREVENTION conservative design, quality assurance, safety culture (follows)				
⇨ Integrate the principles of the defence-in-depth : balanced, gradual and extended defence				All the systems can be considered as indipendent LOD. Their correct implementation leads to improve the defence-in-depth principle
• Take care to the balanced character of the implemented defence				
* *Implement an homogeneous number of Lines of Defence (LOD) for each operating condition (OC : PIE applied to an Initial plant status)*	⇧	⇧	⇧	
• Take care to the gradual character of the implemented defence				
* *Implement functional redundancies: indipendent LOD*	⇧	⇧	⇧	
• Take care to the extensive character of the implemented defence				
* *For each operating condition, implement an number of Lines of Defence (LOD) coherent with the probabilistic objectives →(2a+b)*	⇧	⇧	⇧	
⇨ Minimize the personnel exposure during normal operation				
• Minimize the contact dose				
* *Reduce the corrosion phenomena and the radioactive products transport*	⇩?	⇩?	⇧	PRHR, RRP Increased surfaces of the second barrier. Negligible versus the SG?
• Limit the length of circuits which carry activated fluid				
* *Reduce the portions of circuits that carries primary coolant*	⇩	⇧	⇧	PRHR implemented as an extension of the P.C
• Minimize the maintenance times for normal conditions				
* *Improve the accessibility*	⇩	⇩	⇧	PRHR implemented as an extension of the P.C
* *Foresee equipments and robots*	⇧	⇩	⇧	RRP - Difficulties for IHX accessibility
⇨ Minimize radioactive waste during normal operation	⇨	⇨	⇨	Globally indifferent
• Simplify the chemistry of the primary circuit				
• Reduce the self -generation of radioactive waste				
• Reduce the corrosion phenomenon	⇩?	⇩?	⇨	PRHR, RRP Increased surfaces of the second barrier. Negligible versus the SG?
• Ensure the good materials behaviour under irradiation				
⇨ Minimize the frequency for the Postulated Initiating Events (PIE - abnormal situations; during normal operation and shut down) :				
▫ Control rod withdrawal				
▫ Uncontrolled boron dilution				
▫ LOFA - Sequences initiated by loss of primary coolant flow				
▫ Loss of charge / turbine trip				
▫ Loss of normal feedwater				
▫ Loss of external electrical power supply				
▫ LOCA - Sequences initiated by a leakage of primary coolant	⇩	⇧⇩	⇨	PRHR, RRP Increased surfaces of the second barrier. Negligible versus the SG? RRP tubes ⇧: external loads (pressure outside) are favourable
* *Reduce the number of chipping on primary loops*				
* *Minimise the length of the loops which carry primary fluid*				
* *Minimise the fluids internal energy (primary pressure)*				
* *Reduce the corrosion phenomenon*				
▫ Sequences initiated by loss of secondary coolant or heat sink	⇨	⇩	⇩	RRP, SCS increased lenght of secondary loops. (RRP - small inertia in case of loop rupture)
* *Minimise the length of the loops which carry secondary fluid*				
* *Minimise the fluids internal energy (secondary pressure)*				
* *Reduce the corrosion phenomenon*				
▫ Steam Generator tubes rupture				
* *Minimise the fluids internal energy (ΔP primary/secondary pressure)*	⇨	⇩⇨	⇨	RRP - IHX tubes equivalent to the SG ones; nevertheless the external loads (pressure outside) are favourables
* *Reduce the corrosion phenomenon*				

