

Status Report on Filtered Containment Venting

Committee on the Safety
of Nuclear Installations

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Organisation de Coopération et de Développement Économiques
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**NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS**

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OECD/NEA/CSNI Status Report on Filtered Containment Venting

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LIST OF ACRONYMS

AC	Safety Council (Consejo de Seguridad Nuclear)
CSNI	Committee on the Safety of Nuclear Installations
DBA	Design Basis Accident
DC	Direct Current
DEC	Design Extended Condition
DF	Decontamination Factor
DFM	Dry Filter Method
DEHS	Diethylhexylphthalate
DOP	Dioctylphthalate
ECS	Evaluations Complémentaires de Sûreté
EDF	Electricité De France
EFADS	Emergency Filtered Air Discharge Systems
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat (Swiss) Federal Nuclear Safety Inspectorate
ENSREG	European Nuclear Safety Regulators
EOP	Emergency Operating Procedure
EPG	Emergency Procedure Guidelines
EPR	European Pressurized Reactor
EPRI	Electric Power Research Institute
EU	European Union
FCI	Fuel-Coolant Interaction
FCV	Filtered Containment Venting
FCVS	Filtered Containment Venting System
GE	General Electric
GIAG	(French) Severe Accident Intervention Guide
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HCVS	Hardened Containment Venting System
HEPA	High-Efficiency Particulate Absorption
HPCI	High Pressure Circuit Injection
HSSPV	High Speed Sliding Pressure Venturi
IAEA	International Atomic Energy Agency
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISTP	International Source Term Programme (CEA-IRSN)
JAERI	Japan Atomic Energy Research Institute
LACE	LWR Aerosol Containment Experiments (ORNL)
LB-LOCA	Large Break Loss-Of-Coolant Accident
LCF	Latent Cancer Fatality
LOOP	Loss Of Outside Power
LTO	Long-Term Operation
LT-SBO	Long-Term Station Black-Out
MAAP	Modular Accident Analysis Programme – Integral severe accident code developed by Fauske & Associates Inc.

MACCS	MELCOR Accident Consequence Code System
MCCI	Molten Corium Concrete Interaction
MELCOR	Integral severe accident code developed by SNL for the USNRC
MIRE	Experiments on mitigation of radioactive releases - Mitigation des Rejets à l'Environnement (IRSN)
MMD	Mass Median Diameter
MVSS	Multi Venturi Scrubber System
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NTTF	Near Term Task Force
OECD	Organization for Economic Co-operation and Development
PAR	Passive Autocatalytic Recombiners
PASSAM	Experiments on Passive and Active Systems on Severe Accident source term Mitigation (EU)
PCPL	Primary Containment Pressure Limit
PHWR	Pressurized Heavy-Water Reactor
PRG	Programme Review Group
PSA/PRA	Probabilistic Safety Assessment/Probabilistic Risk Assessment
PSI	Paul Scherrer Institute
PSR	Periodic Safety Review
PSV	Periodic Safety Visit
PWR	Pressurized-Water Reactor
RBMK	Reactor Bolchoï Molchnasti Kanalnyi
RCIC	Reactor Core Injection Cooling (system)
RCS	Reactor Coolant System
R&D	Research & Development
RI	Organic Iodine
RPV	Reactor Pressure Vessel
RSK	(German) Reactor Safety Commission
SA	Severe Accident
SAM	Severe Accident Management
SAMG	Severe Accident Management Guideline
SAMM	Severe Accident Management Measure
SECY	(USNRC) Commission Papers
SNL	Sandia National Laboratory
SOARCA	State-of-the-Art Reactor Consequence Analyses
ST	Source Term
STB	Sump borax baskets (measure proposed by EDF to limit volatile iodine formation from the sump)
ST-SBO	Short Term Station Black-Out
STEM	Experiments on Source Term Evaluation and Mitigation – OECD programme (IRSN)
STUK	(Finnish) Radiation and Nuclear Safety Authority
TECSPEC	TEchnical SPECification
THAI	Experiments on containment Thermal-hydraulics, Hydrogen, Aerosols, Iodine – OECD programme (Becker Technologies)

TMI	Three-Mile Island
UKAEA	United Kingdom Atomic Energy Authority
USNRC	United States Nuclear Regulatory Commission
VTT	(Finnish) Technical Research Centre
VVER	Voda Voda Energo Reactor
WENRA	Western European Nuclear Regulatory Association
WGAMA	Working Group Accident Management & Analysis

EXECUTIVE SUMMARY

Following the Fukushima Daiichi accident, the NEA Committee on the Safety of Nuclear Installations (CSNI) decided to launch several high-priority activities. In particular, stress tests performed after the Fukushima's accident have led many countries to consider the implementation of Filtered Containment Venting Systems (FCVSs) on Nuclear Power Plants (NPP) where these are not currently applied as an enhancement of the response capability to severe accident (SA) situations. Some countries are also considering improving existing FCVSs and their operation procedures for safe and reliable use in conditions which were not necessarily fully addressed at their design stage (e.g., robustness to hazards and hydrogen combustion loads, prolonged or repetitive use during a SA and manual operation without power supply).

A Report on FCVS was released by the CSNI in May 1988. Since then, knowledge and calculation tools to assess radioactive releases due to a SA as well as filtration technologies have progressed significantly and several different FCVSs have been implemented into NPPs worldwide. Further, some countries are now considering that (filtered) CVS can also play a valuable role in managing early stages of accidents with fast containment pressurization even though they were generally designed for managing slow containment pressure build-up. These evolutions in knowledge, technology and strategy led the Working Group on Analysis and Management of Accidents (WGAMA) of the CSNI to launch an action to establish an updated Status Report on FCVSs.

The main objectives of the Status Report on FCVSs in OECD countries, as defined by WGAMA, were to:

- Compile the status on the implementation of FCVS for Light Water (both boiling water (BWR) and pressurized water (PWR) types) and Pressurized Heavy Water Reactors (PHWR) including systems already installed and contemplated;
- Describe the national requirements on the implementation of venting systems and the filtering strategies;
- Describe the different filtered venting systems available as well as their performance;
- Describe design specifications for FCVS;
- Discuss possible disadvantages of containment venting, e.g., inadvertent opening, risk of under-pressure;
- Identify, from an accident management perspective, if there is room for improvements for both the hardware and the qualification of the systems; and
- Summarize the status of containment venting strategies as currently implemented, especially the strategies that require interfacing with decision-making processes to actuate containment venting.

The present Status Report fulfils most of the above listed objectives, however, there were two limitations: first, part of the information concerning the existing filtration systems performance is proprietary and was not disclosed by FCVS designers; second, limited information could be obtained from the various countries concerning venting strategies described in severe accident management (SAM) strategies and guidelines, particularly concerning the description of the interface with the decision-making process. It should be stressed that for each country the decision-making process is highly dependent on the organization for the emergency response.

The Status Report was compiled in consultation with all stakeholders in the nuclear field (end users, safety authorities, technical safety organisations, research institutes, FCVS designers and utilities).

This Status Report provides a comprehensive description of safety requirements associated with FCVS (Chapter 3) and of the status of FCVS implementation (Chapter 4) as provided by the various contributing countries. The different level of detail describing the accident management situation in different countries in relation to FCVS reflects in part the reality of the different levels of the current regulatory and/or technological appraisal of FCVS internationally. Further, the safety requirements differ in various countries being more-or-less prescriptive with FCVS not necessarily explicitly mandated or not considered as the primary measure to prevent containment over-pressurization. The following requirements may be prescribed for FCVS depending on venting strategies and objectives: vent capacity (decay heat removal, pressure decrease rate), vent opening and closing pressures, vent timing (e.g., delay > 1 day), venting system design requirements, consideration of possible hydrogen loads, radiological objectives (maximal extent of land contamination, compatibility with protection measures for plant workers and population (for delayed venting), FCVS decontamination factors (DFs) for radioactive aerosols, for molecular iodine, etc. These are all discussed in detail in the report.

A description of the FCV strategies for emergency operating procedures (EOPs) and SAM domains is provided in Chapter 5. FCVS are considered to be an additional system to protect the containment integrity (maintain the containment function until stable conditions are reached, no matter how severe the accident is). FCVSs are typically to be used in SAs as part of the overall applied SAM strategy for PWRs and BWRs, while they are also used in DBA for some PHWRs (CANDUs). Operation of a FCVS is also considered in some countries and for some reactor designs for accident management other than countering the long-term over-pressurization of the containment, e.g., for BWRs in the case of loss of heat sink to remove decay heat (also for DBA or Design Extension Conditions, or DEC, such as common-cause failures of reactor heat removal systems) or to reduce the hydrogen inventory in the containment.

Chapter 6 presents the well-known existing filtration technologies e.g., scrubbers, deep-bed filtration and different sorption systems. Highlighting of any particular FCVS technology or product in this report is simply a reflection of the fact that such a system is currently available and information has been provided by the corresponding designer. Other systems are being developed and will be commercialized. Details of systems for which information was received from designers can be found in the Appendices of the report. As mentioned earlier, part of the information concerning the existing filtration-systems performance is proprietary and was not disclosed by FCVS designers. However, two major aspects can be underlined concerning existing systems:

- most of the available systems were designed on knowledge-bases which were existing in the late 1980s. Some have been updated depending on the system design and implementation (based on consideration of the results of relevant R&D and plant safety reviews notably additional filtration stages to modify the overall filtration efficiency);
- and, given the possible extension of the domain of FCVS use, the demonstration of the systems performance should be consequently extended to more challenging conditions.

Both aspects are discussed in the report.

It was also thought valuable to provide FCVS general design requirements and specific design aspects and recommend state-of-the-art qualification of filter technologies for reliable function and performance of FCVS. This is provided in chapter 7. This chapter, as well as others in the report (particularly chapters 9 and 10), can be used as a guide for FCVS implementation.

Source-term (ST) evaluations are factored into accident analysis in different countries. It is recognized that ST evaluations are important for FCVS regulatory assessment and as a guide for design and operation requirements of FCVS. ST evaluation studies presented in Chapter 8 of the report are limited to countries which have done specific ST evaluations in view of FCVS performance and provided detailed information.

ST evaluations in general are a part of PSA level 2 studies which are mandatory in many countries and which are not been discussed here. These studies typically include the FCVS performance in reducing the ST, though the system is generally not separately examined. It is worth stressing that the knowledge-base related to “delayed” in-containment re-volatilization and re-suspension processes for radionuclides/aerosols from RCS and containment surfaces and containment pools (sumps and suppression pools) will be extended through on-going R&D programmes.

As for FCVS filtration, besides aerosols, specific attention is being given to organic iodides and iodine-oxide particles as they may contribute significantly to the ST in some accidents. Possible contributions of ruthenium-oxide species to the ST is under investigation in on-going R&D programmes.

Filtration of noble gases released through the venting process has been discussed but, on one hand, no reliable technology exists for efficient retention of these species and, on the other, the benefit of reducing their releases in the environment has to be balanced with drawbacks that could result on-site from radioactivity accumulation in the system designed for their retention.

Deterministic consequence analyses show large reduction of radiological impacts and, in studies performed in France and in the US, of radiological costs (by about an order of magnitude) when comparing effective filtered releases against unfiltered releases. In most countries, calculated reduction of radiological impacts appears sufficient to conclude that FCVS are beneficial to SAM. In the cost/benefits studies performed in the US, these benefits are weighted by the estimated low probability of a SA (i.e., low core damage frequency), and have not been cost-justified.

Chapter 9 and 10 describe currently assessed benefits and negative aspects related to FCVS use and the related potential improvements or countermeasures for existing systems. These chapters may also be used to guide the design, implementation and operation of future FCVS to reduce these risks.

Generally, all contributing countries recognized through this work the potential benefits of FCVS for emergency response, reduction of the extent of land contamination and health effects and increased social acceptability of nuclear power plant installations. FCVS should, however, be considered in conjunction with other SAM strategies, e.g., no large benefit is expected for containment by-pass scenarios which have to be managed by other SAMM.

FCVSs implemented before Fukushima were mainly designed to manage long-term pressure build-up in the containment; new FCVS may perhaps be designed to deal with more challenging conditions (management of early phases of an accident, cycling or long-term use in SA conditions). The robustness (including a design withstanding several external events), the safe use and the reliability of FCVSs for such conditions should be further assessed either to improve existing systems or to propose upgraded design requirements for future systems.

1. INTRODUCTION

In the case of a SA at a nuclear power plant (NPP), filtered containment venting (FCV) is one action that can be used to protect the containment and the facility while mitigating radioactivity releases to the environment.

The Fukushima Daiichi NPP's accident demonstrated that, in the absence of alternatives to reduce the containment pressure build-up (due to steam and incondensable gas accumulation during an accident), the venting of the containment becomes an essential accident management measure for the preservation of its structural integrity. The accident also highlighted two other things: (i) the design and operation requirements of the existing venting systems have to be reassessed both in terms of the strength and pressure resilience when containment venting is initiated and (ii) the importance of having a filtration capacity to reduce environmental releases for safe and reliable utilization in situations resulting from extremely damaging events.

The basic premise of FCVS is that, independent of the state of the reactor itself, the catastrophic failure of the containment structure can be avoided by discharging steam, air and incondensable gases like hydrogen to the atmosphere. However, unfiltered containment venting could result in significant radioactive releases to the environment where these releases may be largely reduced by the implementation of filtering systems on the venting lines as already integrated in some existing venting systems. From a safety perspective, it is also essential for the on-site management of the accident and for the protection of the potentially exposed population to reduce as much as possible the radioactive releases due to containment venting.

Complementary safety evaluations performed after the Fukushima's accident have led many countries to consider the implementation of FCVSs on NPP's where these are not currently applied as an enhancement of the response capability to SA situations. Also, such evaluations led some countries to consider improvement of existing venting systems and of their operating procedures.

The reasons why an updated treatise on FCVSs is necessary at this point in time are the following: filtration technologies and the knowledge concerning radioactive releases in a SA have advanced significantly since the late 1980s when the first FCVSs were implemented; moreover, there is a need to address more deeply SAs and the valuable role filtered venting can play (notably for managing the early phases of an accident).

A first international exchange of information at a Specialists' Meeting on FCVS was organized by the OECD/NEA CSNI in May 1988 [1]. In addition to the exchange of information on various FCVS concepts, associated R&D and their analysis, the objectives of the systems (including the nature of the risks and the challenges in relation to accident management aspects) and the utilization procedures were also discussed. The main outcomes of this Specialists' Meeting were summarized in a specific note published as OECD/NEA/CSNI Report N° 156 [2]. However, based on the experience since their implementation, the design of the systems has, in some cases, been improved and modified. Also, following the Fukushima accident, additional potential improvements for the systems are under consideration, notably for their robustness, safe utilization and improved filtration efficiency. Thus an update was considered necessary.

