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Definition of VVER-440 Research Needs in Plant Life Management and Severe Accident Management

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ABSTRACT

The plant owners of twelve operating VVER-440/213 reactors in the Czech Republic, Hungary and Slovakia have carried out extensive safety enhancement programmes that have improved prevention, mitigation and control of design basis accidents. Recently, there have been a number of projects to study the Severe Accident Management (SAM) aspects of these plants, and the plant owners have also initiated Plant Life Management (PLIM) programmes. This paper describes the results of the VERSAFE Concerted Action among VVER-440/213 plant owners and operators.

The project has been carried out within the 5th Framework Program of the Euratom research. The objective has been to create a network of the VVER-440/213 plant owners and operators, which aims at definition of the further research needs of severe accidents and plant ageing from the utilities' viewpoint. The starting point was to formulate general approaches to SAM and PLIM and based on these to define the additional information expected from the safety research. The final aim was at establishing well-defined research projects that would be oriented to the needs of the end-users. The project was completed in November 2002.

The SAM subgroup defined the safety goals, based on which a general SAM approach was defined. The general SAM approach provided the logical structure for the plant specific studies, which constituted definition of SAM strategies specifically for VVER 440/213 with bubble condenser containment and ice condenser containment. After understanding what a comprehensive SAM strategy would entail for the plants in question, remaining research needs could be pin-pointed in a consistent manner. Among the most important results were the feasibility study on in-vessel retention of molten corium through external cooling of the reactor pressure vessel (RPV), and the identification of still unresolved issues. Management of containment leakages and hydrogen mitigation are also high-priority SAM issues for all the VVER-440/213 plants. The paper outlines the most important remaining research needs in these areas.

The PLIM subgroup defined the general PLIM approach to be conducted. The structure of the work consisted of the five phases defining the PLIM approach, including identification of the critical systems, structures and components (SSC), definition of the component categories, identification of loadings and ageing mechanisms, the method development for the lifetime prediction, and identification of applicable ageing countermeasures. Plant-specific approaches to PLIM and recommendations for a common approach to PLIM programme were discussed, as well. Unresolved issues at the plants and consequent additional research needs on the ageing and PLIM issues were identified. It could be concluded that identified future research can be related to understanding of degradation mechanisms due to the lack of knowledge of the ageing processes and their impact on material behaviour. In addition, many identified unresolved matters are related to the SSC ageing management issues that require more detailed review and further activities to be carried out at the plants.

KEY WORDS: VERSAFE, nuclear, power plant, VVER-440, SAM, PLIM, 5th framework program

INTRODUCTION

The recent and current safety improvement programmes of the VVER-440 plants in Czech Republic, Hungary and Slovakia have been successful in enhancing the level of management of design basis accidents and thus bringing the prevention of severe accidents to high standards. After demonstrating effective accident prevention, the next level of the defence-in-depth was to reduce the risks associated with severe accidents. It is the responsibility of the plant owner or licensee to develop an overall approach to SAM. Another current issue of the plant owners' safety management is to develop the approach to maintaining the achieved safety level until to the end of economically and technically justified lifetime of the plant.

The high-level objective of the VERSAFE Concerted Action was to create a network of the plant licensees that are foreseen to operate the VVER-440/213 reactors within the European Union. The aim was to contribute with the utility views to the preconditions of the plant operation. For this purpose, the specific features of the VVER's in the Central European countries with respect to the already obtained high safety level were taken into account. Figures 1 and 2 show cross sections of the VVER-440/213 bubble condenser containment and of the Loviisa VVER-440/213 ice condenser containment, respectively.