Table 6.9.1

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
1st level :PREVENTION conservative design, quality assurance, safety culture (follows)				
⇨ Minimize the potential for Common Modes (Initiators)				
• Separate and diversify the systems				
* *Diversify the components*	⇧	⇩	⇧	RRP - Difficult to diversify the IHX
* *Keep segregate the single loops*	⇧	⇧	⇧	
• Minimize the potential for flooding	⇨	⇨	⇨	
* *Put out of water the compnents important for safety*				
• Minimize the potential for fires	⇨	⇨	⇨	
* *Implement incombustible materials*				
• Qualify the material for the earthquake	?	?	?	The earthquake response must be carefully analysed
⇨ Minimize the inherent potential consequences for the PIE (oper. and shut down) :				
▫ Control rod withdrawal				
▫ Uncontrolled boron dilution				
▫ LOFA Sequences initiated by loss of primary coolant flow	⇨	⇨	⇨	
* *Foresee an adequate pump inertia*	⇧	⇧	⇧	
* *Foresee the natural convection behaviour*				
▫ Loss of charge / turbine trip	⇧	⇧	⇧	
* *Foresee the natural convection behaviour*				
▫ Loss of normal feedwater	⇧	⇧	⇧	
* *Foresee the natural convection behaviour*				
▫ Loss of external electrical power supply	⇧	⇧	⇧	
* *Foresee the natural convection behaviour*				
▫ LOCA Sequences initiated by a leakage of primary coolant				
* *Minimise the primary depressurisation effects (on the three barriers)*	⇨	⇨	⇨	
* *Ensure the DHR with reduced primary water inventory*	⇨	⇧	⇨	RRP - The DHR function efficiency is still guaranted with low primary water inventory
▫ Sequences initiated by loss of secondary coolant or heat sink	⇨	⇨	⇨	
* *Minimise the secondary depressurisation effects (on the three barriers)*				
▫ Steam Generator tubes rupture	⇨	⇨	⇨	
* *Confine the secondary discharges*				
⇨ Avoid by design (prevent) the sequences that can leads to unacceptable consequences and early releases. Reject the risk for the cliff edge effect				
• Avoid by design the reactivity excursions				
• Avoid by design the core melting under high primary pressure conditions				
* *Participate efficiently to the primary circuit depressurisation*	⇩⇧	⇧	⇧	The systems can actively participate to the primary circuit depressurisation. PRHR ⇩ - SG thermally isolated : primary circuit still pressurized
• Avoid by design the core melting concomitant to the loss of the containment (bypass).				
* *Foresee an ultimate passive DHR system within the containment*	?	?	?	The systems potential for DHR in case of severe accident is not clearly established
* *Set up within the containment all the loops that carry primary coolant*	⇧	⇧	⇧	
* *Foresee the isolation of all intermediate loops at the containment level*	⇧	⇩⇧	⇩⇧	RRP ⇧ whit internal heat exchanger SCS ⇧ With internal pool
• Avoid by design the risks for the steam explosions				
• Avoid by design the risks for the Hydrogen detonation				

Table 6.9.2

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR.
Identification of the contribution linked to the implementation of each system
Favourable ⇧; unfavourable ⇩; indifferent ⇨

SYSTEMS	PRHR	RRP	SCS	Comments
★ **2nd level :CONTROL** control of abnormal operations and detection of failures				
⇨ Detect the Postulated Initiating Events (PIE - operation and shut down) :	⇨	⇨	⇨	Globally indifferent
▫ Control rod withdrawal				
▫ Uncontrolled boron dilution				
▫ LOFA Sequences initiated by loss of primary coolant flow				
▫ Loss of charge / turbine trip				
▫ Loss of normal feedwater				
▫ Loss of external electrical power supply				
▫ LOCA Sequences initiated by a leakage in primary coolant				
▫ Sequences initiated by loss of secondary coolant or heat sink				
▫ Steam Generator tubes rupture				
⇨ Minimize the uncertainties about the plant conditions				
• Implement an adequate instrumentation (for automatic and manual devices)	⇧	⇧	⇧	Passive systems: reduced need for instrumentation and control
* *Foresee an instrumentation able to identify without ambiguity the systems configurations and the consequences on the control parameters*				
• Implement a design that simplify the abnormal sequences	⇧	⇧	⇧	These advantages arise from the passive character of the systems
* *Dispose of the natural convection within the primary circuit*	⇧	⇧	⇧	
* *Dispose of the natural convection within the secondary loops*				
⇨ Simplify the plant inherent behaviour under abnormal conditions (operation and shut down)				
▫ Control rod withdrawal				
▫ Uncontrolled boron dilution				
▫ LOFA - Sequences initiated by loss of primary coolant flow				
* *Foresee an adequate pump inertia*	⇨	⇨	⇨	
* *Foresee the natural convection behaviour*	⇧	⇧	⇨	Easy natural convection on the primary circuit
▫ Loss of charge / turbine trip				
* *Implement passive and efficient functional redundancy*	⇧	⇧	⇧	
▫ Loss of normal feedwater				
* *Implement passive and efficient functional redundancy*	⇧	⇧	⇧	
▫ Loss of external electrical power supply				
* *Implement passive and efficient functional redundancy*	⇩⇧	⇧	⇧	PRHR ⇩ - SG thermally isolated
▫ LOCA - Sequences initiated by a leakage in primary coolant				
* *Foresee the passive cooling of the primary coolant still within the vessel*	⇨	⇧	⇨	RRP - The DHR function efficiency is still guaranted with low primary water inventory
* *Foresee the passive coolant injection to guarantee the primary coolant inventory*	⇨	⇨	⇨	
* *Foresee the passive cooling of the primary coolant rejected in the containment* *(Control the containment temperature and presssure)*	⇨	⇨	⇨	
▫ Sequences initiated by loss of secondary coolant or heat sink	⇩⇧	⇧	⇧?	PRHR ⇩ - SG thermally isolated
* *Foresee the passive cooling of the primary coolant*	⇨	⇨	⇨	SCS - efficient if the secondary breach is isolated
* *Foresee the passive cooling of the secondary coolant rejected in the containmen* *(Control the containment temperature and presssure)*	⇧?	⇧	⇧	The systems can contibute to depressurize the primary circuit (PRHR ?)
▫ Steam Generator tubes rupture	⇨	⇨	⇨	
* *Avoid the activation of the secondary overflow valves*				
* *Confine the secondary discharges*				