This status report gives a comprehensive summary of the current status of the technology and venting strategies in several countries as well as of the envisaged developments for possible improvements to filtration technologies. It also provides FCVS general design requirements and specific design recommendations, notably for state-of-the-art qualification of filter technologies for reliable function and performance of FCVS in SAs.

2. GENERAL BACKGROUND AND OBJECTIVES OF THE STATUS REPORT

2.1 Safety significance

Avoiding a breach of the reactor containment due to overpressure and consequently significant releases of radioactive products into the environment during an accident is the point of using FCVS.

The motivations underlying the utilization of FCVS can be summed up as follows:

- To provide the operator, in addition to other SAMM, with the most appropriate means to manage accidents in a NPP and in particular an additional means for maintaining the containment function until stable conditions are reached, no matter how severe the accident is;
- To limit the level of radioactive releases into the environment with the objective of protecting on-site workers and population, and minimizing ground contamination.

Material to be retained in filtering systems includes radioactive aerosol particles and radioactive gaseous species, especially iodine, inorganic or organic.

A deeper assessment of the performance of existing and future systems, in view of recent R&D results and knowledge gained through operational feed-back and accident analysis (including Fukushima), should help the different stakeholders to determine if improvements are needed and feasible and to define possible future actions.

Noble gas filtration, although it has not been required by any safety authority until now, may also be a desired capability for future FCVS to reduce the short term radiation exposure for the workers on-site and for the population off-site, if sufficient filtration is technically feasible.

Thus, the Status Report shall contribute to review and assess safety approaches related to the confinement of radioactivity in the containment and venting filter system during a NPP accident and to the enhancement of safety performance of current nuclear installations.

2.2 Objectives of the Status Report

The main objectives of the present Status Report are to:

- Compile the status on the implementation of FCVS for Light Water (both boiling water (BWR) and pressurized water (PWR) types) and Pressurized Heavy Water Reactors (PHWR) including systems already installed and contemplated;
- Describe the national requirements on the implementation of venting systems and the filtering strategies;
- Describe the different filtered venting systems available as well as their performance;
- Describe design specifications for FCVS;
- Discuss possible disadvantages of containment venting, e.g. inadvertent opening, risk of under-pressure;
- Identify, from an accident management perspective, if there is room for improvements for both the hardware and the qualification of the systems; and
- Summarize the status of containment venting strategies as currently implemented, especially the strategies that require interfacing with decision making processes to actuate containment venting.

This Status Report may be used as a guide for planning further activities in the area: development of optimized strategies for FCVS, planning future actions for systems design improvements,... It gives a comprehensive summary of the current status of the existing technologies and venting strategies including the developments required for possible improvements to filtration technologies. The Status Report was compiled in consultation with all stakeholders in the nuclear field (end users, safety authorities, technical safety organisations, research institutes, and utilities).

2.3 Planning of the activity, contributing countries and organizations

2.3.1 Planning of the activity

The kick-off meeting of the WGAMA task group on FCVS took place on the 28th of September 2012 at the NEA headquarters in Paris [3]. The contents of the Status Report and the writing group composition were discussed at this meeting. IRSN supported by other organizations was designed as the lead organization for the report writing. The writing group was finally composed of D. Jacquemain from Institut de Radioprotection et de Sûreté Nucléaire (Chairman of the group), S. Guentay from Paul Scherrer Institut, L. Ammirabile from the European Commission, L. Lebel from Atomic Energy Canada Ltd., B. Eckard from AREVA NP GmbH, B. Liebana Martinez from Iberdrola S.A., S. Basu from US Nuclear Regulatory Commission, M. Sonnenkalb from Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH and H.-J. Allelein from Forschungszentrum Jülich GmbH.

Table 2.1: planning of the activity

FCVS CAPS approval by CSNI	June 2012
Preparatory work and formation of the writing group: 'Kick-off'-meeting of the WGAMA task group on FCVS	September 2012
Collection of data from contributing countries	April-August 2013
Preparation of a 1 st draft version of the report	July-August 2013
2 nd Meeting of the WGAMA task group on FCVS	September 2013
Preparation of a 2 nd draft version of the report	September – January 2014
3 rd meeting of the WGAMA task group on FCVS	End of February 2014
Report validation by the WGAMA task group on FCVS	Early March 2014
Transmission to GAMA members for review	March 2014
Transmission for external reviewing	March 2014
PRG Reviewing	April 2014
Foreseen endorsement by CSNI	June 2014

The data used for the Report was collected via a template that was sent to all contributing countries in April 2013. Contributions were received from Belgium, Canada, Czech Republic, France, Germany, Korea, Spain, Sweden and the United States in June 2013 and completed during the summer 2013.

The second meeting of the writing group took place 5-6 September 2013 at the NEA headquarters in Paris. The objective of the meeting was to exchange information on the status of FCVS systems in the contributing countries, updating the information gathered at the 1988 Specialists Meeting on FCVS and discuss the content of the first draft of the Status Report.

A second version of the template was formalized following the September meeting and additional contributions were obtained from Finland, Japan, Mexico, Slovenia and Slovakia. It has to be noted that both the International Atomic Energy Agency (IAEA) and the OECD/Nuclear Energy Agency (NEA) were involved in this task.

A third meeting of the writing group was organized on the 27th of February 2014 in Madrid to finalize the report for a submission to the WGAMA task group in March 2014 for review in parallel with an external review which was performed by Joanne Ball from Atomic Energy Canada Ltd. (Canada) and Luis Herranz from Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain). CSNI/PRG reviewing took place in April 2014 and endorsement by the CSNI was received in June 2014.

2.3.2 Contributing countries and organizations

The following countries and organizations were involved in the working group:

Belgium: GdF Suez Tractebel Engineering, Bel V, Westinghouse

Canada: Atomic Energy Canada Ltd., Canadian Nuclear Safety Commission

Czech Republic: UJV Řež (Nuclear Research Institute Rez plc)

Finland: STUK (Radiation and Nuclear Safety Authority)

France: Electricité de France, Institut de Radioprotection et de Sûreté Nucléaire

Germany: AREVA NP GmbH, Forschungszentrum Jülich GmbH, Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH

Japan: Japan Atomic Energy Agency, Japan Nuclear Energy Safety Organization

Korea (Republic of.): Korea Atomic Energy Research Institute

Mexico: Comisión Nacional de Seguridad Nuclear y Salvaguardia

Netherlands: Ministry of Infrastructure and Environment

Russian Federation: Federal State Unitary Enterprise (FSUE) VO Safety

Slovak Republic: Nuclear Regulatory Authority

Slovenia: Slovenian Nuclear Safety Administration

Spain: Consejo de Seguridad Nuclear, Iberdrola S.A., Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Universitat Politècnica de Catalunya

Sweden: Swedish Radiation Safety Authority, Westinghouse

Switzerland: Paul Scherrer Institute, Swiss Federal Nuclear Inspectorate, IMI Nuclear

United States of America: US Nuclear Regulatory Commission.

International organizations also contributed to the working group: the IAEA, the European Commission and the OECD/NEA under the auspices of which the report was established.

3. STATUS OF FILTERED CONTAINMENT VENTING REGULATORY REQUIREMENTS

This section provides a description of national requirements about FCVS intended to be used under SA conditions and their evolution since first introduced established from references [1,2] and updates completed in templates received in between July and November 2013.

Belgium

No FCVS is presently installed in Belgian Nuclear Power Plants (NPPs). However, analyses for the implementation of FCVS in 5 of the 7 Belgian PWRs, which will be in operation beyond 2015 are currently being conducted. Art. 21.4 of the Royal Decree published on November 30th 2011 requires that the containment shall be protected from overpressure in a SA. This requirement is highlighted in the Western European Nuclear Regulators Association (WENRA) reference level F.4.5. There are no further national requirements or specific guidance related to the implementation of FCVS. FCVS design criteria will be defined by the utilities and will be assessed by the regulator.

The specification of design criteria is currently in progress. The presently considered filtration system is a liquid system for which some general specifications can be exposed:

- The vent shall require manual operation, based on a specific criteria associated to the measurement of the containment pressure;
- The opening of the venting valve shall be possible from the control room as well as locally, via a manual actuation;
- The access to the rooms and systems needed for the correct working of the FCVS should be guaranteed;
- The shielding should be sufficient to limit the dose to a maximum of 50 mSv per agent and per intervention;
- The FCVS only operates during beyond design basis events. Therefore, the single failure criterion does not apply. System redundancy is thus not foreseen except for the containment isolation function;
- The FCVS must be available during all plant operating states except during the periods when maintenance activities have to be performed on the FCVS;
- After the first opening of the containment isolation valves, the FCVS is designed to work without assistance during at least 24h;
- The permanently installed reserves of water and chemical additives on site shall allow for a FCVS autonomy of at least 72h after the accident initiating event;

- After a period of maximum 10 days from the accident initiating event, it is assumed that the conventional safety systems (for example cooled recirculation) would have been recovered ensuring a long term controlled stable state of the NPP;
- Provisions against explosion of combustible gases in the FCVS should be foreseen;
- The FCVS is actuated when the “venting opening pressure” is reached, and stopped when the pressure decreases below the “venting closing pressure”. These plant-specific thresholds are determined based on containment design pressure and fragility curves. Multiple venting phases are thus considered if the containment cooling system is not recovered;
- The FCVS has to resist to the following external hazards: earthquake, flooding and extreme weather conditions (extreme winds, lightning, rainfall, temperature range, snowfall).

Canada

Regulatory requirements in Canada are addressed in two ways: through regulations, which are set forth by the Canadian Nuclear Safety Commission, and through national standards. Containment is an essential requirement for NPPs in Canada, but FCVS is never explicitly mandated. There do have to be systems in place that can limit the release of radioactive material following a nuclear accident, and although FCVS is a means of doing this, their installation is not strictly mandated at all operating power plants in Canada and it is not the only strategy that is allowed. Based on the CNSC Fukushima Task Force recommendations [4], more advanced FCVS is becoming an expectation, but the important thing, in the view of the Canadian regulator, is that the integrity of reactor containment is maintained, and off-site releases are minimized.

For regulations, there are three regulatory documents that apply in the context of FCVS:

- R-7, “Requirements for Containment Systems for CANDU Nuclear Power Plants” [5];
- RD-337, “Design of New Nuclear Power Plants” [6];
- REGDOC-2.3.2, “Accident Management: Severe Accident Management Programmes for Nuclear Reactors” [7].

In addition, there is one national standard that is referenced by the regulations, and that utilities must comply with in order to meet national requirements: CSA N290.3-11, “Requirements for the Containment System of Nuclear Power Plants” [8].

The R-7 regulation [5] is the basic document that describes the fundamental safety requirements for containment systems for all Canadian nuclear power plants. It states many general requirements for the containment, but important points in this context are expressed in R-7(2.2), that equipment must be in place to maintain the continuity of the containment envelope, reduce the pressure and free radioactive material in the containment atmosphere, and *limit the release of radioactive material* following an accident. In addition R-7 (3.3) which outlines dose limits under accident conditions states that "The containment system shall be capable of limiting the release of radioactive material such that the reference dose limits are not exceeded.

A more current regulatory document, RD-337 [6], was issued to cover additional requirements for new or newly refurbished power plants, but again, it does not specifically state that FCVS must be installed. In RD-337(8.6.1), the regulation reiterates that a leak-tight containment envelope must be maintained, that radionuclides in the containment atmosphere must be controlled, and, again, that *releases of radionuclides to the atmosphere must be limited*. This document does go farther, however, in RD-

337(8.6.12) to state that in the case of a SA, *unfiltered and uncontrolled releases from containment must be precluded*.

RD-337 also states the safety objectives that must be met for power plants. In particular, RD 337(4.2.1) states that public dose, as predicted for the 30 day period following an accident by a deterministic safety analysis, must be less than 20 mSv for design basis accidents (DBA). RD 337(4.2.2), in addition, states that, according to a probabilistic safety analysis, the acceptable frequency for core damage is 10^{-5} per reactor year, the acceptable frequency for ^{131}I releases of more than 10^{15} Bq is 10^{-5} per reactor year, and the acceptable frequency for ^{137}Cs releases of more than 10^{14} Bq is 10^{-6} per reactor year. The core damage frequency, iodine release frequency, and cesium release frequency are metrics used by the Canadian regulator to assess a nuclear power plant's accident prevention and accident mitigation capabilities. These were derived from IAEA standards for nuclear safety principles [9].

The regulatory expectations for SAM are outlined in the REGDOC-2.3.2 regulatory document [7], and two of the primary goals of any SAM strategy, defined in REGDOC-2.3.2(3.1), are that containment integrity should be maintained and that the release of radioactive products to the environment should be minimized. Likewise, viable actions that should be in place as part of the SAM response, according to REGDOC-2.3.2(5.1), should be to include, among other things, a means to control containment pressure while also controlling radioactive releases; containment venting is one of the plant design capabilities suggested in REGDOC-2.3.2(5.2) to achieve this.

Following the Fukushima Daiichi accident in 2011, a CNSC Fukushima Task Force compared how a similar, large external event would impact nuclear power plants in Canada, and developed several recommendations on how their resilience could be improved [4]. Filtered venting, particularly using designs that could be deployed during a SA, was recommended as a means to improve containment performance and prevent unfiltered releases of radioactive products, as noted in Section 6.4.7 (#2). Expectations for FCVS going forward are that designs be able to handle the large gaseous discharges, aerosol loads, and fission product loads that could be expected during a SA, and also consider the potential for hydrogen combustion downstream of the event and, where applicable, multi-unit accidents. The goal of these recommendations, in this regard, is to strengthen reactor defence in depth, and to improve the regulatory framework and processes.

In summary, there is no direct statement that FCVS must be used in nuclear power plants in Canada. FCVS is specifically referenced in the national standard, N290.3-11 [8], that applies to containment systems and in N290.3-11(9.4) as a means to control the discharge of radionuclides to the atmosphere, but in neither it is an explicit requirement. Rather, what is stated is that releases can be prevented by either isolating the containment, or filtering the discharge, but at least one of these two strategies must be employed as a means of radionuclide management. However, because FCVS is a system that can be used to help meet the national standards and regulatory requirements, it has been universally applied in one form or another by the Canadian utilities.

Czech Republic

Currently no NPPs operating in Czech Republic are equipped with FCVS. It is expected that evaluations should provide the needs for implementation of FCVS to both Czech NPPs within the response to the stress test observations and national action plan. Currently, application of FCVS at the Temelin NPP (VVER-1000/320 type of reactor with full pressure containment) seems likely, however, not for the Dukovany NPP (VVER-440/213 type of reactor), since these units have a hermetic room concept with low design pressure insufficient for a passive operation of the FCVS. The main reason for the application of

FCVS strategy at the VVER-1000/320 would be in the interconnection with the solution which will be retained for the strategy for melt retention, either in-vessel with external vessel cooling or ex-vessel using corium spreading in a room adjacent to the reactor cavity and cooling by top flooding. Strategies and design specifications of a potential FCVS are not currently available.