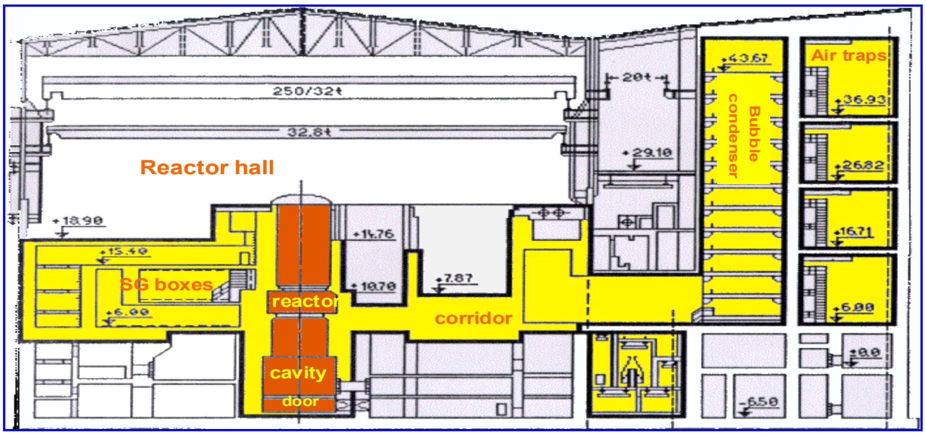

Fig. 1 VVER-440/213 bubble condenser containment (representative of VVER-440/213 plants in Czech Republic, Hungary and Slovakia)

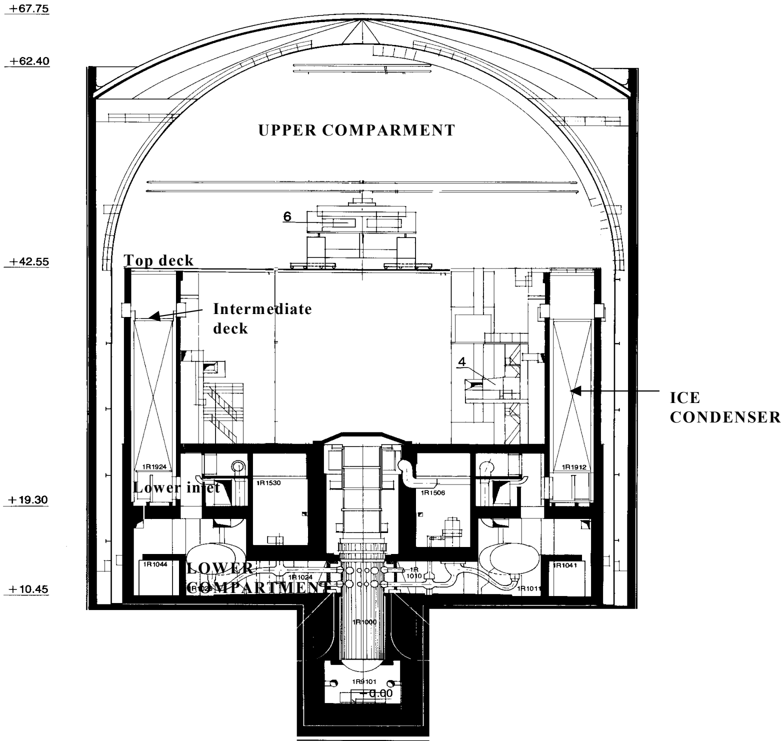

Fig 2 Ice condenser containment of Loviisa VVER-440 plant in Finland

The project aimed at an overview on the comprehensive approaches to two safety management issues that are of concern for the near future, i.e.

1. Severe Accident Management (SAM)
2. Plant Life Management (PLIM)

There are already results from the related national research projects and from the related EU sponsored PHARE projects. The project reviews and utilizes the existing results when applicable. The selection of the final approach to the SAM and PLIM for the individual plants has to be consistent with the plant-specific features and with the national and utility requirements. However, the project strived for harmonization of the utility views in order to obtain maximal benefits of the unified approaches.

Accordingly, the VERSAFE aimed at defining the needs for additional information from safety research, when developing generic and plant-specific approaches to the SAM and PLIM issues. The role of national research institutes and organisations of the partner countries has been crucial, since it was important to create and maintain the expertise on the national level. A further objective has been to enhance possibilities of well-defined research projects that are oriented towards the needs of the end-users to be accepted into the EU regional assistance program (PHARE).

