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Severe Accident Management Development Program for VVER-1000 and VVER-440/213 Based on the Westinghouse Owners Group Approach

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ABSTRACT

The development of the Westinghouse Owners Group Severe Accident Management Guidelines (WOG SAMG) between 1991 and 1994 was initiated in response to the U.S. Nuclear Regulatory Commission (NRC) requirement for addressing the regulatory severe accident concerns. Hence, the WOG SAMG is designed to interface with other existing procedures at the plant and is used in accident sequences that have progressed to the point where these other procedures are not applicable any longer, i.e. following core damage. The primary purpose of the WOG SAMG is to reach a controlled stable state, which can be declared when fission product releases are controlled, challenges to the confinement fission product boundary have been mitigated, and adequate heat removal is provided to the core and the containment.

Although the WOG SAMG is a generic severe accident management guidance developed for use by the entirety of the operating Westinghouse PWR plants, provisions have been made in their development to address specific features of individual plants such as confinement type and the feasibility of reactor cavity flooding. Similarly, the generic SAMG does not address unique plant features and equipment, but rather allows for consideration of plant specific features and strategies.

This adaptable approach has led to several SAMG development programs for VVER-1000 and VVER-440 type of power plants, under Westinghouse' s lead.

The first of these programs carried out to completion was for Temelin NPP – VVER-1000 – in the first quarter of 2003. Other ongoing programs aim at providing a similar work for VVER-440 design, namely Dukovany, Mochovce and Bohunice NPPs.

The challenge of adapting the existing generic WOG material to plants other than PWRs mainly arises for VVER-440 because of important differences in confinement design, making it more vulnerable to ex-vessel phenomena such as hydrogen burn. Also, for both eastern designs, cavity flooding strategy requires special consideration and adaptation on a case by case basis.

The purpose of this paper is to provide some insights on how SAMG programs can be implemented for VVER-1000 and VVER-440 type of plants based on the WOG SAMG generic approach, and identifies areas of technical concerns encountered in the process. Solutions are proposed based on the experience of past and ongoing programs.

1 OVERVIEW OF THE WOG SAMG

The Westinghouse Owners Group Severe Accident Management Guidelines (referred to as WOG SAMGs) [1] were developed in the early nineties in response to the U.S. Nuclear Regulatory Commission (NRC) requirement for addressing the regulatory severe accident concerns. Their primary purpose is to provide a basis for individual Westinghouse PWR plant owners to develop their own plant specific SAMG.

Although accident management refers to all measures available to recover the plant from an accident, distinction should be made between PREVENTIVE and MITIGATIVE measures. Preventive measures include those actions that will prevent or delay the occurrence of core damage, while mitigative strategies aim at reducing considerably the consequences of core damage, i.e. minimise fission product releases once the accident has progressed beyond core damage. Preventive accident management strategies are therefore implemented first, and are based for all Westinghouse plants and for the majority of VVER plants on the WOG symptom based Emergency Response Guidelines (ERGs). Only in the unlikely occurrence that the strategies contained in these procedures would not be successful in restoring core cooling and preserving fuel integrity will the primary purpose of accident management shift from preserving the core to minimising the consequences of core damage. In this situation, accident management guidance will be provided by the SAMG package, which contains all instructions for the implementation of mitigative severe accident management measures. It is important to note that due to the change in accident management priorities – from preserving core integrity to minimising fission product releases – some of the preventive measures implemented in the early stages of the accident may no longer be appropriate or, if continued, may serve a completely different purpose.

Because of the sequential use of the preventive and mitigative accident management packages (ERGs and SAMGs), when the accident progresses beyond core damage, it is very important that the SAMGs are designed to interface smoothly with the ERGs. More generally, the SAMGs are designed to interface with the Site Emergency Plan at the plant to ensure a consistent and co-ordinated response to severe accident conditions.