Finland

The Safety Authority (STUK) required utilities in June 1986 to be prepared against SAs. The design purpose of the filtered vent was to decrease the containment pressure in SA sequences when energy and fission products are released into the containment, if the pressure exceeds a specified limit.

FCVS were installed in 1990 at both BWR units as a plant modification. Venting from both wet-well and dry-well are possible.

The regulatory guide YVL 1.0 [10,11] specifies that the release of a steam-gas mixture accumulated in the containment into the environment shall not be designed as the primary measure of preventing containment pressurization. A containment filtered venting system shall be designed which can be used to remove any overpressure caused by non-condensable gases possibly released in a later phase of an accident. This, however, is going to be changed from the obligatory requirement to have FCVS to a more general requirement for pressure decrease capability:

- 338. Venting of the steam-gas mixture accumulated in the containment into the environment shall not be used as the primary means for the containment pressure control.
- 339. Following a SA, it must be possible to decrease the pressure difference across the containment pressure boundary to a level consistent with the safe state following a SA.
- 340. With design solutions where containment pressure decrease in compliance with requirement 339 is done by venting gas from the containment into the environment, the venting system must be provided with an efficient filter. After filtering, the released gases shall be routed to the plant ventilation stack.

There are no specific decontamination factors (DF) requirements for the FCVS performance in terms of filtration efficiency, but the overall goal for the frequency of such accidents where the releases exceed 10^{14} Bq of ^{137}Cs shall be less than 5×10^{-7} /year. This requirement is applied for new reactor as such, and to existing reactors as far as reasonably practicable.

There are no regulatory requirements for usage of FCVS in design basis accident (DBA), but they can be credited in specific design extension conditions (DEC) situations (e.g. common cause failures of other containment residual heat removal systems) as diverse means to remove the heat from the containment.

Despite the provision of the Containment Heat Removal System (CHRS) in the EPR design, the Finnish safety authorities have requested that a filtered containment vent is provided as an additional means of containment pressure control in the case of total loss of the containment cooling capability and especially to ensure the pressure decrease to a safe level in the long-term.

France

Initial requirements

The decision to add a filtered venting line to all French PWRs presently in operation (900, 1 300 and 1 450 MWe PWRs) was taken in July 1986 following the publication of the WASH 1400 report [12] and the TMI2 accident on the basis of probabilistic analyses of the consequences of SA scenarios for a large range of possible events or groups of events. In particular, these analyses have shown that in some scenarios the containment pressure could increase slowly for several days due to steam and non-condensable gases production linked to the accident progression in-vessel and ex-vessel. This pressure increase could eventually threaten the containment leak-tightness and mechanical integrity. Therefore a specific ultimate procedure, named U5, associated to a FCVS has been implemented with the following objectives:

- First to keep the containment pressure below its design value by allowing planned releases to preserve the containment leak-tightness and integrity (as part of the defence-in-depth concept);
- Second, to limit the associated radioactive releases to a level compatible with the off-site emergency plans, by means of a coarse and simple filter.

The following requirement relative to FCVS was initially issued by the French Safety Authority:

Whenever a core-melt occurs, the radioactive releases into the environment must be compatible with the feasibility of the off-site emergency plans; that means that for some hypothetical, but still conceivable scenarios, provisions have to be made to delay and limit the consequences of the loss of the containment: the U2, U4 and U5 ultimate procedures – the latter providing a venting of the containment through a filtration system – have been elaborated for that purpose¹.

The existing containment venting system was designed in accordance with the following basic principles (see Appendix 1 for the system description):

- a minimal delay of 24 hours after the beginning of the accident has to be considered before the opening of the system. This delay allows for a sufficient decrease of the radioactive substances concentrations in suspension in the containment atmosphere before the opening of the system and provides a period of time to provision protection measures for the population (preventive evacuation, sheltering) compatible with the level of the radioactive releases resulting from the use of the FCVS system and eventually to recover alternative containment heat evacuation means;
- the opening of the system is done manually and decided by the competent public authorities when the containment pressure reaches the design pressure following a progressive pressure rise;
- the venting efficiency should allow to maintain (and eventually decrease) the containment pressure below its design value;

¹ The U2 procedure deals with containment leaks localization and isolation. The U4 procedure deals with measures to prevent early containment failure that could result from the erosion of the containment concrete base-mat by corium (after the reactor vessel failure).

- the containment conditions considered for the FCVS design were obtained via calculations performed in the late seventies for several typical accidental sequences (notably sequences studied in the WASH 1400 report):
 - a containment pressure of 5 bar (close to the containment design pressure)²,
 - a containment temperature of 140°C (413K);
 - a flow rate through the FCVS line of 3,5 kg/s; the flow rate has to be high enough to ensure that after opening of the system, the containment pressure will not overstep the design pressure;
 - a composition for the containment atmosphere of 33% of air, 29% of steam, 33% of CO₂ and 5% of CO, the issue of the hydrogen risk in the FCVS line was only addressed later on;
 - a volumetric mass of 4 kg.m⁻³;
 - aerosols of aerodynamic mass median diameter of 5 µm with a mass concentration level of 0.1g/m³
- a minimal filtration efficiency criterion was initially considered: a minimal DF of 10 for the aerosols in view to lower the radioactive releases to level compatible with the off-site emergency plans (noble gases were and are not considered).

Additional requirements following decision of installation of FCVS (mid-80's to mid-90's)

Following the decision of installation of FCVS on French NPPs additional detailed studies were performed to assess the hydrogen combustion risk in the FCVS system and the risk induced by the high level of radioactivity which would result from the trapped radioactive aerosols in the sand bed filter (limitation of the possibilities of intervention on the plant site after FCVS use). These studies resulted in additional requirements and modifications of the FCVS to limit these risks.

Modifications were implemented to prevent steam condensation in the FCVS line during operation of the FCVS system. This was done by the installation of an electrical system which heat the fluid and surfaces of the FCVS line before opening the FCVS line. If the FCVS line was initially cold at opening, steam condensation would occur and would result in an increase of the volume fraction of hydrogen in the FCVS line and consequently in an increase of the hydrogen combustion risk.

Note that by 2007, all containments of French PWR's were equipped with hydrogen passive autocatalytic recombiners (PARs) to limit the hydrogen combustion risk in containments. This also contributes significantly to the limitation of the hydrogen risk in the FCVS system since PARs operation should result in oxygen depletion in the containment via catalytic reaction with hydrogen.

Modifications were implemented to reduce radioactive aerosols masses in the sand bed filter after the use of the FCVS system. This was done by the installation of a metallic aerosol filter inside the reactor building at the inlet of the FCVS line in view of:

² The design pressure was set to a sufficiently high pressure value to maximize the available time to recover safety systems and especially containment spray systems, to maximize the radioactive decay of fission products and the deposition of aerosols into the sump, to maximize the time allowed for setting off-site emergency plans, to minimize the risk of large containment failure including the failure of the venting line up to the isolation valves, to minimize the risk of damage of the safety systems especially the containment spray system. Each plant has its own containment design pressure value (around 5 bars for French PWRs).

- Reducing the radiation dose rate in the sand bed filter and limit the “sky shine effect” in the building on the roof of which the filter is installed;
- Limiting the temperature rise in the sand bed filter due to the residual power.

A bypass line of the metallic filter was also installed to allow for continued operation of the FCVS system if metal filter clogging was to occur.

Even if no specific requirements were set by the French Safety Authority for the DF values for the FCVS, large efforts were put into the determination of the metallic and sand bed filters filtration efficiencies for aerosols and molecular iodine via separate effects and full-scale experimental programmes. DFs of 1000 for the aerosols and of 10 for molecular iodine are credited for the full FCVS (no organic iodide retention considered); the metal filter contributing to improve by a factor of 10 the global aerosol DF of the FCVS.

Additional requirements examined during the 3rd plant safety reviews (PSR) of the 900 MWe PWRs series (2003-2008)

In France, periodic safety reviews (PSR) are conducted every ten years. The periodic safety review applies to all PWRs of a series and is conducted on a period of time that may exceed 5 years. After this generic review, each reactor of a series is upgraded based on the conclusions of this PSR during its periodic safety visit (PSV) and on some reactor specific issues if any.

The 3rd PSR of the 900 PWRs series was conducted between 2003 and 2008 and included a detailed analysis of SA issues. Concerning the existing FCVS, a remaining issue is that iodine (particularly organic iodides species) would have a major impact on accident consequences in case of FCVS activation during a SA (since their retention on existing FCVS is considered low).

Based on the IRSN review and position and the French Safety Advisory Group position, the French Safety Authority requested EDF “*to study, for mid-2006, the interest and feasibility of measures able to reduce the risk of molecular or organic iodine release in case of use of the filtered containment venting system U5*”.

EDF has provided in 2006 a preliminary analysis indicating that scrubber FCVS could be a more efficient solution to trap iodine. It was concluded that additional research was necessary before deciding a FCVS upgrade. No decision for upgrading FCVS was taken in the framework of the 3rd PSR of the 900 MWe PWRs.

Additional requirements in relation with plants long term operation (2011-2012)

In 2009, EDF has informed the French Safety Authority of its long term operation (LTO) project for the French PWRs based on a safety upgrade programme. EDF objective is to keep open the possibility to operate existing PWR for 60 years. This has conducted to a review of the EDF LTO project for the PWRs safety upgrades programme and the plant ageing management programme.

The initial PWRs safety upgrades programme mainly concerned a reinforcement of electric and core cooling supplies. One major point of discussion concerned the SAM, with the objective of approaching generation II and generation III PWRs (EPR) safety levels.

For SAs, safety objectives can be summarized as follows:

- practically eliminate situations that would yield large (early) release (this objective is applied in all PSR);
- minimize the impact of the accident during the long term phase (this objective is associated to LTO):
 - o to improve the filtration efficiency of the FCVS in view of reducing as much as possible radioactive releases;
 - o to study alternative solution to remove the residual heat from the containment without containment venting;
 - o to define measures able to prevent containment base-mat penetration by corium.

Additional requirements after the Fukushima accident (Stress tests) (2011-2014)

Step 1: stress-test review (2011)

During the stress-test review conducted in France following the Fukushima accident, the FCVS was again in discussion. In addition to the filtration efficiency and hydrogen risk control (previously discussed), the FCVS resistance to hazards was considered as well as the multi-units accident and the site management after opening a FCVS on one reactor.

Based on the IRSN review and position also endorsed by the French Safety Advisory Group, the French Safety Authority defined the following requirement (see <http://www.ensreg.eu/EU-Stress-Tests/Country-Specific-Reports/EU-Member-States/France> for additional details):

ECS - 29: Reinforcement of the U5 venting-filtration system ("sand-bed filter")

Before December 31 2013, the licensee shall submit to the French Safety Authority a detailed study of the possible improvements to the U5 venting-filtration system, considering the following points:

- resistance to hazards;
- limitation of hydrogen combustion risks³;
- efficiency of filtration in case of simultaneous use for two reactors;
- improved filtration of fission products, in particular of iodine compounds;
- radiological consequences of opening the device, in particular for accessibility of the site, and for the radiological atmosphere of the emergency premises and of the control room.

It is important to note that following the Fukushima accident, the filtration efficiency is only one of the characteristics of the FCVS that must be addressed. The robustness to hazards and minimization of site impact for accident management must also be considered.

³ Even if the hydrogen risk in the U5 FCVS system was already taken into consideration, the possibility of combustion of hydrogen with the O₂ initially contained in the FCVS line is currently being assessed.

Step 2: “Hard-core” safety systems

In 2012, the EDF proposal of a limited set of reinforced system (for external hazards) was reviewed by IRSN and presented to the French Group Permanent. The initial EDF proposal was based on the use of FCVS as ultimate solution for containment heat removal associated to reinforced water injection in the primary circuit. This solution was not retained because the core-melt prevention could not be achieved easily in case of cooling by the steam generator but also because the accident management strategy could not respect the integrity of the secondary (primary circuit) and third (containment) barriers.

In January 2014, new decisions (N° 2014-0394 to 0412, see <http://www.asn.fr/>) were taken by the French Safety Authority to complement existing safety requirements for French NPPs defining safety “hard-core countermeasures” based on post-Fukushima complementary safety evaluations.

Situations retained as the “hard-core situations” are external hazards (seism, flooding (including high intensity rains), extreme winds, lightning, hail and tornados) with a severity above that considered in the reference safety requirements for the design of the installation. “Hard-core situations” involve:

- Total loss of electric supplies (except “hard-core” supplies);
- Total loss of cold sources (except “hard-core” sources);
- External hazards listed above;
- Situations resulting from the degraded state of the installation, site and environment following “hard-core” external hazards.

For these “hard-core situations”, countermeasures should be in place:

- To prevent a core melt-down accident or to limit its progression;
- To limit large radioactive releases;
- To allow the plant operator to ensure its role in the management of the crisis.

To limit large radioactive releases in a “hard-core situation”, countermeasures should exist for the containment isolation and avoidance of containment bypass situations. These countermeasures aim at maintaining the containment integrity without the opening of the containment FCVS and should consider accidents with total core melting and vessel rupture following “hard-core situations”. EDF is required to study by the 31/12/2014 countermeasures allowing the containment residual power evacuation without the opening of the FCVS for “hard-core situations”.

Situation in 2014

The main challenge is to combine the requirements formulated for LTO and those defined after the Fukushima accident.

To answer both ECS-29 and LTO objectives, EDF proposed in December 2013:

- to implement, as part of the “hard-core countermeasures”, dedicated means to remove the decay heat from the containment with a recirculation loop cooled by a dedicated heat sink;
- to increase the seismic resistance of FCVS presently installed on the French plants⁴;

⁴ FCVS was not originally designed for seism, except the containment penetration and the parts inside the reactor building (parts inside the containment were designed to prevent damages to safety important equipments in case of seism).

- to install STB (Borax) baskets in the containment sumps of 1300 MWe and N4 NPPs to maintain the sump pH basic (this is not considered necessary in other reactors equipped with Ag-In-Cd control rods since effective gaseous iodine trapping by silver-containing particles is expected). This should have a very significant impact on possible gaseous iodine releases from the sumps in case of failure of NaOH addition by the spray system for these reactors.