WORK PROGRAMME

The project has been divided into four work packages. The contents of these work packages aim at achieving the objectives of the project:

1) Status review, definition of the subgroup work and expected results. As a starting point for the work, a status review of SAM and PLIM applications as well as the progress made so far in the respective research areas of VVER-440 reactors was carried out. The partners presented an overview of the related work in their own countries and from the completed PHARE projects that are related to SAM and PLIM work.

2) Severe Accident Management: approach and methodology. The dedicated SAM subgroup was established to carry out the detailed review of the VVER-440/213 specific features important to SAM and to define candidate approaches to the SAM. The co-ordinator prepared the background material to the meetings and the partners presented the status in their countries in detail. As a result of this work, the co-ordinator wrote, based on his own experience and on the discussions during the meetings, a thorough report of the status and recommendations.

3) Plant Life Management: approach and methodology. The dedicated PLIM subgroup was established to carry out the detailed review of the VVER-440/213 specific features in relation to ageing and PLIM. The work was based on the detailed review of the status of the efforts taken by the partners in their VVER-440 plants. The structure of the work conducted in the subgroup consists of the five phases defining the PLIM approach, and it includes identification of the critical SSCs, definition of the component categories, identification of loadings and ageing mechanisms, the method development to the lifetime prediction, and identification of applicable ageing countermeasures.

4) Presentation of the results. The obtained results of the formulation of generic approaches to the VVER-440 have been collected to the Final Report in the form of Handbooks on SAM and PLIM. These documents include recommendations of both subgroups. The recommendations concerning the safety research needs to support the development of the generic and plant-specific VVER-440 SAM and PLIM approaches make an essential part of these documents.

MAIN ACHIEVEMENTS

Status at the beginning of the project in 2001: Partners' presentations on their SAM and PLIM efforts

SAM/Hungary: The efforts the Paks Nuclear Power Plant (NPP) on severe accident analyses and SAM started within the Hungarian AGNES project (national project for re-evaluation of the Paks nuclear safety) in 1991-1994. The SAM approach is continued with the emergency operating procedures (EOP) development project that is going on for the Paks NPP. A new extended PSA level 2 project has been launched to assess the large radioactive releases from the safety point of view during 2000-2002. Hungarian regulatory requirements do not specify in detail the approach to SAM that the nuclear power plant should follow.

Among the mitigation aspects, Paks is interested in the feasibility of in-vessel retention for preventing RPV failure. It is also recognized that reliable prevention of containment failure would require a hydrogen management scheme, and mitigation of slow overpressurisation. Paks studies the potential plant modification needs for a severe accident spray system, in-vessel melt retention through external cooling of the vessel, and filtered containment venting. Hydrogen mitigation approaches are also being considered. The approach of Paks is to identify the required systems on the basis of results of a level 2 PSA by the end of 2004.

SAM/Slovakia: The EOPs were developed for the Bohunice V2 units with Westinghouse starting from 1994. The EOPs are considered as validated and they have been in use since 1999 at both Bohunice and Mochovce NPPs, and currently their status is fully implemented. The VUJE Institute has performed numerous MELCOR and STCP analyses for the V2 units. The work done within PHARE Project 4.2.7a/93 included a large number of MAAP analyses and initial formulation of the preventive and mitigative SAM functions.

The PHARE projects are considered to serve as useful starting points for SAMG development. Bohunice and Mochovce have started their SAMG development in early 2002. There is an interest in considering the VERSAFE project results for inclusion into the SAMGs that will be applied to the VVER-440/213 plants, especially with regards to in-vessel retention of molten corium. Also hydrogen and containment leakage mitigation are interesting aspects to the plants.

SAM/Czechia: There is a common project among the Ministry for Industry, Nuclear Research Institute Rez and the Dukovany NPP during 2001-2004 to support a SAM strategy. Based on the requirement of the Czech Regulatory Body (SUJB) a proposal regarding the selection of severe accidents sequences and the measures for decrease of their risk was prepared by the Dukovany NPP in co-operation with NRI Rez. The SUJB accepted the report in January 2000. The PSA level 2 study has been applied to analyse improvement measures for severe accident prevention and mitigation. According to the PSA results mainly preventive measures are substantial. The work is continuing on control room habitability, establishing the Technical Support Centre and SAM Guidelines. The Dukovany NPP started development of SAMGs from October 2001. The Westinghouse approach and methodology is used for development of SAMGs.