The objectives of the WOG SAMG can be separated into two categories. First, the following objectives represent the primary goals of severe accident management in the WOG generic SAMG philosophy:

1. Return the core to a controlled, stable state
2. Maintain or return the containment to a controlled, stable state
3. Terminate fission product releases from the plant

In addition to the primary objectives, the following secondary goals should be achieved while implementing the SAMG:

1. Minimise fission product releases while achieving the primary goals
2. Maximise equipment and monitoring capabilities while achieving the primary goals

The WOG SAMG are structured into a well-defined process for choosing appropriate actions based on actual plant conditions. In this structure, decision making is the Technical Support Centre' s (TSC) responsibility. Indeed, the WOG SAMGs are a primarily TSC destined tool, as it is considered that the control room operators should remain focused on prevention of core damage events (i.e. they are responsible for implementing the EOPs up to the time when a transition to the SAMG package is made). The TSC should hence be the focal point for mitigation of severe accidents. This approach is considered as the most beneficial under the high stress conditions of a severe accident.

The broad scope of the WOG SAMG is to provide structured guidance in the form of the following sequential steps:

1. Diagnose plant conditions using a symptom based approach
2. Prioritise response according to plant specific vulnerabilities as identified during SAMG development
3. Assess equipment availability to respond to diagnosed symptom
4. Identify and assess possible negative impacts due to implementing responses
5. Determine whether to use available equipment based on potential consequences of identified negative impacts
6. Determine whether implemented actions are effective and identify additional actions
7. Identify long term concerns for the implemented strategies

This sequence of actions constitutes the basis of the WOG SAMG philosophy, and is built into a series of guidelines that form the bulk of the WOG generic SAMG. The entirety of the generic package comprises of:

- Two Severe Accident Control Room Guidelines (SACRGs)
- A Diagnostic Flow Chart (DFC) and a Severe Challenge Status Tree (SCST)
- Eight Severe Accident Guidelines (SAGs) and four Severe Challenge Guidelines (SCGs)
- Two Severe Accident Exit Guidelines (SAEGs)
- Seven graphical Computational Aids (CAs)

2 APPLICABILITY TO VVER-1000 AND VVER-440/213

The WOG SAMG is a generic severe accident management guidance developed for use by the entirety of the operating Westinghouse PWR plants. The generic guidance hence specifically includes those systems and features and the typical accident progression phenomena which are common to Westinghouse PWRs. A reference plant approach was used to define systems and features, except those dealing with broad areas of the confinement design. The broad areas of containment design and features, which are addressed by specific feature include: a) confinement type (i.e. large dry, sub-atmospheric and ice condenser containments), b) the ease with which the reactor cavity can be flooded with limited water supplies, and c) the containment fission product boundary challenges during severe accidents. Therefore, provisions have been made in the development of the WOG generic SAMG to address specific features and strategies of individual plants.

Although originally intended for implementation at Westinghouse PWR plants, the generic SAMG material structure and philosophy is by no means design specific, such that it can easily be applied to non-Westinghouse design plants, as well as to plants other than PWRs. However, because its response to a severe accident is strongly dependent on the plant design, plant specific implementation of the WOG SAMG should include identification and incorporation of the Individual Plant Examinations (IPE) insights. Thus, plant specific vulnerabilities, containment fission product boundary challenges, specific design features and severe accident response should be accounted for and reflected in the SAMG structure and TSC diagnostic tools. This constitutes most of the work to be performed during SAMG development programs for VVER design plants.

The implementation of the SAMG at a plant also requires that the interface between the existing Plant Emergency Operating Procedures and the SAMG be identified. This process has been clearly documented in the WOG EOPs Maintenance Program, and thus a smooth transition between the two WOG packages is ensured for all plants that have implemented these EOPs, as it is the case for many VVER-1000 and VVER-440.

This adaptable approach has led to several SAMG development programs for VVER-1000 and VVER-440 type of power plants, under Westinghouse's lead. The first of these programs carried out to completion was for Temelin NPP – VVER-1000 – in the first quarter of 2003. Other ongoing programs aim at providing a similar work for VVER-440 design, namely Dukovany, Mochovce and Bohunice NPPs.