In view of recent safety evaluations and research results (*e.g.* Phebus PF, ISTP and OECD/STEM and BIP programmes) [13], much larger focus has been given in France to the necessity of improved retention of gaseous iodine species, notably organic iodides, and the need for considering retention of gaseous ruthenium, which may produce short and long term consequences if released into the environment. Although currently no decision has been taken on the necessary steps to obtain a higher retention performance of installed FCVS (replacement or back fitting), and on what the level of the recommended retention performance (DFs) should be, large experimental programmes, involving main French players, EDF, IRSN, AREVA, and also some international organizations being involved in some common international projects led by IRSN are underway (EU PASSAM and French National Research Agency MIRE projects [14]).

Germany

In response to the SAs at Three Mile Island (TMI) and especially after the Chernobyl accident in 1986, the German Reactor Safety Commission (RSK) was asked to check whether any measures to enhance the NPPs safety and to cope with SAs are possible and if so, what these measures could be [15]. The results of the German Risk Study "Deutsche Risikostudie Kernkraftwerke - Phase B" (1981-1989) [16] the first large comprehensive study including deterministic and probabilistic results of SAs based on a PWR reference plant, significantly influenced the development with respect to SAM in Germany. First requirements for a Severe Accident Management programme regarding beyond-design-basis events starting from power operation only were published in autumn 1988 after intensive discussions within the RSK [15]. The concept was called "Anlageninterner Notfallschutz" and the primary intention was the prevention of SAs starting at power operation. Some selected mitigation measures for dominating phenomena were proposed as well. For both necessary hardware modifications have been considered. The FCVS was one of the systems which was recommended and installed very early [17]. German utilities decided to follow all RSK recommendations related to Accident Management voluntarily; as such provisions have been outside of the plants design requirements.

The RSK issued recommendations for containment filtered venting in December 1986 for PWRs, and June 1987 for BWRs [15,18,19,20]. The decision for filtered venting systems was based, in part, on plant-specific accident analyses [16] that considered containment venting systems to be relatively important accident management systems. The analyses for PWR showed that:

- The most frequent SAs are likely to lead to a medium or long-term containment failure;
- If severe core damage can be stopped or if an early containment failure can successfully be prevented, there still remains the potential for late overpressure failure.

The aim of the FCVS is to limit the pressure increase in the containment and by this preventing a loss of containment integrity due to a long term pressure increase and an associated large release of activity before the failure pressure is reached (cliff edge effect). The pressure in the containment will be reduced from approximately the design pressure to half of that value. In a PWR, this will take approx. 24 to 48 h. At the same time, water has to be injected beneficially into the sump to prevent boiling. In a BWR, this

process only takes approximately 10 – 20 min. The pressure increase in the containment is limited by a controlled release of gases through the system and at the same time a minimization of the radiological consequences for the environment.

Important aspects from the RSK recommendation for PWR [15] are described below:

a) Design and set-points for operation

- Opening approximately at the testing pressure level of the containment vessel;
 - Pressure limitation when depressurizing without water insertion into the containment vessel;
 - Pressure reduction (orientation value) to a level of about one half the testing pressure of the containment vessel within about two days;
- Design of the valves to be closable even at the testing pressure of the containment vessel;
- Design of the valves for a stepwise opening and closing;
- Activation of the possibilities for water insertion into the containment vessel from the moment of depressurisation in order to compensate for the released amount of water (to prevent sump dry-up).

b) Loads to be considered

- Out to the outer or second of the double closure valves: failure pressure of the containment vessel or, alternatively, twice the design pressure.
- For the adjacent system:
 - Pressure, temperature and composition of the mixture that would develop and flow through the maximum valve cross-section corresponding to the accident conditions;
 - Design margins for the pipes and supports to take dynamic loads into consideration, or, alternatively, a safety margin of 2 with regard to the operating loads.

c) Construction requirements

- Preferably a stationary installation of the system components down-line from the closure valves: depending on the design solution, connection of the down-line system component by an adapter that will be installed on demand;
- In-line closure valves that, if required from the standpoint of accessibility, shall be remotely controlled and have an available power supply in the case of required operation. It may be assumed that at the point in time of the depressurisation after several days, a neighbouring mains grid supply with the required power, or the emergency power supply, will again be available;
- Removal of the condensate accumulating along the pressure relief path;
- A high-efficiency particulate air filtration system kept in readiness at the site of the power plant.

The RSK is convinced of the effectiveness of the concept of depressurisation of PWR containment vessels and recommends its technical realisation in accordance with the requirements specified above.

Important aspects for BWR 69 from the RSK recommendation [15] are described in the next paragraph. The containments of the BWR type 72 differ considerably from those of the BWR type 69. The

licensee of BWR type 72 developed an inerting/recombination concept and a pressure suppression concept which took into account the differences of the plant design and considered the RSK recommendations. The concept was separately discussed and approved by the RSK [18] and thereafter realized.

Just as with the recommendation for a filtered depressurisation of the containment vessel in pressurized water reactors, the RSK recommends that, within the framework of plant-internal accident management, a depressurisation system for the containment vessel of boiling water reactors of the construction line 69 is made available which shall meet the following requirements:

a) Design and set-points for operation

- Opening approximately at a pressure level between the design pressure and testing pressure of the containment vessel;
- Heat removal from the pressure suppression system via the volumetric flow shall correspond to at least the residual heat remaining after utilizing the entire heat capacity of the pressure suppression pool (wet-well);
- Valves designed to be closable even at the testing pressure of the containment vessel;
- Valves designed for a stepwise opening and closing;
- Possibility for water insertion into the Venturi (steam) scrubber to compensate for water volume lost by evaporation due to the residual heat of the fission products retained in the hydraulic seal;
- Possibility for sampling;
- Determination of the amount released during depressurisation from the pressure at the orifice pressurized to a critical pressure ratio;
- Determination of the radioactivity released during depressurisation, either directly or indirectly (e.g. by a detailed assessment).

b) Loads to be considered

- Out to the outer or second of the double closure valves: failure pressure of the containment vessel or, alternatively, twice the design pressure;
- For the adjacent system:
 - Pressure, temperature and composition of the mixture that would develop and flow through the maximum valve cross-section corresponding to the accident conditions;
 - Design margins for the pipes and supports to take dynamic loads into consideration, or, alternatively, a safety margin of 2 with regard to the operating loads.

c) Construction requirements

- Stationary installation of the system components down-line from the closure valves;
- In-line closure valves that, if required from the standpoint of accessibility, shall be remotely controlled and have an available power supply from the assured battery power supply;
- Stationary installation of a filter system (preferably a Venturi scrubber with a down-line connected high efficiency particulate air filter).

Specifications for filter-systems in venting lines of PWR and BWR containments are taken from RSK references [15] and [19] and are summarized in the following 3 tables.

Table 3.1: Thermal-hydraulic initial and boundary conditions at the beginning of venting

	PWR	BWR
opening pressure of ventline ¹⁾	< testing pressure (of containment)	< testing pressure (of containment)
temperature	according saturation pressure	according saturation pressure
water steam content	< 100%	< 100%
H ₂ /O ₂ content	no combustible gas mixture inside or upstream of the filter system ²⁾	
load by water droplets	potentially by condensation in pipes and armatures and by water droplets in the containment (< 5 g/m ³)	
mass flow rate	mass flow rate according decay heat at opening of vent-line by taking into account potential heat-sinks and the required water injection in case of venting	mass flow rate according decay heat after consumption of the heat capacity of the wet well
start of venting	2 to 3 days (according the decay heat when reaching the testing pressure)	> 4 hours (according the decay heat when reaching the testing pressure)

¹⁾ It is assumed that the testing pressure will not be exceeded for PWR. For BWR it is allowed to exceed the pressure slightly for some sequences if there is sufficient margin to the failure pressure.

²⁾ RSK assumes effective measures to reduce the H₂-content in the containment.

No venting is assumed after 7 days of the beginning of a core melt accident

Table 3.2: Design of the filter-system for airborne materials

	PWR	BWR
aerosol mass	40 kg ³⁾	20 kg ³⁾
decay heat		
aerosols	2 kW	180 kW
gaseous iodine	5 kW	7 kW
minimum filtration efficiency		
aerosols	99.9 %	99.9 %
elementary iodine	90.0 %	90.0 %
organic iodine	0.0 %	0.0 %

³⁾ In order to increase the operation flexibility of the filter-systems the indicated value of the aerosol mass has to be multiplied by a factor of 1.5

Table 3.3: Load of the filter systems by fission products (related to the core inventory)

	PWR	BWR
elementary iodine	10 ⁻³	4 x 10 ⁻⁴
organic iodine	10 ⁻³	2 x 10 ⁻⁴
CsI, CsOH	2 x 10 ⁻⁴	3 x 10 ⁻²
Te	3 x 10 ⁻³	

The scenarios to be considered for the individual design of the venting system have been defined in the protocol of the 263th RSK-meeting on 24.06.1991 [20]:

- PWR: "Transient with total loss of steam generator feed water supply and primary depressurization before core melting. Core dry-out happens at about 5 hrs. After RPV failure at low pressure there are two scenarios considered: a) complete quenching of melt in cavity and long term evaporation of sump water with early venting within 2 to 3 days and b) dry MCCI for 8 h and thereafter wet MCCI after water ingress into cavity; late venting after 4 days."
- BWR: "LOCA with late failure of water injection into RPV at the time the wet-well cooling gets active. Core melting is assumed after failure of wet-well cooling. Core relocation into the lower plenum and residual water evaporation will lead to containment venting at about 4 h."
- Hydrogen risk inside the venting system is handled by inert gas injection before the operation of the venting system and pressure boundary design pressures of up to 5 to 10 bar.
- Hydrogen risk in SAs inside the containment was separately handled. PARs have been installed in all PWRs. For BWR-69 N₂ inerting of the containment was implemented. For BWR-72 only the wet-well was inerted, while PARs have been installed in addition in the dry-well and the wet-well.

All the German PWR and BWR units were equipped with wet (sliding pressure Venturi scrubber) or dry (metal fibre filter) FCVS after the RSK decision was made (see tables 4.1 and 4.2).

Currently (after national and ENSREG stress test in 2011-2012) possibility of hydrogen deflagration in the FCVS outlet piping before the off-gas leaves the stack for PWR is again under investigations. Details are provided in the national action plan of Germany.

Japan

FCVS for preventing the containment vessel failure due to over-pressurization is required by the new regulatory requirements set in 2013. Basic requirements are that equipment and procedures for reducing the atmospheric pressure and temperature inside the containment vessel shall be installed in order to prevent containment vessel failure in the event of a severe core damage, referred in Paragraph 2(9) of "Outline of new regulatory requirements for Light Water Nuclear Power Plants" (Severe Accident Measures). The following detailed requirements were set for FCVS:

Equipment for radioactive material reduction:

- (i) Containment filtered venting system shall reduce the amount of the radioactive material contained in the exhaust air.

Equipment against flammable gas:

- (ii) Containment filtered venting system shall be equipped with equipment for preventing explosions of flammable gases.

Detrimental impact prevention:

- (iii) Piping of containment filtered venting system shall not be shared with other systems (for example, SGTS) or those of other units, etc. However, this may not be necessary if there are no detrimental effects.

- (iv) Equipment and procedures shall be prepared to prevent the containment failure due to negative pressure in case of activating filtered venting system depending on the necessity.

On-site operation

- (v) Isolation valves for containment filtered venting system shall be able to be opened and closed easily and surely by manual operation.
- (vi) Radiation protection measures, such as shielding and isolation shall be implemented in order to enable operation of containment filtered venting system onsite manually even at the times of severe core damage.
- (vii) Measures, such as preparing required equipment and materials available in the neighbourhood shall be implemented in order to enable operation of isolation valves for containment filtered venting system even in the event of loss of drive power for isolation valve.

Rupture discs

- (viii) Bypass valves shall be installed in parallel in case rupture discs are used. However, this rule shall not apply to the cases where rupture discs set to rupture at such sufficiently low pressures that operation of the containment filtered venting shall not be disturbed (aiming not at the isolation of the containment vessel but at nitrogen charging for example) or the equipment to break the rupture disc by manual force is installed.

Connecting positions to the containment

- (ix) Containment filtered venting system shall be connected to the positions free from any detrimental impact of molten core and submersion in the long term.

Radiation protection

- (x) Radiation protection measures, such as shielding shall be implemented in order to reduce exposure from the highly active used filters.

Mexico

Mexico has two BWRs of the Mark II type in the Laguna Verde NPP. Following the events of the Fukushima Daiichi NPP, the USNRC issued an order for a reliable SA capable hardened venting system (HCVS) for this type of reactor (*cf.* regulatory requirements in the US).

The same regulatory requirement was issued by the National Nuclear Safety and Safeguards Commission (CNSNS) in Mexico and the Federal Commission of Electricity (CFE) of Mexico, operator of the Laguna Verde NPP, will implement SA capable venting systems from wet- and dry-wells in compliance with the HCVS. The venting systems to be implemented do not include any external filtration feature.

Russian Federation

There is presently no national regulatory requirement defined for the implementation of FCVS as SAM in Russia. Nevertheless, the “General Regulations on Ensuring of Nuclear Power Plants Safety” document⁵ states that direct discharge of radioactive materials during beyond design basis accident (BDBA) can only be permitted if it is compatible with protection measures for the population as established by regulations in the “Norms of Safety Radiation” NRB-99-2009.

After the Fukushima’s accident, Russia launched a programme under the supervision of the regulatory body to actualize measures to reduce the consequences of BDBA. One of the measures under consideration is the possibility to install FCVS in VVER-440 units at Kola and VVER-1000 units at Kalinin.

Slovak Republic

Regulatory requirements related to the evaluation of SAs have been implemented in Slovak national legislation since 2006. However, the development and implementation of the accident management programme including SAs had been started even earlier (in the nineties). Symptom-based emergency operating procedures (EOPs) addressing design basis accidents and the preventative part of SAs were fully implemented in 1999 (for events initiated during power operation) and in 2006 (for events initiated during shutdown of the reactor or in the spent fuel pool). Plant specific severe accident management guidelines (SAMG) were developed and prepared during 2002-2004. The overall study defining technical specifications of modifications needed for implementation of SAMG was prepared in 2004-2005. The SAM implementation project was initiated in 2009. The implementation process accelerated after the Fukushima accident, with a deadline of 31 December 2013 for Bohunice NPP and 31 December 2015 for Mochovce unit 1 and 2 NPP (for unit 3 and 4 the SAM is included in the basic design). The SAM includes a dedicated means for the primary circuit depressurization, hydrogen management using passive autocatalytic recombiners, containment under-pressure protection, in-vessel corium retention by external cooling of the reactor vessel, dedicated large external tanks with boric acid solution and a dedicated power source and pumps aimed at possible spent fuel flooding, reactor cavity flooding and/or heat removal and washing out the fission products from the containment atmosphere by sprays, associated instrumentation and control needed for SAM, plants upgrading against an extreme external events, etc.