SAM/Finland: The Loviisa NPP is a 2-unit VVER-440/213 with ice condenser containments. The whole SAM approach of Loviisa follows the Fortum interpretation of the requirements of the Finnish regulatory authority STUK. Accordingly, the integrated ROAAM (Risk-Oriented Accident Analysis Methodology) study was performed to ensure consistency and comprehensiveness of the approach. The starting point is the well-based prevention as demonstrated by extensive PSA studies. The applied strategies for the critical SAM safety functions (primary circuit depressurization, hydrogen management, in-vessel retention and long-term containment decay heat removal) required extensive plant specific research. The implementation of the plant modifications will be completed in 2003 as well as the implementation of SAM guidelines and training.

PLIM/Hungary: The Paks NPP has initiated wide efforts in the area of PLIM. There is a draft regulatory guide by the Hungarian authority HAEA on the assessment of the ageing phenomena. The guide requires that there has to be a lifetime management strategy. The task is being conducted by the personnel of technical, maintenance, safety and operational divisions of the Paks NPP. The list of the priority equipment has been worked out. Ageing mechanism and ageing management (AM) assessments for some priority equipment have been carried out. Specific cases are the pressurizer surge line monitoring and feedwater line monitoring.

PLIM/Slovakia: Slovenske Elektrarne is in process of preparing the PLIM plans for both the Mochovce and Bohunice NPPs. The Mochovce plant has established an internal QA procedure covering the Ageing Management Program (AMP). The respective program is being developed for the Bohunice plant. The AM covers SSCs including RPV material degradation, primary coolant system components, secondary side components as well as I&C and electric equipment.

PLIM/Czechia: The legislative base of the Dukovany PLIM and the main steps of the PLIM process have been defined. The main goal is that the PLIM program should assure the operation of the SSCs of the plant to the 2025 with acceptable safety margin.

PLIM/Finland: The PLIM of the Loviisa plant will make an important element of the operating license renewal in 2007, since the original design target of 30 years operation was only a rough estimate. Key areas of the Loviisa PLIM are in management of erosion-corrosion and fatigue in piping systems, the RPV embrittlement, the steam generators (SGs), austenitic castings, reactor internals embrittlement, I&C and electrical equipment and building structures.

Status at the beginning of the project in 2001: PSA studies as background information for VERSAFE

The status of PSA studies varies somewhat among the plants. The level 1 PSA is well developed for all plants for internal events, and to some extent also for external events. Results from shutdown state PSAs are becoming available. The same basic conclusion could be drawn for all plants, for which shutdown state PSA results were reported. The core damage frequency due to shutdown state events is very significant, in some cases dominant, compared to core damage frequency resulting from at-power sequences (internal events). It is still under discussion what could actually be done to either improve prevention of core damage or mitigate consequences for sequences originating from shutdown states. It may not be feasible to try to retain the containment function for a bubbler condenser containment during shutdown. This issue was immediately identified as an item requiring further studies.

Severe Accident Management

The IAEA safety goals [2], [3] have been adopted in the SAM Handbook, and the formulations have been extensively discussed during the project meetings. Generally it was felt that the goals are reasonable, and widely accepted in the participating countries. It was, however, pointed out that the goal *"severe accident management and mitigation features could reduce by a factor of at least ten the* probability *of large off-site releases requiring short-term off-site response"* is currently a challenging one for the plants. Both the coolability issue and shutdown state sequences without a containment function were mentioned as examples. Fulfilling the criterion also requires that containment bypass sequences should be reliably prevented.

Among the plant-specific approaches, coolability strategies and mitigation strategies in containment were discussed in-depth during the project.