3 DEVELOPMENT AND IMPLEMENTATION OF PLANT-SPECIFIC SAMG

The plant-specific implementation program of the generic SAMG package requires a methodical approach and consists of the successive completion of series of tasks. The overall scope of such an implementation program can be divided into the following major steps:

1. Elaboration of a technical database regrouping all necessary information for the understanding of plant specific challenges and behaviour in severe accident conditions. This database regroups all conclusions and results of previously performed analysis work, such as plant specific level 2 Probabilistic Safety Assessment (PSA), or other previously completed programs. In the case of VVER-440/213, such programs include the EU sponsored PHARE programs.

2. Development of the TSC diagnostic tools reflecting the changes needed to the generic structure in order to account for plant specific design features and behaviour in severe accident conditions as highlighted by the technical database.

3. Selection of the plant specific strategies to be used in response to the diagnosis of the plant status using the TSC diagnostic tools, and documentation of the equipment capabilities, flow path alignment and support conditions for the implementation of the identified strategies.

4. Writing of the plant specific versions of the generic SAMG package components, definition of their associated setpoints based on plant specific parameters and development of the computational aids.

4 IMPORTANT VVER-440/213 AND VVER-1000 FEATURES FOR SAMG DEVELOPMENT

4.1 Bubbler Condenser (VVER-440/213 only)

The Bubbler Condenser system is a passive pressure reduction system, designed to limit the pressure increase in the confinement in the event of high-pressure transients releasing primary or secondary coolant into the confinement.

The Bubbler Condenser system consists of a tower made up of three volumes, the shaft, the water trays and the air trap. In case of a high-pressure transient in the confinement, the gas/steam mixture is distributed from the confinement to the different levels of trays by the shaft system. It is then condensed in twelve levels of water tray pool, while the non-condensable gases are held in four air trap volumes. In addition, passive spraying from the water trays also contributes to reducing the confinement pressure.

For scenarii other than high-pressure transients in the confinement, the Bubbler Condenser system has no significant passive impact on the confinement condition. Therefore, intentional drainage of the bubbler trays can be considered as a primary strategy for achieving the purposes of confinement flooding, which constitutes one of the means in SAMG for returning the plant to a controlled stable state. The total volume of water contained in the trays of the Bubbler Condenser system is of the order of 1500 m^3.

4.2 Cavity Structure (both VVER-1000 and VVER-440/213)

Both VVER-1000 and VVER-440/213 designs include a room of small volume (of the order of 300 m^3) in which the reactor vessel is located, separated from the rest of the confinement by double hermetic doors. This particular configuration leads to specific considerations during SAMG development, such as feasibility of water ingression into the cavity, evaluation of corium spreading area and spreading patterns, and study of the cavity failure modes and vulnerabilities. These are discussed in more detail in section 5.1.

4.3 Other Confinement Features (VVER-440/213 only)

VVER-440/213 confinement design consists of a series of hermetic rooms, or compartments, interconnected through openings of various sizes. The confinement's pressure boundary is hence defined by the sum of these compartments, representing indeed a hermetic zone, but not forming a homogeneous confinement as observed in a standard PWR containment. The implications of this structure for SAMG development include study of atmosphere mixing, flame propagation from one compartment to another and potential for Deflagration to Detonation Transition (DDT).

In addition, the confinement of a VVER-440/213 plant is not designed for sustaining high pressures because of its passive pressure reduction system, and hence its structural integrity is lower than that of a large dry containment. As a result of that, the SAMG should focus on providing strategies that prevent the occurrence of those events that could produce a high-pressure transient in the confinement. Such events include High Pressure Melt Ejection (HPME) and its associated phenomena or hydrogen burn at sufficient concentration to create a pressure peak big enough to challenge the confinement integrity.

Finally, VVER-440/213 confinements used to be characterised by a natural leakage rate higher than that of PWRs, which could potentially impact SAMG strategies dealing with fission product releases. However, recent estimates have shown that the confinement tightness of many VVER-440/213 plants has significantly improved over the years, and is now generally close to what is observed in a large dry containment plant (of the order of 4-5% of total volume per day). As far as SAMG are concerned, a reduced natural leakage rate results in shifting the consideration of the challenge from fission product releases to the increased concern of long-term overpressurization from gases produced during the ex-vessel phase of the accident.