Slovak NPPs are not equipped with FCVS for SAM. Based on the national action plan after the stress tests performed in NPPs, by the end of 2015 the necessity of filtered venting of the containment and other potential technical measures for long-term heat removal from the containment and reduction of radiation load of the environment will be analysed, considering measures implemented within the SAM project and taking into account activities in this area by other operators of VVER-440/V213.

Slovenia

In 2001, there was the first IAEA RAMP mission at the Slovenian Krško NPP. The RAMP mission report is available on the SNSA web site at http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Porocila/PorocilaEU/ramp_krsko_final.pdf. In relation to the problem of hydrogen and non-condensable gases content in the containment, installation of a

⁵ “General Regulations on Ensuring of Nuclear Power Plants Safety”, OPB-88/97, NP-001-97, Gosatomnadzor of Russia, 1998

dedicated FCVS was mentioned in the RAMP report as a possibility for venting these gases out of the containment, but this was not issued as a separate recommendation.

In 2003, the first Periodic Safety Review (PSR) was performed at the Krško NPP. Based on PSR findings an action plan was compiled which also included the recommendations of the RAMP mission. One of the actions was related to the problem of high concentrations of hydrogen and non-condensable gases in the containment that could lead to overpressure of the containment. In the scope of this action, a MELCOR analysis of a SA with core melt, failure of reactor pressure vessel, ejection of core to the wet cavity and MCCI was performed.

In 2009, the Slovenia Nuclear Safety Administration (SNSA) issued a new regulation “Rules on radiation and nuclear safety factors” (JV5)⁶. In the Annex I of the JV5, the requirements for the Nuclear power plant design basis are included based on WENRA Reference Levels established in 2008. WENRA Issue F: “Design Extension of Existing Reactors” was included in articles 1.12 and 1.13 of the Annex I of the JV5:

- 1.12 Severe accidents:
“...the response of the nuclear power plant to selected severe accidents shall be analysed to minimise harmful impacts of releases of radioactivity. A sequence of events shall be established to determine and implement reasonable preventive and mitigating measures...”
- 1.13 Equipment and instrumentation in case of a SA:
“...In the case of a severe accident, the nuclear power plant equipment shall be capable of: ...
 - *...controlling combustible gases in the containment;*
 - *preventing excessive pressure rises in the containment;...”*

For the existing Krško NPP these requirements for SAs should be addressed only for the Krško NPP lifetime extension, as it is defined in the Article 62 of the JV5:

“Upon the plant life extension of the Krško nuclear power plant or extension of the service life of its SSCs, if approved, the facility operator shall undertake a study of the response of the nuclear power plant to severe accidents in accordance with Chapter 1.12 of Annex 1 and, based on the findings of this study, propose any appropriate measures and implement them as quickly as practicable.”

Following the Fukushima Daiichi accident in 2011 and the EU stress test campaign SNSA issued first a decision on the extraordinary periodic safety review according to the Article 81 of the “Ionising Radiation Protection and Nuclear Safety Act”. The scope of the extraordinary PSR was defined by the ENSREG specifications for European Stress Tests. The Slovenian National Report on Nuclear Stress Tests is available on the SNSA web site at [http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Novice/Slovenian Stress Test Final Report.pdf](http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Novice/Slovenian_Stress_Test_Final_Report.pdf). In chapter 6.2.2.2 the prevention of containment overpressure is described which can be performed with existing systems at the plant at the time, where ventilation is passing through a HEPA-charcoal-HEPA filtering system to the environment.

In September 2011, SNSA issued a second decision and required that the operator performs modernization of safety design features for prevention of SAs and mitigation of their consequences

⁶http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Zakonodaja/SlovenskiPredpisi/PodzakonskiAkti/ang_prevodi/JV5_za_objavo.pdf.

according to the requirement of the Article 1.12 in the Annex I of the JV5 (see above). The decision also required preparation of a safety upgrade programme for SAs, including also actions to ensure containment integrity in conditions of high temperature, overpressure and elevated hydrogen concentrations, as well as actions to ensure minimal and controlled radioactive releases to environment with limits of less than 0.1% of volatile fission products and particulates reactor core inventories. Krško NPP prepared the analysis of potential safety improvements that was reviewed by a TSO independent evaluation report. The Krško NPP then issued the safety upgrade programme in January 2012 which was approved by the SNSA at the beginning of February 2012.

In March 2012 the peer review of the stress tests was performed at the SNSA and the Krško NPP. The peer review report is published on the SNSA web site: <http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Novice/CountryReportSIFinal.pdf>.

In Chapter 4.2.4.1 the upgrading programmes are presented and the installation of FCVS is listed among the actions to be implemented by 2016.

Slovenia reported on the Krško NPP safety upgrade programme in the “Slovenian Report for the Second Extraordinary Meeting of the Parties of the Convention on Nuclear Safety, Report on actions, responses and developments influenced by the Fukushima Daiichi NPP accident”, that is available also on the SNSA web site at <http://www.ursjv.gov.si/fileadmin/ujv.gov.si/pageuploads/si/Porocila/NacionalnaPorocila/Slovenia.pdf>. The installation of a filtered venting system was already scheduled for 2013 and it was described as “*Filtered venting system capable of depressurizing containment and filtering over 99.9% of volatile fission products and particulates (not including noble gasses)*”.

The Krško NPP prepared the modifications of FCVS and Passive Autocatalytic Recombiners (PAR) for hydrogen control in the containment to be installed during the refuelling outage in 2013. The Krško NPP presented the application for passive FCVS in June 2013. Installation of the passive FCVS was successfully completed during the refuelling outage in October and November 2013. Currently the FCVS is approved for passive use only because installation of radiological monitor and flow-meter in the venting stack has not been delivered and installed yet due to short time available for implementation. Other requirements that the Krško NPP needs to fulfil for active use of the FCVS are assessment of radiological consequences to the environment in case of active venting by FCVS and qualification of containment instrumentation for the design extension conditions (DEC). The EOP and SAMG need to be updated to take into account the implemented modifications of PAR and passive FCVS by April 2014. The Krško NPP has also to provide an analysis with MAAP of the actually implemented PAR and FCVS for a station black-out scenario leading to a SA. The same scenario has to be analysed also with MELCOR and this independent analysis will be performed by the TSO. Both analyses have to be presented to the SNSA by end of April 2014.

South Korea

Fukushima accidents triggered the discussion on the need to protect containment failure by over pressurization and mitigate the uncontrolled release of activity into the environment. In the process, the requirements will be proposed soon through the general TECSPEC which is expected to include filtering efficiency (Decontamination factor), operating periods (such as autonomous operation time), passive characteristics (in case of electricity loss), equipment and system design/performance requirements etc. No special requirements are expected yet but prevention of aerosol re-suspension and iodine-species re-volatilization may be required because these phenomena (in FCVS) can be one of long-term main suppliers

for the radioactive release. Currently, a PHWR (Wolsong-1) unit has finished installing FCVS at the end of 2012 as a starter (during preparation to get the approval for the continued operation after 30 years operation). The remaining 23 NPP units (20 PWR, 3 PHWR) in Korea have plans to install FCVS by the end of 2018.

Spain

Spanish plants are not equipped with FCVS. It was a regulatory request after post-Fukushima stress tests to all utilities to provide CSN with an analysis of the different alternatives available in the market for FCVS by 31st December 2013 and final solution chosen to be implemented by each Plant. Implementation of the modification on site is requested by CSN to be performed before the end of 2016.

Spanish BWRs have already installed hard venting system (non-filtered). The GE Mark III BWR-6 licensee has been required by CSN to analyse the possibility of implementing a FCVS, including assessment of the available technologies. After evaluating the report submitted by the plant in 2012, CSN required the licensee to implement a FCVS by 2017.

Switzerland

Consideration of adding a pressure relief in LWR containments in the Post-Chernobyl era, catalogue of measures against design basis accidents was initiated in November 1986 leading to Specification of Actions in 1987 and draft regulatory guidance in 1988.

Regulatory requirements defined the vent capacity, which corresponds to steam production at 1% of decay level (BWRs), and in large dry containments to 0.5%, if this capacity is sufficient for accident scenarios producing slow pressurization.

Target values for retention efficiency to avoid long term land contamination and to limit effectively the thyroid dose were defined to be DF of 1000 for aerosols and DF of 100 for elemental iodine. As a response to regulatory requirements, FCVS installations in Swiss plants were completed during the 1989 – 1993 timeframe.

Currently, the Swiss regulatory authority has no plans to modify its requirements for the FCVS performances, except that, as a result of Fukushima problems, it has asked utilities to look at the potential hydrogen deflagrations in the outlet vent pipes, especially when hydrogen rich vent gas after the filter meets air in the outlet piping.

Sweden

Subsequent to the TMI 2 accident in 1979, Sweden was the first country who recognized the need for the FCVS as the Swedish Parliament established in its 1980/81 Energy Bill New General Guidelines which focused on the prevention of core damage but at the same time recognized that no matter how small the probability may be for such accidents, measures should be taken to ensure that a core melt accident should not cause any casualties and only limited ground contamination. Following this decision, issue of a “regulatory decree,” in October 1981, it further required that FCVS (FCVS) should be constructed in such

a way that at least 99.9% of the core inventory of each radionuclide isotopes, excluding noble gases, will be retained in the reactor containment and the filter system during a SA. The regulatory decree mandated all Swedish reactors be equipped with containment venting systems by the end of 1988.

The $< 0.1\%$ ^{134}Cs and ^{137}Cs in a reactor core of 1800 MW thermal power release limit reflects the very high value assigned to avoiding the social consequences of large scale ground contamination. In fact, this limit may mean that the area contaminated by long-lived radionuclides causing ground doses in excess of what is allowed in occupational exposure to radiation, typically is limited to a few tens of square kilometres [1].

The first commercial nuclear power plant equipped with a containment venting filter system, a gravel bed type, was Barseback in 1985 (now decommissioned). The other Swedish plants were equipped with Multi Venturi Scrubber filters of the FILTRA-MVSS type, developed in Sweden, in 1988.

Currently the use of the containment filtered venting system during prolonged SA conditions (more than 24 hours) is being evaluated since the current systems are designed to operate passively for 24 hours.

USA

Currently, there are no regulatory requirements for an FCVS to be installed in any nuclear power plant in the United States, nor are the plants currently equipped with an FCVS. Following the accident at the Fukushima Daiichi nuclear facility in Japan, the NRC staff, in SECY-11-0137 [21], proposed regulatory actions to address the recommendations of the Fukushima Near-Term Task Force (NTTF) [21a]. Subsequent to the NTTF report, the order (EA-12-050) [21b] requiring reliable hardened containment vents for boiling water reactor (BWR) plants with Mark I and Mark II containment designs was issued on March 12, 2012. The NRC staff identified an additional issue in SECY-11-0137 related to possible upgrading of the containment vents, including the addition of engineered filters, to improve reliability during SA conditions and limit the release of radioactive materials if the venting systems were used after significant core damage had occurred. Subsequently, in SECY-12-0157 [22], the NRC staff recommended, based on a quantitative analysis of accident source terms, health consequences, and potential reduction of risks, supplemented by qualitative arguments for defence-in-depth, that the Commission approves the requirement to install an engineered FCVS for BWRs with Mark I and Mark II containments that is intended to prevent the release of significant amounts of radioactive material following the dominant SA sequences. In effect, this recommendation, if approved by the Commission, would have provided further improvement to the previously ordered reliable hardened venting system by making it SA capable and also assuring that the radioactive release is minimized through the use of an external filter. The Commission directed the NRC staff to modify the reliable hardened vent order (EA-12-050) in the short term to include SA capability, while proceeding with the development of a more comprehensive technical basis and, in the longer term, rulemaking for a dry-well filtration and SAM strategy for BWRs with Mark I and Mark II containments. Accordingly, the NRC issued a new order EA-13-109 [23] in June 2013 for a reliable, SA capable hardened venting system, otherwise defined as the Hardened Containment Venting System (HCVS).

This HCVS order requires that all BWRs with Mark I and Mark II containments shall have a reliable hardened containment venting system that includes a SA capable containment wet-well vent and may also include a SA capable containment dry-well vent. This requirement shall be implemented in two phases. In Phase 1, licensees of BWRs with Mark I and Mark II containments shall design and install a venting system that provides venting capability from the wet-well during SA conditions characterized by elevated temperatures, pressures, radiation levels, and combustible gas concentrations, such as hydrogen and carbon

monoxide, associated with accidents involving extensive core damage, including a breach of the reactor vessel by molten core debris. In Phase 2, licensees of BWRs with Mark I and Mark II containments shall design and install a venting system that provides venting capability from the dry-well under SA conditions. Alternatively, the licensees shall develop and implement a reliable containment venting strategy that makes it unlikely to have to vent from the containment dry-well during SA conditions.

The nuclear industry in the United States is in the process of developing a guidance document to comply with the Phase 1 requirements of the HCVS order. The nuclear industry is also engaged with NRC in the discussion of Phase 2 HCVS requirements. Concurrently, the work is in progress, at both the NRC and the industry to develop the technical basis for containment vent filtration and accident management strategies rulemaking. With regard to the rulemaking topic, the NRC staff is performing additional source term analysis and other related activities, based on updated information from the industry on the emergency procedure guidelines (EPG) and severe accident management guidance (SAMG). It is worth noting these guidelines continue to evolve.

Other OECD countries

No information was obtained for UK, China and India.

4. STATUS OF IMPLEMENTATION OF FILTERED CONTAINMENT VENTING SYSTEMS

FCVSS have been implemented in varying degrees around the world. There are several different designs presented in Chapter 6 and Appendices, generational changes in technology, and applicability from purely design basis accidents up to fully SA rated.

On the basis of the responses submitted by the member countries to the survey promoted by the WGAMA Task Group on Filtered Containment Venting, and complemented by additional sources including the EU stress tests report [24], the country-specific short summaries on the implementation of the filtered containment venting systems (FCVS) are presented below. In Table 4.3 at the end of the chapter a general overview of the implemented FCVS is also given (a detailed description of the commercially available systems is provided in Appendices).

4.1 Belgium

Belgium has 7 reactors (all PWRs) on 2 sites (Doel (4 units), Tihange (3 units)), generating more than half of its electricity.

No FCVS is presently installed in Belgian NPPs. However, analyses for the implementation of FCVS in 5 of the 7 Belgian PWRs are currently being conducted (i.e., in the 5 units which will operate beyond 2015⁷). Liquid filtration systems are presently considered (no design yet finalised).