The plant modifications required for in-vessel retention (IVR) were carried out in the year 2000 for Loviisa Unit 1, and have been planned for the refuelling outage of 2002 for Loviisa Unit 2. The feasibility of IVR for the bubble condenser containment plants was actively discussed during the VERSAFE meetings. Several important issues were identified early on, such as timing of cavity flooding, the sufficiency of water resources with or without the bubble tower, and the possibility to lose water through a ventilation line. The approach is fundamentally different from the Loviisa case, since cavity flooding would be an active measure. In Loviisa, the cavity would be filled with water passively due to the features of the ice condenser containment. Therefore one should carefully also outline the adverse effects of this cavity flooding approach, in order to create a basis for decision making.

Feasibility studies of in-vessel retention of corium on Bohunice V2 NPP as a reference plant [4] were produced within the VERSAFE project. The following issues determining the feasibility of IVR were thoroughly studied:

- Availability of flow paths for water flooding the cavity (in particular, possibilities for preventing backflow through ventilation lines and clogging of flow paths).
- Availability of water sources (especially, the approach to draining the bubble condenser tower trays and the sequence dependence were studied).
- Timing aspects (especially, in-vessel phenomena, draining of bubble condenser trays, filling the cavity, and actuation timing).

Also for the bubble condenser containments, a number of plant modifications would be required in order to make in-vessel retention through external cooling work. The following remaining research needs regarding the feasibility of in-vessel retention were identified during VERSAFE:

- What are the consequences of the fact that the RPV cannot be quite as deeply submerged in water as in case of Loviisa? Analyses or experiments may be required to clarify this issue.
- The long-term effect of in-vessel retention through external cooling to pressurise the containment should be considered. There has to be scheme for mitigation of long-term containment overpressurisation, since with moderate leakage rates it is obvious that containment pressure will increase as water is vaporised around the RPV. The requirement for mitigation of long-term overpressurisation is in fact present in any case, and is not solely linked to IVR.
- The impact of the focussing effect in a potentially thinning metallic layer should also be clarified.

Adverse effects of cavity flooding should be outlined. Since one of the potential adverse effects is related to pressurised thermal shock (PTS) of the RPV due to external flooding, there is a common point of discussion between SAM and PLIM subgroups.

Ex-vessel strategies should be considered in parallel with studying the feasibility of IVR. This is important, since the plants have to make decisions on whether to rely on the IVR or alternatively on the ex-vessel cooling of the corium. Such a decision necessitates sufficient knowledge of various alternatives, and particularly of their benefits and disadvantages as well as potential adverse effects. The logic of this decision process is outlined in the SAM Handbook.

The containment strategy selection and related analysis or research efforts were structured according to Figure 3. The idea with the structure is that the starting point has to be the management of pre-existing containment leakages, which will affect hydrogen mitigation. The combined approaches, again, for leakage management and hydrogen mitigation, will largely determine the approach for mitigation of slow overpressurisation. Leakage modelling (including e.g. deposition of aerosols in concrete cracks) was viewed as a definite research need for SAM development for VVER-440's.