Note that none of the above considerations are valid for a VVER-1000, for which the confinement is structurally similar to a large dry PWR containment. The only significant impact from VVER-1000 plant design on SAMG development will hence be caused by the reactor cavity geometry and location (above the auxiliary building), and will impact SAMG strategies dealing with containment flooding and primary system depressurisation.

4.4 Primary System Loop Seal

The first priority when entering the SAMG is to deal with the earliest challenges that can be encountered in a severe accident scenario. One of these very early challenges is creep rupture of the steam generator tubes, which can result from a sustained high primary to secondary pressure difference with high temperature gases flowing through the steam generator tubes.

However, the VVER-440/213 hot leg loop design includes a section where cold gases can be trapped and condensed, forming a loop seal and hence isolating the secondary side from the primary. Hot gases coming from the reactor vessel will therefore remain on the reactor vessel side of the loop seal, and the pressure difference across the steam generator tubes will be limited. Therefore the occurrence of steam generator creep rupture in a hot leg loop seal configuration is very unlikely. This hence needs be reflected in the SAMG structure, and constitutes a significant departure from the generic WOG SAMG.

5 MAIN TECHNICAL CONCERNS ASSOCIATED WITH PLANT SPECIFIC FEATURES

5.1 (Early) Cavity Flooding

5.1.1 Discussion for VVER-440/213

Because of the very high vulnerability of VVER-440/213 plants to cavity door failure and penetration melting after vessel rupture, it will always be beneficial to get some water in the cavity to the highest possible level. In addition, some water in the cavity will help mitigating further challenges occurring after vessel rupture such as corium attack of the cavity basemat and fission product releases. Because the cavity geometry prevents corium dispersion on the confinement floor, cooling of the corium is difficult and core concrete interactions are enhanced, hence justifying the need for water on the cavity floor before vessel failure. If the water level in the cavity can be increased above the reactor vessel lower head before vessel failure, then it is expected that in-vessel retention of core debris can be achieved from ex-vessel cooling, hence avoiding the need to mitigate all the ex-vessel phenomena and challenges. Also, if the cavity doors do fail, this is equivalent to a confinement bypass, as the doors lead to a room not part of the hermetic confinement boundary. Protection of the cavity hence constitutes a very high priority for VVER-440/213.

The increased water injection capability due to the Bubbler Tower is therefore of particular importance in SAMG. Indeed, the potential for efficient confinement/cavity flooding is directly dependent on the water inventory available at the plant. Consequently, the time at which this drain down is initiated (and the time needed for efficient drainage of the trays) is the major limiting factor for early cavity flooding in the course of a severe accident, considering that there is a direct injection pathway into the cavity, which is not always the case. Even with a dedicated water injection pathway into the cavity, it was evaluated ([2] & [3]) that the time needed for drain down of the bubbler tower trays remained the critical factor for success of rapid cavity flooding and it therefore should be initiated as soon as entering the SAMG package.

In the generic SAMG, water injection in the containment is a two-phase process, with a first guideline aiming at establishing a water level adequate for ECCS and containment spray recirculation, cooling of corium debris dispersed in the cavity, and for external vessel cooling if possible in the plant configuration. The second guideline for containment flooding has a higher water level target and is used for cooling remaining debris in the ruptured vessel and establishing controlled stable state. This is not applicable to VVER-440/213, as the time needed to reach the second level once the first one has been established is relatively short due to the cavity geometry. It hence becomes possible to combine the two guidelines into one [4], with a single water level target (the highest one). Also, the lack of control on the cavity flooding process means that it is not appropriate to have two distinctive target levels.