Table 6.9.2

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
★ **2nd level :CONTROL** control of abnormal oper. and detection of failures (follows)				
⇨ Elaborate a forgiving design				
• Ensure appropriate physical margins				
* *Improve the system efficiency*	⇧	⇧	⇧	RRP - The DHR function efficiency is still guaranted with low primary water inventory
* *Increase the common range covered by complementary systems*	⇧	⇧	⇧	The risk for overcooling in case of complete system intervention must be evaluated
• Ensure appropriate grace period	⇧	⇧	⇧	
* *Increase the process internal inertia*				
* *Provide the passive access to adequate external inertia*				
• Limit the intervention of safeguard functions (unnecessary safety systems actions)	⇧	⇧	⇧	Potentially favourable. The role of the systems must be clearly defined
* *Foresee control and limitation devices*				
⇨ Take into account aggravating situations (coherently with the PIE category)				
• Take into account the corrective functions unavailability for maintenance	⇧	⇧	⇧	Separate loops for all the systems
* *Foresee an internal redundancy*				
• Take into account the PIE with cumulative system failures	⇧	⇧	⇧	
* *Take into account the Operating Conditions (OC) with the Loss of Offsite Power*	⇧	⇧	⇧	
* *Take into account the OC considering the Single Failure Criterion*	?	?	?	
* *Take into account the OC with internal and external hazards*				PRHR and SCS are perhaps more sensible to the external hazards - must be verified
⇨ Simplify the reactor operations and maintenance procedures under abnormal conditions (human factor for operation and shut down)				
• Improve the quality of the information (operation data)				
• Simplify and automatize the procedures for the plant oper. under abnormal cond.	⇧	⇧	⇧	Easily operate
* *Improve the man-machine interface*	⇧	⇧	⇧	Dedicated systems
* *Limit the interactions among systems that perform the same function*	⇧	⇧	⇧	Passive systems
* *Implement safety system automatisation*				
• Simplify and automatize the procedures for the plant inspection, maint. and repair	⇩	⇩	⇧	PRHR, RRP : difficult to access; SCS ⇧ if the pool is outside the containment
* *Improve the accessibility*	⇩	⇩	⇧	
* *Foresee equipments and robots*				
⇨ Minimize the personnel exposure under abnormal conditions (oper. And shut down)				
• Strengthen the first barrier				
• Strengthen the second barrier	⇩	⇧	⇧	RRP, SCS favourable except in case of primary/secondary breach
* *Reduce the portions of circuits that carries primary coolant*				
• Reduce the time for the intervention under abnormal conditions	⇩	⇩	⇧	PRHR, RRP : difficult to access; SCS ⇧ if the pool is outside the containment
* *Improve the accessibility*	⇩	⇩	⇧	
* *Foresee equipments and robots*				
⇨ Minimize the radioactive waste under abnormal conditions (oper. And shut down)				
• Strengthen the first barrier				
• Strengthen the second barrier				
* *Conceive the circuits connected to the primary*	⇧	⇧	⇨	RRP with intermediate heat exchanger within the containment (intemal heat exchanger)
- permanently → installed within the containment	⇨	⇨	⇨	
- temporarely → eventually outside but isolable				
* *Conceive the circuits connected to the secondary*	⇨	⇧	⇧	
→ designed to the maximum injection pressure	⇨	⇨	⇨	
→ in order to confine the discharge within the containment				
• Strengthen the third barrier	⇧	⇧⇩	⇧⇩	PRHR ⇧ for the AP600 configuration
* *Limit the number of containment penetrations*				RRP ⇧ with internal heat exchanger
				SCS ⇧ if the pool is inside the containment