4.2 Bulgaria

Bulgaria has 2 reactors (VVER-1000) on 1 site (Kozloduy) delivering about 35% of its electricity. Both units are equipped with High Speed Sliding Pressure Venturi (HSSPV) type FCVS (described in Appendix 4).

4.3 Canada

Canada has 19 operating nuclear reactors (all PHWRs) on 4 sites (Bruce (8), Darlington (4), Pickering (6), Point Lepreau (1)), providing about 15% of its electricity, and all stations currently have some form or other of filtered venting installed.

⁷ Doel 1 and Doel 2 NPPs are expected to be shutdown in 2015

Single-Unit Stations

The Point Lepreau Nuclear Generating Station is the only operating single-unit station and has a large, dry containment of the same style seen at most PWR-type reactor facilities. During design basis accidents, isolation of the containment building, and keeping the containment building completely sealed, is the main strategy to prevent radioactive releases from this plant. To make the overall containment system more robust and resilient to beyond design basis and SAs, however, an emergency FCVS was installed during the plant's 2008-2012 refurbishment. The system installed was an AREVA HSSPV-type system, which is described in Appendix 4.

Multi-Unit Stations

The multi-unit CANDU stations in Canada have a relatively unique containment design compared to others around the world. They are designed to operate under negative pressure, and as shown in Figure 4.1, instead of having a single, broad containment dome, each reactor building is connected to a shared vacuum building that, in the case of an accident, is intended to act as a reservoir to keep the containment pressure sub-atmospheric.

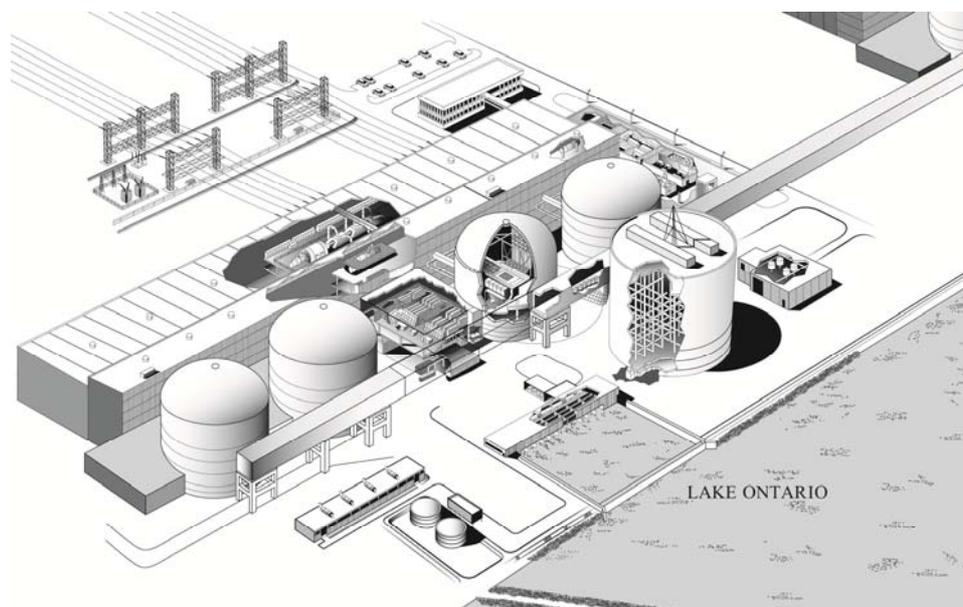


Figure 4.1 Containment at the Pickering multi-unit CANDU station, showing individual reactor buildings connected to vacuum building

The strategy for this style of containment system is to limit radioactive releases by maintaining a negative pressure for as long a time as possible. The vacuum buildings at these stations, which are kept poised at about 15 kPa during normal operations, are one part of this strategy. However, in order to ensure that sub-atmospheric pressures can be maintained for the entire progression of a design basis accident, while still avoiding releases of radioactive particulates and iodine, emergency filtered air discharge systems (EFADS) are employed as part of the overall containment design.

The EFADS, as shown in Figure 4.2, are multistage filters. In addition to a demister stage, which removes most of the radionuclide-bearing water aerosols and recirculates them back into containment, the EFADS are equipped with HEPA filters to remove micron and submicron aerosols, and a charcoal filter to remove volatile radionuclides like iodine. The second HEPA filter is also intended to capture any carbon

particulates that might be released from the charcoal bed. A heater is installed upstream of the HEPA and charcoal filters to vaporize any water aerosols that pass through the initial demister stage, as the downstream stages can be sensitive to moisture. The different stages in the EFADS are specified to have the following removal efficiencies:

- 99% aerosol removal in the demister section (recirculated back to containment);
- > 99.97 aerosol removal in the HEPA filter sections;
- > 99.8% molecular and organic iodine removal in the charcoal filter section.

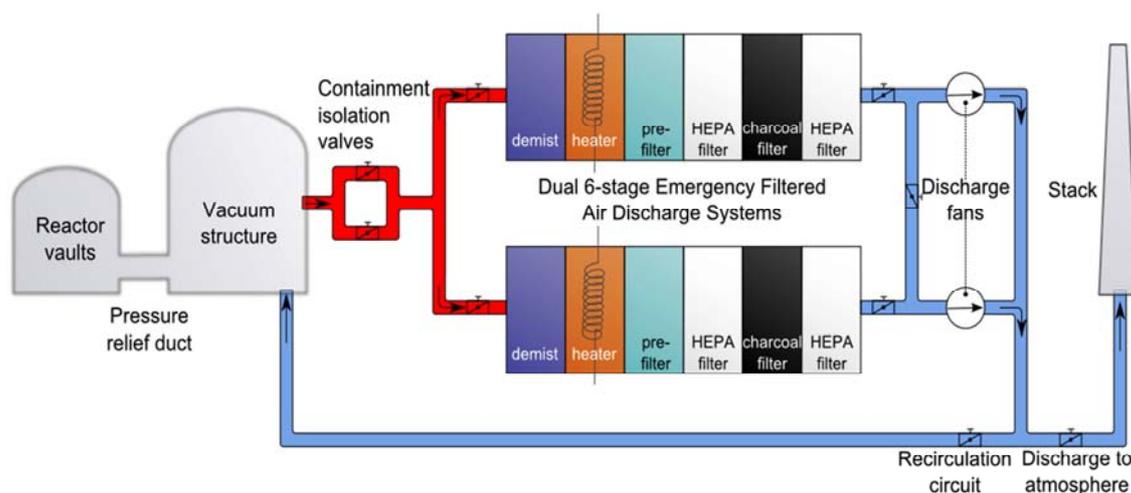


Figure 4.2 Schematics of the EFADS system implementation

In the context of design basis accidents, such as loss of coolant accidents, fuel handling accidents, earthquakes, or other events, the EFADS will operate to ensure that containment pressure remains at least about 0.1 kPa below atmospheric. The systems can be operated manually from the secondary control rooms, and can either recirculate back into containment (for preliminary sampling and monitoring purposes), or discharge to atmosphere. However, since electricity is required to operate both the vacuum pumps as well as the moisture control system upstream from the particulate and charcoal filters, the EFADS would not work as designed in the case of a total station blackout. The demister section would still likely perform as designed, but the performance of the HEPA and charcoal filters would eventually be degraded by the moisture ingress.

The Westinghouse DFM design being proposed for the 4 units at Darlington by end of 2015 is presently in its conceptual design stage. Assessment for Bruce and Pickering NGS are ongoing and due by end of 2014.

4.4 Finland

Finland has 4 reactors (2 VVER-440, 2 BWRs) on 2 sites (Loviisa (2), Olkiluoto (2 BWR)) providing nearly 30% of its electricity. A fifth reactor (EPR) is now under construction at Olkiluoto and 2 more are planned.

In the two BWR units at Olkiluoto (Olkiluoto 1 & 2) HSSPV-type FCVS have been installed, as well as other SAM systems, in the late 1980's in the aftermath of the Chernobyl accident. The function of the

filtered venting system is to enable release of steam and gases from the containment to the environment in a controlled way in cases where pressure rise may threaten the integrity of the containment. The system consists of pressure relief lines from wet-well and dry-well, a two stage filter unit and an exhaust line to the environment. The filter unit consists of a wet scrubber (filled with water containing sodium hydroxide and sodium thiosulfate) with Venturi nozzles followed by a combined droplet separator and stainless steel fibre filter (Figure 4.3).

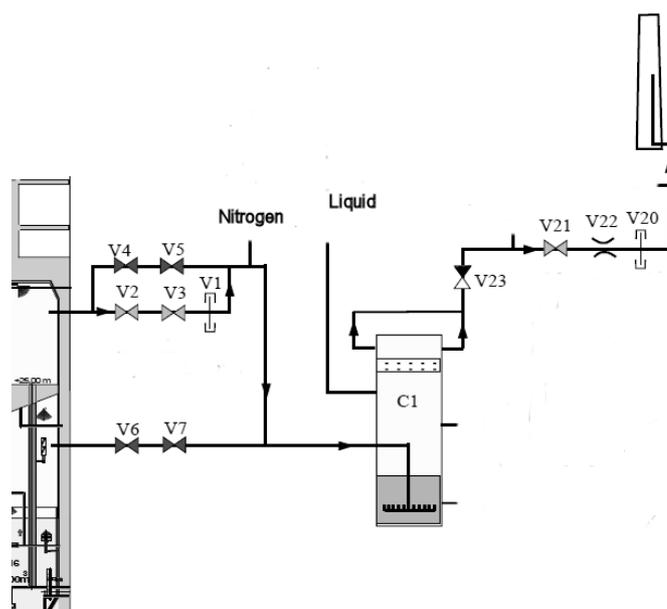


Figure 4.3: Simplified diagram of the Olkiluoto 1 & 2 FCVS

The system is able to relieve approximately 6 kg/s of saturated steam at 0.3 MPa containment pressure. The system design target: 6 kg/s steam relief, corresponds to steam production by decay heat 24h after reactor scram in a reactor with 2160 MW thermal power. Despite the power upgrade to 2500 MW, the system venting capacity has been considered adequate.

The FCVS is designed to filter 99.9% of aerosol particles, 99% of gaseous iodine and 60-80% of gaseous organic iodine.

To prevent hydrogen burns, the filter unit and system pipes are filled with nitrogen up to the rupture membrane V20; oxygen content within the pipe is under 4%.

The cleaned gas is released to the environment through a separate discharge pipeline which has been installed inside the plant stack and which goes all the way up to the stack outlet.

The dry-well venting line penetrates the containment wall close to the ceiling. The filter unit is located within the reactor building. The system valves are manually operated (i.e. there are no pneumatically operated or motor operated valves in the system). There is a bypass line with a rupture disc in the pressure relief train to dry-well. The rupture disc (V1) is designed to burst at 0.55 MPa.

The FCVS is not used in normal plant conditions; it is activated only in severe reactor accident conditions. Containment venting is started by bursting of the rupture disc in the dry-well venting line or

manually opening valves. The severe accident EOPs instruct the operators to wait for opening of the line with rupture disc. Initiation is hence passive and does not require any operator actions.

Venting from the upper dry-well is preferred because Olkiluto 1 and 2 SAM involves containment water filling. A discharge from the top of the dry-well enables use of the filtered vent even when most of the containment has been filled with water. If containment venting becomes necessary before containment water filling has started and before the rupture disc is open, the wet-well gas space line should be used. This further reduces releases due to the purifying effect of the condensation pool.

The system does not require operator attention during the first 24 hours after activation. In the long run, makeup water has to be supplied into the system. It has been estimated that during operation in a SA 15% of the iodine inventory, 10% of caesium and 5% of tellurium inventory in the core would be trapped in the filter unit. This amounts to an estimated decay heat of ~150 kW, requiring liquid addition only after 48-72 hours.

Contrary to the FCVS installed in Olkiluoto 3, the systems installed in Olkiluoto 1 & 2 does not include a return line into the containment for liquid containing fission products that would significantly reduce exposure while operating the system.

Under request of the Finnish safety authorities the EPR unit (Olkiluoto 3) under construction will have a FCVS with similar operation as those in Olkiluoto 1 & 2 as an additional means of containment pressure control in the case of total loss of the containment cooling capability. Although being able to protect the containment from over-pressurisation, the main purpose of the FCVS is to enable decrease of the containment pressure in the long-term after the SA, as the containment pressure is managed by a dedicated containment heat removal system (CHRS) that provides heat removal and containment spray in order to maintain the containment pressure within design limits under SA (core damage) conditions.

The two VVER-440 units at Loviisa (Loviisa 1 & 2) have steel shell containments that are vulnerable to sub-atmospheric pressures, which may arise after large amounts of non-condensable gases have escaped the containment, and thus no FCVS has been nor is planned to be installed. As an alternative means to protect the containment from over-pressure, a containment external spray system has been installed in 1990 to remove the heat from the containment in a SA when other means of decay heat removal from the containment are not operable. Other severe accident management measures (SAMM) have been installed at the units in 1990's.

4.5 France

France has 58 reactors (all PWRs of 3 standard types) on 19 sites (Bellemeville (2), Blayais (4), Bugey (4), Cattenom (4), Chinon (4), Chooz (2), Civaux (2), Cruas (4), Dampierre (4), Fessenheim (2), Flamanville (2), Golfech (2), Gravelines (6), Nogent (2), Paluel (4), Penly (2), St Alban (2), St Laurent (2), Tricastin (4) that produce almost three quarters of its electricity. One EPR is under construction at Flamanville.

In France, all reactors in operation (900 MWe, 1300 and 1450 MWe PWRs) are equipped with a sand-bed type FCVS developed by EDF. A dry metallic pre-filter is placed upstream the sand-bed filter inside the containment to retain most of the radioactive particles. The system is described in detail in Appendix 1.

Improved FCVS systems are under investigation to fulfil the requirements exposed earlier for Gen II reactors. No decision to implement upgraded FCVS is yet taken.

No provisions were initially made to equip the EPR reactor in construction in Flamanville with a FCVS since the reactor is designed with a Containment Heat Removal System (CHRS) (spray system) dedicated to SAs to remove the containment heat. After the Fukushima's events, the French Safety Authority required EDF to answer:

ECS - 28: Control of the containment pressure during a severe accident

Before June 30 2012, the licensee shall present to the French Safety Authority systems already included in the preliminary safety report or eventual additional systems that should be considered in the "hard-core"⁸ safety systems to ensure the containment pressure control in case of a severe accident.

To answer ECS-28, EDF has investigated different solutions including FCVS but proposed to install a mobile equipment for containment spray from outside able to extend the time before the pressure in the containment can reach the ultimate containment strength. For EDF, the additional time is sufficient to restore the containment heat removal system;

The French Safety Authority has not required today any additional solutions (FCVS).