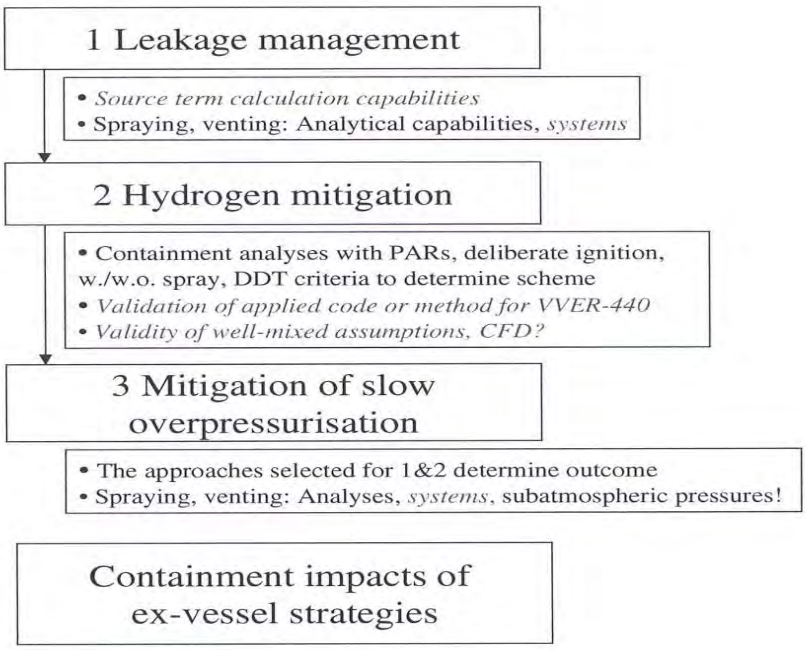

Fig. 3 Summary of discussion on containment strategies. Items in italics are research or development issues that have been identified.

Containment analyses with different combinations of e.g. PARs, deliberate ignition, and spraying should be carried out in order to create a basis for decision making on hydrogen mitigation. The importance of comparing code calculation results with relevant experimental results was stressed, particularly if plant modifications are to be considered. The partners considered it important to discuss applicability of available experimental results for code validation purposes in the SAM Handbook. The VVER-440/213 owners are planning to continue research efforts in the Electrogorsk bubble condenser test facility. One of the interesting topics would be the hydrogen distribution in the bubble condenser containments.

Since most of the containments represented in VERSAFE have managed to reach significantly reduced leakage rates, mitigation of long-term overpressurisation has to be part of the SAM approach. The selected strategy should follow from what was done at steps 1 (for leakage mitigation) and 2 (for hydrogen mitigation) of the containment strategy. The options are containment spraying or filtered venting.

The determination of research needs in containment strategies focussed on the need for validation of codes and models in all three items of Figure 3, namely leakage management, hydrogen mitigation, and mitigation of slow overpressurisation, especially when considering hardware modifications related to SAM. In particular, the need for developed capabilities in release calculations was emphasised by the relatively high leakage rates of this type of containment. Also the hydrogen issue may require some advanced modelling capabilities. Therefore, it was recommended that a larger integrated project should be formed among the bubble condenser plant owners and associated research institutes for running appropriate experiments and the validation exercises. The primary objective in such a proposal is to develop the expertise and the capabilities that could be directly utilised by the licensees.

Plant Life Management: approach and methodology

The starting point for the PLIM group work has been the main views on PLIM issues and conclusions of PLIM activities by the participants at their plants and the partner organisations in their country. One of the main objectives of the work has been to seek for harmonisation of utility views, however, accounting at the same time for plant-specific features.

Formulation of the general PLIM approach in the project has been based on the AM process of the critical SSCs presented in the IAEA Safety Report [3]. In the process, as presented in Figure 4, different activities at the plant relevant to the AM of SSCs are illustrated. This process, however, does not include the economic issues, which also are an essential part of PLIM.