Table 6.9.3

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR.

Identification of the contribution linked to the implementation of each system

Favourable ⇧; unfavourable ⇩; indifferent ⇨

SYSTEMS	PRHR	RRP	SCS	Comments
★**3rd level : PROTECTION** safety systems and protection systems				
⇨ Minimize the uncertainties about the plant conditions under accidental conditions				
(operation and shut down)	⇧	⇧	⇧	Passive systems: reduced need for instrumentation and control
• Implement an adequate instrumentation (for automatic and manual devices)				
* *Foresee an instrumentation able to identify without ambiguity the systems configurations and the consequences on the control parameters*	⇧	⇧	⇧	These advantages arise from the passive character of the systems
• Implement a design that simplify the accidental sequences				
* *Reduce the number of possible systems response configurations*				
* *Dispose of a primary circuit natural convection configuration*				
* *Dispose of a primary circuit natural convection configuration*				
⇨ Simplify the reactor management under accidental conditions (oper. And shut down)				Due to the degraded situation, the systems favourable contibution is due to the passive character of their intervention
▫ Control rod withdrawal				
▫ Uncontrolled boron dilution	⇧	⇧	⇧	
▫ LOFA - Sequences initiated by loss of primary coolant flow	⇧	⇧	⇧	
▫ Loss of charge / turbine trip	⇧	⇧	⇧	
▫ Loss of normal feedwater	⇧	⇧	⇧	
▫ Loss of external electrical power supply	⇨	⇧	⇨	RRP - The DHR function efficiency is still guaranted with low primary water inventory
▫ LOCA - Sequences initiated by a leakage in primary coolant				
	⇧	⇧	⇧	SCS - efficient only if the secondary breach is isolated
▫ Sequences initiated by loss of secondary coolant or heat sink	⇧	⇧	⇧	
▫ Steam Generator tubes rupture				
⇨ Take into account aggravating situations (coherently with the PIE category)				
• Take into account the safeguard functions unavailability for maintenance	⇧	⇧	⇧	
* *Foresee a functional redundancy*				
• Take into account the PIE with cumulative safeguard system failures (multiple failure situations)	⇧	⇧	⇧	
* *Take into account the Operating Conditions (OC) with the Loss of Offsite*	⇧	⇧	⇧	
Power	?	?	?	PRHR and SCS are perhaps more sensible to the external hazards - must be verified
* *Take into account the OC considering the Single Failure Criterion*				
* *Take into account the OC with internal and external hazards*	⇨?	⇨?	⇨?	A systems contribution can perhaps be envisaged
• Take into account the loss of the redundant systems (complementary situations)				
* *Foresee an ultimate passive DHR within the containment*				