4.6 Germany

Germany has currently 9 reactors (7 PWRs, 2 BWRs type 72) on 8 sites (Brokdorf, Grafenrheinfeld, Grohnde, Gundremmingen (2 BWR units), Isar, Neckarwestheim, Philippsburg) delivering about 16% of its electricity⁹. In Germany, all reactors in operation¹⁰ are equipped with FCVS. Table 4.1 and Table 4.2 give an overview of the accident management measures in German BWRs and PWRs.

Table 4.1: Implementation of accident management measures in BWRs (marked NPPs are put out of operation after Fukushima)

Measure	KKB	KKI 1	KKP1	KKK	KRB B	KRB C
AM manual (NHB)	●	●/1991	●/1989	●/1988	●/1991	●/1991
Filtered containment venting (combined Venturi scrubber)	●/1988	●	●/1989	●/1988	●/1990	●/1990
Containment inertisation	●/1988	●	●/1988	●/1988	□	□
Containment dry-well inertisation	□	□	□	□	●/1990	●/1990
PAR in dry-well and wet-well	□	□	□	□	●/1999	●/2000
Supply-air filtering for the control room	●/1998	●	●/1989	●/1988	●/1990	●/1990
Sampling system in the containment	○	●/2007	●/2001	○	●/2009	●/2009

✓ design ● realised through back-fitting measures ○ applied for □ not applicable

⁸ The "hard-core" safety systems should be operational for extreme natural phenomena and for long duration loss of electrical and cooling sources which can affect all the installations of a given site.

⁹ Eight NPPs (4 BWRs, 4 PWRs) were permanently shut-down in March 2011 as a direct political decision after the Fukushima events.

¹⁰ Also these shut-downs in March 2011 had FCVS installed.

Table 4.2: Implementation of accident management measures in PWRs (marked NPPs are put out of operation after Fukushima)

Measure	KWBA	GKN 1	KWBB	KKU	KKG	KWG	KKP 2	KBR	KKI 2	KKE	GKN 2
AM manual (NHB)	●/ 1990	●/ 1988	●/ 1990	●/ 1989	●/ 1993	●/ 1992	●/ 1990	●/ 1987	●/ 1991	●/ 1994	●/ 1988
Assured containment isolation	●/ 1991	●/ 1990	●/ 1991	●/ 1991	●/ 1991	✓	●/ 1990	●	●	✓	✓
Filtered containment venting (metal fibre filters and molecular sieve combinations) (combined venturi scrubbers)	●/ 2002	●/ 1992	●/ 2003	●/ 1992	●/ 1993	●/ 1993	●/ 1990	●/ 2003	●/ 1991	●/ 1991	●/ 1990
Catalytic recombiners to limit hydrogen formation	●/ 2010	●/ 2001	●/ 2003	●/ 2000	●/ 2000	●/ 2000	●/ 2001	●/ 2003	●/ 2000	●/ 1999	●/ 1999
Supply-air filtering for the control room	●/ 1989	●/ 1991	●/ 1989	●/ 1989	●/ 1992	●/ 1990	●/ 1990	●/ 1998	●/ 1989	✓	●/ 1988
Sampling system in the containment	○	●/ 1999	●/ 2010	●/ 2001	●/ 2003	●/ 2000	●/ 2001	●/ 2007	●/ 2002	●/ 2000	●/ 2002

✓ design ● realised through back-fitting measures ○ applied for □ not applicable

The most commonly used filtered venting system consists of a Venturi scrubber combined with a metal fibre fleece filter downstream of the Venturi scrubber (AREVA FCVS – former Siemens KWU, see Appendix 4). They are operated in sliding pressure mode (compared to atmospheric operation mode) with a throttling orifice downstream of the Venturi scrubber vessel. The Venturi section is operated at constant optimised speed conditions to ensure high efficient aerosol and elemental iodine retention. For that reason the Venturi scrubber section is essential for the robust process by providing safe decay heat transfer (cooling by evaporation) and highest aerosol loading capability and had been favoured by RSK for applications with high decay heat requirements. The scrubbing liquid contains some chemicals (mainly caustic soda) for retention of gaseous iodine. For minimization of the radiation loads, the possibility of flushing back of scrubbing liquid containing radioactive aerosols via the inlet pipe to the concerned containment is provided.

The systems are designed for a gas and steam flow (venting flow) at saturated steam conditions corresponding to approx. 1% of the rated thermal reactor power. The metal fibre filters are designed as deep-bed-filtration stage. Their purpose is retention of remaining fine aerosols and droplet separation for low re-suspension rates.

That optimized sliding pressure filtered venting process provides very high aerosol retention efficiency of > 99.99% even for small size aerosols with a MMD of approx. 0.5 µm and high elemental

iodine retention of > 99.5% clearly fulfilling the requirements of RSK (aerosol > 99.9%, elemental iodine > 90%).

The venting system is permanently installed in all plants. In BWR plants it is connected directly via a line coming from the pressure suppression pool (Figure 4.5), and in PWR plants via a line tied in directly from the containment in the peripheral area downstream of the isolation valves (Figure 4.4 and Figure 4.6 or 4.7). This outgoing line is diversely secured several times with valves (both remote-controlled and manually operated) against inadvertent opening. The outlet flow is released under controlled conditions via the Venturi scrubber through the cleaning solution and the filters in a separate line, in most cases through the stack. Activity measurements in the stack are carried out simultaneously by means of the stack instrumentation as well as with the help of a separate containment sampling system. With its help, analyses of the containment atmosphere are carried out to estimate the source term prior to venting.

For PWR application with limited aerosol quantities and low filter decay heats a second method - the metal fibre filter and molecular sieve combinations - was designed and implemented in some of the plants. Two of them are still in operation. The Dry Filter Method (DFM) was developed by the “Karlsruhe Nuclear Research Center” H. Krantz-TKT. The system is owned today by Toshiba/Westinghouse (see Appendix 2). Two different system designs have been implemented, as shown in figures 4.6 and 4.7.

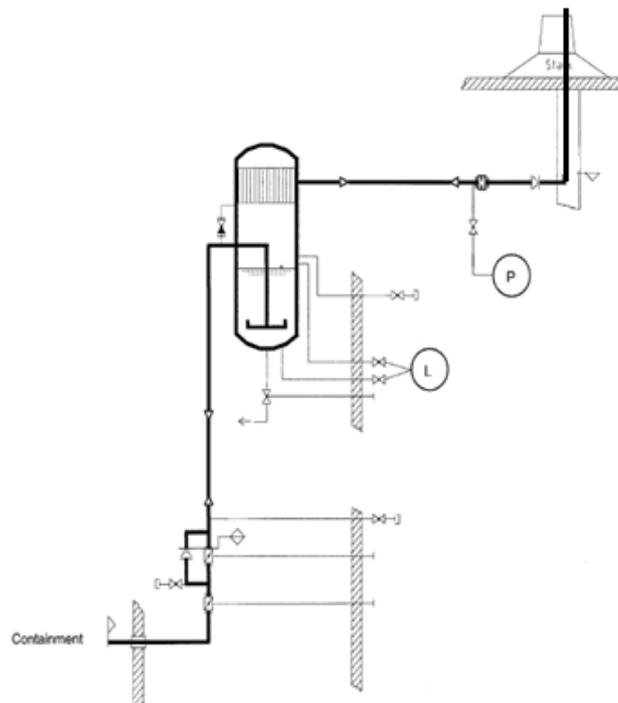


Figure 4.4 Sliding pressure Venturi scrubber venting system with internal metal fibre filter

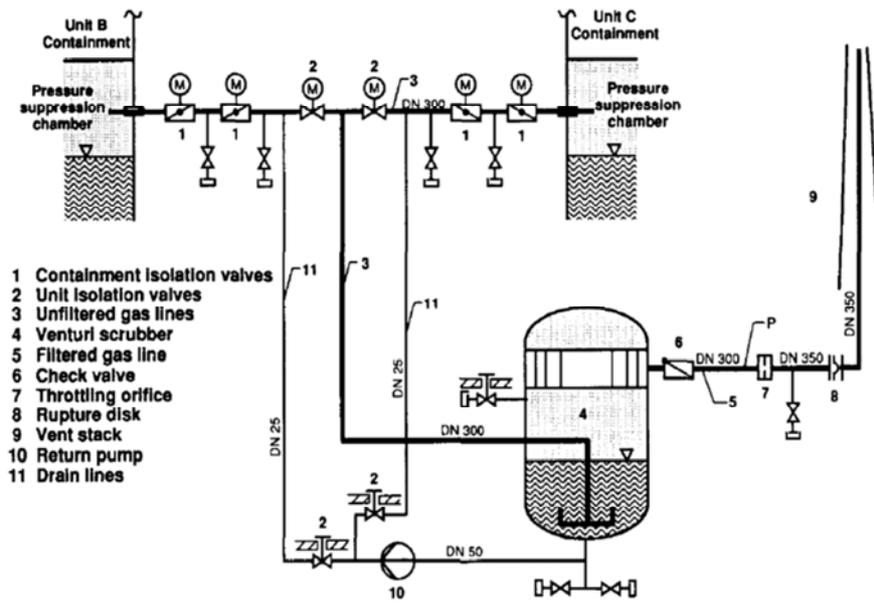


Figure 4.5 Sliding pressure Venturi scrubber venting system with internal metal fibre filter for BWR type 72 plant; one system for both units

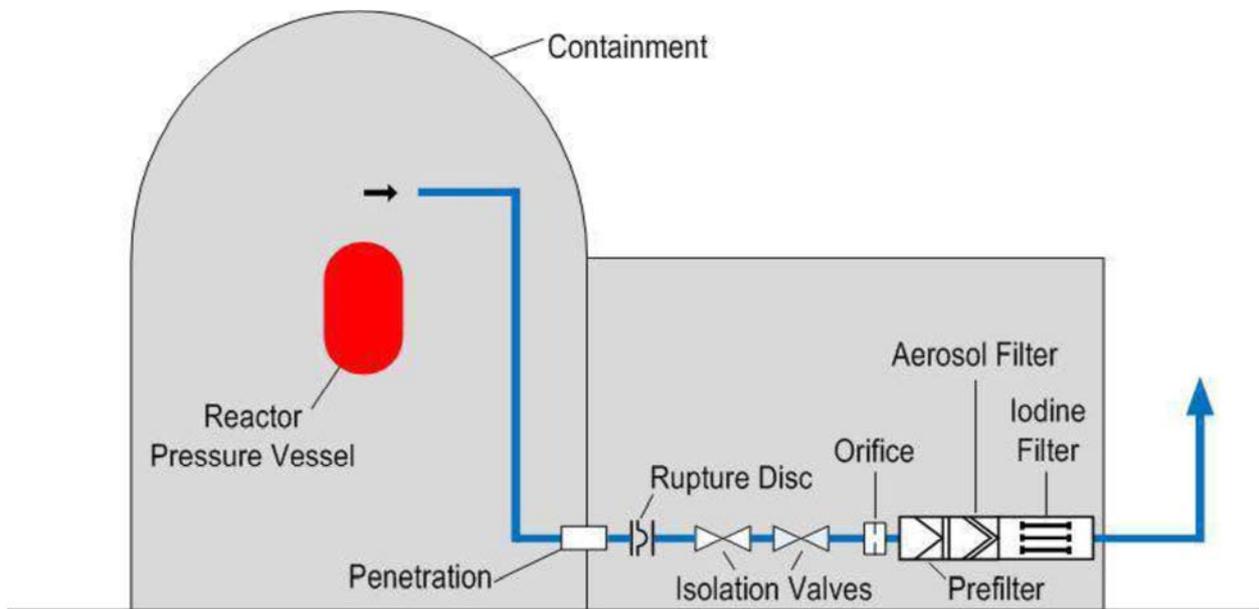


Figure 4.6 Atmospheric metal fibre filter (MFF) system with molecular iodine filter, method developed at FZK (now KIT), implemented by KRANTZ / YIT

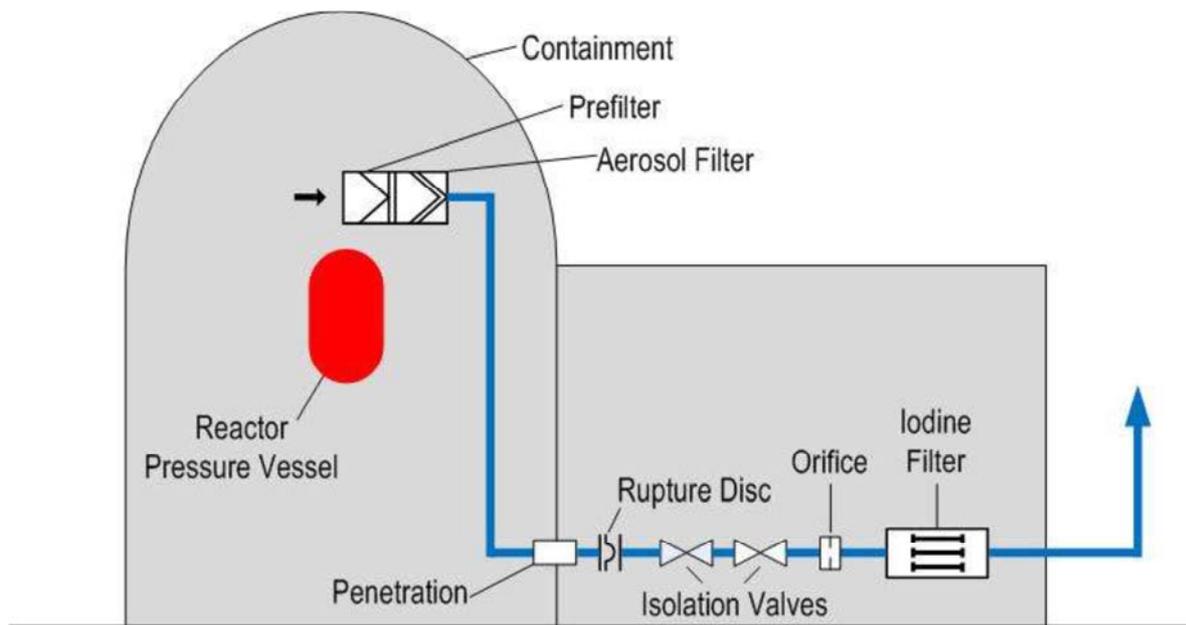


Figure 4.7 Pressure operation metal fibre filter (MFF) system with molecular iodine filter, Method developed at FZK (now KIT), implemented as KRANTZ-TKT/RWE-Method; all NPPs using this method are shut off now

4.7 Japan

Japan has 48 operating reactors (24 BWR, 24 PWR) on 16 sites¹¹ (excluding the 6 Fukushima Daiichi BWR reactors) generating about 18% of its electricity. Japanese NPPs are presently not equipped with SA capable FCVSs.