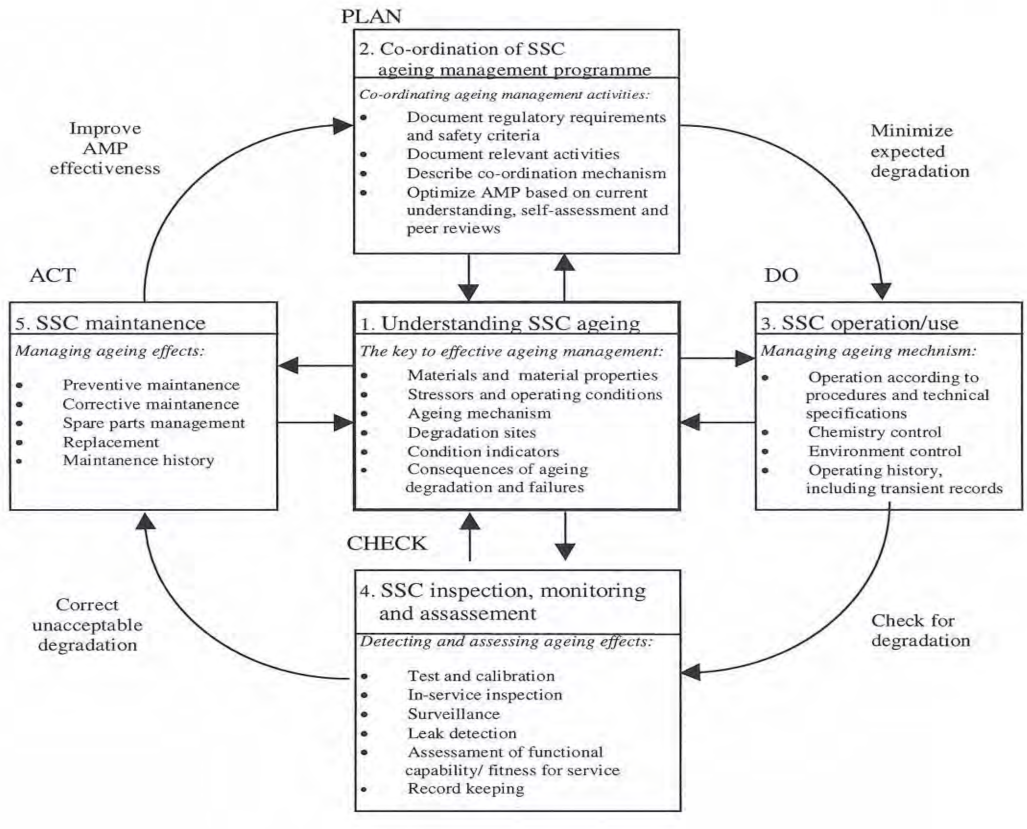

Fig. 4 A systematic ageing management process [1].

It can be concluded that effective AM process includes e.g. ageing phenomena assessment, knowledge of the inspection and testing practice, operational practice, maintenance practice, monitoring practice, data collection, record keeping, documentation and information exchange practice. Data collected should include e.g. design, fabrication, condition monitoring and inspection data as well as operation and maintenance history. Effective AM requires also development of models. In addition, training should be emphasised regarding most of the phases of AM process.

In addition to manage the technical issues relevant to PLIM, also human and organisational factors should be considered in the frame of PLIM at the plant. However, most efforts have been focused on technical matters in the project. It is not seen rational to recommend certain form of organisation for all plants. Exchange of experience on these matters as well as on training matters is seen very useful, though.

Based on the main conclusions of the described PLIM activities so far and plans for the future for individual plants, it can be summarised that PLIM issues are currently handled differently at the participating plants:

- Some plants have started an AMP to carry out assessments of selected SSCs' life. On the other hand it is a common approach to carry out case-specific assessments of SSC ageing or AM as well as to investigate ageing mechanisms on component based needs.
- AM and PLIM issues are being handled in different types of organisations. A special AM group may have been established to concentrate on PLIM issues or there are several persons in different departments working with ageing management issues and involved with PLIM at the plant.
- Due to different types of organisations the plants are in different situation as regards to the matters for lifetime prediction of SSCs and identification of applicable ageing countermeasures. At some plants the plant organisations perform and are responsible for all activities but at other plants the comparable activities are performed by outside organisations.
- The PLIM programme may rather be aimed at the plant life extension at some plants.

When formulating the common views and points of divergence one must bear in mind that there are also other differences among the plants. Actual or possible differences recognised which might also affect the selection of critical SSCs are:

- different design of SSCs or SSC type used,
- location of the plant may affect the selection of SSC as priority component,
- former and/or current operation practices might be different,
- maintenance practices might be different,
- different codes are used for lifetime and AM,
- criteria used for selecting the priority components for AM assessments might differ (categorizing criteria).

The PLIM programme as well as formulation of the structural approach to PLIM in the project consist of five main issues: (1) Identification of the critical SSCs, (2) Definition of the component categories for the PLIM, (3) Identification of loadings and ageing mechanisms, (4) Method development for the lifetime prediction, (5) Identification of applicable ageing countermeasures.