Table 6.9.3

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
★**3rd level : PROTECTION** safety systems and protection systems				
⇨ Minimize the potential for Common Modes (mutual agressions, internal or external hazards) • Separate and diversify the safety systemes * *Avoid any physical interaction between the systems in case of failure*	?	?	?	The contribution can be effectively appreciated only after accurate design analysis
⇨ Simplify the accidental intervention procedures under accidental conditions (human factor for operation and shut down) • Ensure an adequate information (abnormal situation) • Simplify and automatize the procedures for the accident management * *Improve the man-machine interface* * *Limit the interactions among systems that perform the same function* * *Implement safety system automatisation* • Simplify and automatize the procedures for the plant inspection, and repair * *Improve the accessibility* * *Foresee equipments and robots*	⇧ ⇧ ⇧ ⇩ ⇩	⇧ ⇧ ⇧ ⇩ ⇩	⇧ ⇧ ⇧ ⇧ ⇧	Easy to operate Dedicated systems Passive systems PRHR, RRP :difficult to access; SCS ⇧ if the pool is outside the containment
⇨ Reduce the core melt frequency • Improve the availability of the safeguard systems • Implement an adequate functional redundancy for the important safety functions	⇧ ⇧	⇧ ⇧	⇧ ⇧	These generic favourable contributions must be quantified through probabilistic safety assessment
⇨ Minimize the offsite accidental release (without core melt) • Conceive the plant in order to guarantee no necessity for protective measures * *Strengthen the third barrier*	⇧	⇧⇩	⇧⇩	PRHR ⇧ for the AP600 configuration RRP ⇧ with internal heat exchanger SCS ⇧ if the pool is inside the containment

Table 6.9.4

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
★ **4th level : MAJOR ACCIDENT MANAGEMENT** accident management including the confinement protection				
⇨ Take into account the severe accident configurations • Ensure the safety function accomplishment under severe accident conditions ∗ *Foresee the DHR with severe accident configurations:* - *Corium within the primary vessel*	⇧?	⇧	⇧?	RRP - The efficiency versus the DHR function is still guaranted with low primary water inventory For the PRHR and SCS the efficiency must be demonstrated
- *Corium within the containment (core catcher)*	⇧?	⇧?	⇧?	
• Protect the material against the potential hazards (steam explosion, H2 deflag., etc.) ∗ *Protect the material against the following hazards: corium, H_2 deflagration, temperature, pressure, etc*	⇧	⇩	⇧	RRP - More sensible to the potential in-vessel agressions
⇨ Minimize the uncertainties about the plant conditions under severe accidental conditions (operation and shut down) • Implement an adequate instrumentation • Elaborate a design that simplifies the inherent plant accidental scenarii	⇧?	⇧?	⇧?	Internal containment natural convection configurations: the systems efficiency must be demonstrated
⇨ Simplify the reactor operations procedures under severe accident conditions • Improve the grace delay ∗ *Implement an ultimate passive DHR for the corium cooling*	⇧?	⇧?	⇧?	Internal containment natural convection configurations: the systems efficiency must be demonstrated
⇨ Minimize the offsite accidental release (low pressure core melt situations) • Conceive in order to need only very limited protective measures in area and in time ∗ *Qualify the third barrier to the configurations with the low pressure core melt: guarantee its cooling*	⇨?	⇨?	⇨?	The systems contribution to the third barrier strenght must be evaluated

Table 6.9.4

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
★ **4th level : MAJOR ACCIDENT MANAGEMENT** accident management including the confinement protection				
⇨ Avoid by design (prevent) the sequences that can leads to unacceptable consequences and early releases. Reject the risk for the cliff edge effect. **(For recall → must be realized at the prevention level.)** • Avoid by design the reactivity excursions • Avoid by design the core melting under high primary pressure conditions				
* *Participate efficiently to the primary circuit depressurisation*	⇩⇧	⇧	⇧	The systems can actively participate to the primary circuit depressurisation. PRHR ⇩ - SG thermally isolated : primary circuit still pressurized
• Avoid by design the core melting concomitant to the loss of the contain. (bypass).				
* *Foresee an ultimate passive DHR system within the containment*	?	?	?	The systems potential for DHR in case of severe accident is not clearly established
* *Set up within the containment all the loops that carry primary coolant*	⇧	⇧	⇧	
* *Foresee the isolation of all intermediate loops at the containment level*	⇧	⇩⇧	⇩⇧	RRP ⇧ whit internal heat exchanger SCS ⇧ With internal pool
• Avoid by design the risks for the steam explosions				
• Avoid by design the risks for the Hydrogen detonation				

Table 6.9.5

PRHR system; or RRP system; or SCS system for the Decay Heat Removal of a future standard PWR. Identification of the contribution linked to the implementation of each system **Favourable ⇧; unfavourable ⇩; indifferent ⇨**				
SYSTEMS	**PRHR**	**RRP**	**SCS**	Comments
★ **5th level : CONSEQUENCES MITIGATION** offsite emergency response				
⇨ Delay the offsite release ⇨ Minimize the offsite radioactive release				

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