5.1.2 Discussion for VVER-1000

For VVER-1000 the concern is different, as this type of plant cannot benefit from the water inventory of a Bubbler Tower for containment flooding. Therefore, the maximum attainable water level in the cavity is limited by the available water inventory at the plant, and complete cavity flooding is generally not possible, hence precluding the possibility of in-vessel corium retention from external vessel cooling. Thus, there is no need for two separate guidelines as in the generic WOG SAMG for containment flooding, as all the possible purposes of increasing containment/cavity water level will be achieved via a single target level, lower than the reactor vessel lower head. In addition, there is no straight pathway for water ingression into the cavity, and hence some plant modifications are required to allow water into the cavity. It was suggested [5] that the double cavity doors would be systematically opened upon entry into the SAMG in order to allow water ingression. An additional benefit achieved from opening the cavity doors is that the corium spreading area is increased in case of vessel failure, hence facilitating core debris cooling and reducing the potential for basemat attack.

5.2 Hydrogen Management Scheme

5.2.1 Discussion for VVER-440/213

VVER-440/213 containment design leads to potential challenge to containment integrity from hydrogen burn very early into the accident progression, i.e. before vessel failure. This is due to the fact that large amounts of hydrogen produced from the oxidation of the Zirconium material in the reactor core will be released to the confinement. The VVER-440/213 core contains about 18000 kg of Zirconium inventory [6], of which the expected oxidised fraction during the in-vessel phase of a severe accident can be as high as 70%. The corresponding hydrogen mass produced from this oxidation is of the order of 500 kg, but will be strongly dependent on the accident sequence and operators actions in the course of the accident. This range of hydrogen production is not different from that encountered in a standard large dry PWR containment, but the consequences of its release to a VVER-440/213 confinement can be quite dramatic due to the lower confinement structural strength. This issue leads to emphasising the need for a well-established hydrogen management scheme reflecting the specific concerns of the VVER-440/213 confinement design. As a result of that, hydrogen management is given the highest priority in the Westinghouse approach to SAMG development for VVER-404/213. Because of the design characteristics of these plants, the Westinghouse approach to hydrogen management for VVER-440/213, although different from one plant to another, is mainly based on a reliable hydrogen burn strategy. In effect, if burns can be initiated early into the hydrogen production phase and release to the confinement process, then the hydrogen concentration should be maintained around the flammability limit, and away from concentrations representing a threat to the confinement. This is only possible if a condition close to homogeneous confinement atmosphere mixing is established. Different analysis done with MAAP4/VVER using various containment noding schemes ([7] & [8]) all tend to show that quite good containment atmosphere mixing is indeed achieved, except for the air traps and the Bubbler Tower wetwell volumes. Therefore, the Westinghouse approach to hydrogen management for VVER-440/213 is mainly based on a reliable hydrogen burn strategy.

5.2.2 Discussion for VVER-1000

Because of the similitude in the containment structural strength between a VVER-1000 and a standard PWR, the Westinghouse approach to hydrogen management for a VVER-1000 is that of the WOG generic SAMG, in which the hydrogen is considered as a low priority challenge. Strategies developed for dealing with hydrogen are plant-specific, but can be grouped into two main categories depending on their purpose: 1) hydrogen burn; and 2) containment inerting. In addition, a strong impact from the hydrogen recombiners on the flammability conditions in the containment (both in terms of hydrogen and oxygen concentration) also led to adapting slightly the generic strategies.

6 CONCLUSION

The generic WOG SAMG material was used as the basis for the development of SAMG programs for VVER-1000 and VVER-440/213 plants. This adaptation was possible since the generic SAMG material structure and philosophy is not design specific. It however required a careful assessment of the plant vulnerabilities and specific features to be incorporated into the SAMG structure. The main technical issues addressed during the development phase of the SAMG programs were early cavity flooding and hydrogen management scheme. The concept of in-vessel retention was applied to VVER-440/213, while it was not relevant for VVER-1000. Hydrogen management is a very sensitive issue for VVER-44-/213 and was treated as the highest priority challenge. No major specific hydrogen concerns have been identified for VVER-1000. The recent SAMG implementation programs have permitted the elaboration of a VVER-1000 and VVER-440/213 “generic” Westinghouse SAMG material, comparable to what has been existing and extensively been used for PWRs since 1994.

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