Identification of the dominant and possible degradation mechanisms of the identified priority SSCs for the participating plants has been performed. The aim has been to identify the critical SSCs at the plants, finally aiming at harmonising the list of critical SSCs for VVER-440/213 plants as well as identifying the relevant ageing mechanisms of these SSCs. In this context it has been concluded that methodology and criteria for categorizing the SSCs should be finalised before identification of the critical SSCs. Categorizing the components as e.g. critical or non-critical, active or passive depends mainly on factors such as their significance to safety, cost of replacement, replaceability, maintenance issues and operational availability including economical factors as well as regulatory and design requirements. A common understanding of the ageing mechanisms and terms used is also needed to be able to identify the relevant ageing mechanisms acting on SSCs.

To avoid leaving the approach described for critical SSC on a too general level it would be useful to assess every critical SSC in more detail so that all the critical parts and sensitive spots as well as dominant ageing mechanisms of these spots would be assessed and defined. Such an approach, however, is too broad to be fully implemented during this project.

To assure the safe and reliable operation of the SSC for the planned lifetime of the plant the method development for the SSC lifetime prediction is required. To do this, one should consider operation condition monitoring, in-service inspections, load monitoring with sequential calculations, water chemistry monitoring related to some components and material research. Successful AM of the SSC requires also identification of applicable ageing countermeasures. The plant lifetime can be controlled by inspection, maintenance and refurbishment programmes, by controlling the plant operation and by modification programmes.

The plants are in different situation as regards to the issues of method development for the SSC lifetime prediction and identification of applicable ageing countermeasures due to different types of organisations. Guidelines how to perform measures for SSC AM, for techniques to be used as well as requirements or limits for lifetime prediction are needed at the plants. Further, a more detailed review of each component considering appropriate measurements and analysing programs is also seen useful.

An objective of this project was to identify future research needs and unresolved issues of the utilities with respect to ageing and AM of the SSCs as well as the PLIM issues. It could be concluded that identified additional research can be related to understanding of degradation mechanisms, the lack of knowledge of the ageing processes and their impact on material behaviour. In addition, many identified unresolved matters are related to SSC AM issues that require more detailed review and further activities to be carried out at the plants.

Evaluation of Results, Formulation of the Handbooks and Reporting

The main contents of the final report is the outcome of SAM and PLIM subgroups' work, i.e. it consists of the SAM and PLIM Handbooks.

SAM Handbook is structured into four main sections with subsections:

- **General approach to severe accident management** *(Background, Safety requirements, SAM approach)*
- **Identification of candidate strategies** *(Depressurisation of the primary circuit, Prevention of induced steam generator tube rupture (SGTR), Confirmation of containment function, Mitigation strategies in containment, Coolability strategies)*
- **VVER-440/213-specific severe accident management approach** *(Based on all identified candidate strategies)*
- **Research needs and approaches** *(Based on all identified candidate strategies)*

Research needs and approaches with respect to the plant-specific SAM strategies are the most important findings or recommendations of VERSAFE. There are also suggestions how to generate the missing knowledge; e.g. through improved analyses, new experiments in new or existing facilities, scaling analyses etc.

The structure of the PLIM Handbook is:

- **General approach to plant life management programme**
- **Plant specific features**
- **Research needs of the utilities**

The PLIM approach in this project, recommendations for a common approach to PLIM programme and plant-specific approaches to PLIM are described. The unresolved issues and consequent additional research needs on the PLIM issues are discussed also on the point of view being able to co-ordinate the research.

Final Summary Report that summarises the work as well as the key conclusions and recommendations will be published by the European Commission. The contents of the report has been decided among the project partners.

CONCLUSIONS AND BENEFITS

The project work is considered successful, and the partners have taken an exceptionally active role in the discussions and preparation of the supporting material. The interest and expectations of the Central European partners in obtaining useful results from the project was obvious in the project meetings with a wide and high expertise level participation. The benefit of the work is foreseen in bringing a common understanding of the SAM and PLIM issues among the VVER-440/213 owners. The definition of the research needs will lead to a possibility to co-ordinate the research efforts in order to obtain maximum benefits and ensure that the research efforts will be oriented to the end-users' needs. The original objectives of the project were achieved.

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