Both BWR and PWR utilities are preparing to install new SA capable FCVSs. For BWRs, some utilities plan to install new systems where venting is possible both from the wet-well and the dry-well.

At the present time, the implementation of Dry filter systems or High Speed Pressure Venturi type systems is envisaged in PWR units and the implementation of High Speed Pressure Venturi type systems or another wet scrubber with metal fibre filter system is envisaged in BWR units (see Appendices 2 to 4 for description of commercially available systems).

¹¹ Fukushima-Daini (4 BWR), Genkai (4), Hamaoka (3 BWR), Higashi Dori (1 BWR), Ikata (3), Kashiwazaki-Kariwa (7 BWR), Mihama (3), Ohi (4), Onagawa (3 BWR), Sendai (2), Shika (2 BWR), Shimane (2 BWR), Takahama (4), Tokai (1 BWR), Tomari (3), Tsuruga (1 BWR, 1 PWR)

4.8 Mexico

Mexico has 2 BWRs of the Mark II type in the Laguna Verde Nuclear Power Plant (LVNPP), located in the municipality of Alto Lucero de Gutiérrez Barrios (Veracruz, Mexico), generating about 5% of its electricity.

The LVNPP original design includes an emergency venting of the primary containment through a 12-inch pipe which discharges into the secondary containment to relieve excess pressure and to maintain its primary containment integrity during an emergency condition that exceeds a design basis accident.

Following the regulatory requirements issued by the National Nuclear Safety and Safeguards Commission (CNSNS) after the Fukushima Daiichi events, the LVNPP has already started the installation of reliable hardened containment venting systems (HCVS) for its two BWRs with Mark II containments with connections from wet-well and dry-well. The venting systems to be implemented do not include any external filtration feature.

4.9 The Netherlands

The Netherlands has 1 reactor (PWR) at 1 site (Borssele) generating about 4% of its electricity. The Borssele reactor is equipped with a HSSPV-type FCVS.

4.10 Romania

Romania has 2 reactors (PHWR) at 1 site (Cernavoda) delivering almost 20% of its electricity.

AREVA was recently awarded a contract by the Canadian group SNC-Lavalin Nuclear to provide HSSPV-type FCVSs (FCVS) for Units 1 and 2 at CNE Cernavoda nuclear power plant.

4.11 Russian Federation

Russia has 6 VVER-440 reactors (4 on the Kola site and 2 on the Novovorenezh site) and 11 VVER-1000 reactors (4 on the Balakovo site, 4 on the Kalinin site, 2 on the Rostov site and 1 on the Novovorenezh site). It also has 13 RBMK reactors, 4 small graphite moderated BWR reactors and one fast breeder reactor. Russian NPPs are presently not equipped with FCVS. After Fukushima accident, FCVS installation is considered as a SAMM in some of the VVER reactors (at Kola and Kalinin sites).

FCVS have been developed in the late eighties in the ex-Soviet Union for VVER containments but they were not implemented in reactors. These systems consist of a first liquid filtration stage including a jet scrubber and a droplet separator for aerosols filtration and a second dry filtration stage composed of a dry-packed filter containing a thermal-resistant inorganic sorbent for gaseous iodine filtration (see references [52] and [53] for a more detailed description)¹². These systems, as other FCVS systems that are

¹² A more compact dry filtration system composed of a first stage of packed alumina granulates and a second stage of a packed thermal-resistant inorganic sorbent (same sorbent than in the other system) was also developed and is considered as a possible alternative design.

implemented in reactor worldwide, were tested in the international ACE programme. They were shown to have performances similar to other systems under the tested conditions with aerosols $DF > 10,000$. Such DFs were shown to be sufficient to fulfil the radiological objectives defined by Russian regulation.

4.12 Slovakia

Slovakia has 4 reactors (VVER440/V213) on 2 sites (Bohunice and Mochovce) generating about half of its electricity.

Slovak NPPs are not equipped with FCVS for SAM. Based on the national action plan after the stress tests performed in NPPs, by the end of 2015 a necessity of filtered venting of the containment and other potential technical measures for long-term heat removal from the containment and reduction of radiation load of the environment will be analysed, considering measures implemented within the SAM project and taking into account activities in this area by other operators of VVER-440/V213.

4.13 Slovenia

The Krško NPP installed the Westinghouse DFM FCVSs in 2013. Currently, only the passive operation mode of the system was approved. The SA scenario for the design of the FCVS is a station blackout scenario. In this scenario no safety related equipment is credited and the water present in the containment (wet cavity) is only from the primary coolant system and the accumulators (passive). The scenario assumes no manual actions and no crediting of SAME equipment (mobile generators, pumps, compressors, connection pipes etc.) or SAMG actions. MCCI occurs following cavity dry-out after the first venting cycle.

In the event of a severe containment over-pressurisation, such as happened in the March 2011 accident at Japan's Fukushima Daiichi plant, the passive FCVS would allow depressurisation to occur while minimizing the radioactivity released into the environment. During depressurisation, the metal fibre aerosol filters would retain airborne radioactive aerosols and radioactive iodine and its organic compounds would be retained by the iodine filter – a zeolite molecular sieve doped with silver that bounds the iodine.

The FCVS consists of 5 aerosol filters (in parallel) inside the containment. The penetration of the containment to the auxiliary building is equipped with a rupture disk and two sets of isolation valves on parallel lines; the valves are used in the active mode of the filtered venting. The iodine filter is placed in the auxiliary building and radiological shielding was installed around the iodine filter to enable the personnel to approach the isolation valves in need of manual start of venting (active mode). The release to the environment is made via a dedicated robust stack that leads to the top of the reactor building. All the components are Seismic category I and qualified for DEC seismic acceleration of $PGA = 0.6g$ (while design bases $PGA = 0.3g$). The containment penetration section is ASME class II and the rest of the system is non-safety related. The stack was qualified also for extreme wind (tornado) and extreme outdoor temperatures.

The design specifications for filter efficiency were $DF > 1,000$ for aerosols, $DF > 100$ for elemental iodine and $DF > 10$ for organic iodine. Tests confirmed that these specifications can be achieved. The passive venting of the containment starts at 6 bar (abs) with rupture of a disk that provides the pressure boundary of the containment. The iodine filter is inerted by nitrogen gas to prevent hydrogen burn at the venting of containment atmosphere. After containment pressure decrease following a venting, a check

valve isolates the iodine filter from the stack at 4 bar (abs) and the iodine filter is passively filled again with nitrogen gas.

The installation of some components for the FCVS will continue in the scope of the Krško NPP safety upgrade programme that is planned to be implemented by 2018. For the FCVS, the installation of radiological monitor and flow-meter in the venting stack is planned to enable measurements of releases to the environment. The qualification of containment instrumentation for design extended conditions (DEC) has to be performed. By installation of the new Emergency Control Room (ECR) and power supply to the isolation valves for the active mode of the venting, it will be possible to control the FCVS remotely from the ECR.

Other planned measures to preserve the containment integrity are installation of means to provide borated coolant injection into the containment (spraying and flooding) and into the reactor coolant system. In the 2013 outage, 22 PAR were installed in the containment to control the hydrogen concentration in case of design basis or SA. Additional pressurizer pressure release valves PORVs will be installed, qualified for DEC events that will provide means for depressurizing the reactor pressure vessel in case of core damage. A mobile heat exchanger (cooled by mobile equipment or air) will be provided for cooling of containment sump or reactor coolant system.

4.14 South Korea

South Korea has 23 reactors (19 PWR, 4 PHWR) on 4 sites (Hanbit (6), Hanul (6), Kori (6), Wolsong (1 PWR, 4 PHWR)) providing about 30% of its electricity.

In the Wolsong-1 PHWR unit, the installation of the first FCVS (HSSPV type) was completed at the end of 2012 (during the preparation to acquire the approval for the continued operation after 30 years operation). The remaining 22 Korean NPP units (19 PWR, 3 PHWR) are planned to be equipped with FCVS by the end of 2018, and an open tender is being prepared.

4.15 Spain

Spain has 7 reactors (6 PWRs, 1 BWR) on 5 sites (Almaraz (2), Asco (2), Cofrentes (1 BWR), Trillo (1), Vandellos (1) generating about 20% of its electricity. Another BWR (Santa Maria de Garoña) reactor has been permanently shut-down in July 2013 due to economic issues.

Spanish PWRs have no FCVS installed. After post-Fuskushima stress tests the Spanish Regulatory Body (CSN) required by the 31st of December 2013, an analysis of the different alternatives available in the market for FCVS and the final solution chosen to be implemented by each plant. Implementation of the modification on site (including FCVS) is requested by CSN to be performed before the end of 2016.

The Spanish BWR has installed a (non-filtered) hard venting system. GE Mark III BWR-6 licensee has been required by CSN to analyse the possibility of implementing a FCVS, including assessment of the available technologies. After evaluating the report submitted by the plant in 2012, CSN required the licensee to implement a FCVS by 2017.

4.16 Sweden

Sweden has 10 reactors (3 PWRs, 7 BWR) on 3 sites (Forsmark (3), Oskarshamn (3), Ringhals (1 BWR, 3 PWR) delivering about 40% of its electricity.

By decision of the Swedish Government an extensive back-fitting, completed by the end of 1988, was performed for all Swedish nuclear power reactors including the installation of FCVS.

The FCVS at all Swedish reactors is a Multi Venturi Scrubber System (Filtru-MVSS) developed by ASEA Brown Boveri (ABB) Atom (today Toshiba/Westinghouse, see Appendix 2).

4.17 Switzerland

Switzerland has 5 reactors (3 PWRs, 2 BWRs) on 4 sites (Beznau (2), Gösgen (1), Leibstadt (1 BWR), Mühleberg (1 BWR)) providing about 35% of its electricity.

In the early nineties all Swiss nuclear power plants were back-fitted with a FCVS. Three different types of FCVS are installed:

- The HSSPV type system installed in the PWR unit at Gösgen;
- The Filtra-MVSS type system installed in the BWR unit at Mühleberg;
- The SULZER-CCI-type FCVS developed by SULZER CCI (today IMI CCI nuclear) installed in the PWR and BWR units of Beznau and Leibstadt.

All FCVS consists of a pool or tanks, filled with water and chemicals, and Venturi or sparger based scrubbers. The venting line to the exhaust stack or to venting stack will be opened automatically by a rupture disc or via a parallel line by opening a valve remotely or manually.

The decontamination factor (DF) of the FCVS has to be > 100 for Iodine, > 1,000 for aerosol; some plants expect a DF up to 10 times higher than required. The depressurization flow is defined by the type of containment, the design pressure of the containment, the required capacity for decay heat removal and hydrogen prevention.

In addition to function tests of the components (valves) the FCVS's are tested at the end of the containment leak rate tests (4-10 years) to depressurize the containments.

4.18 United States

The United States have 104 reactors (69 PWR, 35 BWR) on 64 sites¹³ generating about 19% of its electricity.

¹³ Arkansas (2 P), Beaver Valley (2 P), Braidwood (2 P), Browns Ferry (3 B), Brunswick (2 B), Byron (2 P), Callaway (1 P), Calvert Cliffs (2 P), Catawba (2 P), Clinton (1 B), Columbia Generating Station (1 B), Comanche Peak (2 P), Cooper (1 B), Crystal River (1 P), D.C. Cook (2 P), Davis-Besse (1 P), Diablo Canyon (2 P), Dresden (2 B), Duane Arnold (1 B), Farley (2 P), Fermi (1 B), Fitz Patrick (1 B), Fort Calhoun (1 P), Grand Gulf (1 B), Hatch (2 B), Hope Creek (1), Indian Point (2), Kewaunee (1), La Salle (2), Limerick (2), McGuire (2), Millstone (2), Monticello (1 B), Nine Mile Point (2 B), North Anna (2 P), Oconee (3 P), Oyster Creek (1 B), Palisades (1 P), Palo

The nuclear industry in the United States and the NRC are working on the development of guidance documents for implementing a SA capable venting system in compliance with the Order to Modify Licenses with Regard to Reliable Hardened Containment Vents Capable of Operation Under Severe Accident Conditions (EA-13-109). This order requires that all BWRs with Mark I and Mark II containments shall have a reliable hardened containment venting system (HCVS). The HCVS includes a SA capable containment wet-well venting system and may also include a SA capable containment dry-well venting system. This requirement shall be implemented in two phases. In Phase 1, licensees of BWRs with Mark I and Mark II containments shall design and install a venting system that provides venting capability from the wet-well during SA conditions characterized by elevated temperatures, pressures, radiation levels, and combustible gas concentrations, such as hydrogen and carbon monoxide, associated with accidents involving extensive core damage, including accidents involving a breach of the reactor vessel by molten core debris. In Phase 2, licensees of BWRs with Mark I and Mark II containments shall design and install a venting system that provides venting capability from the dry-well under SA conditions; alternatively, the licensees shall develop and implement a reliable containment venting strategy that makes it unlikely to have to vent from the containment dry-well during SA conditions. Currently, it is anticipated that the implementation will be done by 2018 or earlier. The venting system to be implemented in this time frame may not include any external filtration feature.

The containment venting issue for other reactor and containment types (e.g., BWR Mark III containment, ice condenser, large dry pressurized water reactors, etc.) will be considered in the long-term (under Near-Term Task Force Tier III work scope).

4.19 Other countries

No information was obtained for UK, China and India.

Verde (3 P), Peach Bottom (2 B), Perry (1 B), Pilgrim (1 B), Point Beach (2 P), Prairie Island (2 P), Quad Cities (2 B), River Bend (1 B), Robinson (1 P), Saint Lucie (2 P), Salem (2 P), San Onofre (2 P), Seabrook (1 P), Sequoyah (2 P), South Texas (2 P), Summer (1 P), Surry (2 P), Susquehanna (2 B), Three Mile Island (1 P), Turkey Point (2 P), Vermont Yankee (1 B), Vogtle (2 P), Waterford (1 P), Watts Bar (1 P), Wolf Creek (1 P)

Table 4.3: Status on the implementation of FCVSs

Country	NPPs	no FCVS ¹⁴							Comments
			HSSP V	Metal + sand-bed	DF M	FILTR A- MVSS	SULZE R CCI	EFAD S	
Belgium	7 PWR	□							Planned in 5 units which will operate beyond 2015 (no design selected yet)
Bulgaria	2 VVER 1000		●						
Canada	19 PHWR Single unit (1) Multi units (18)		●		○			●	HSSPV for Point Lepreau single unit, DFM planned in 4 Darlington units 4 EFADS shared among 18 reactor units, EFADS are designed for DBA
Czech Republic	4 VVER-440 2 VVER- 1000	■							Under assessment in conjunction with SAMM for corium cooling (in or ex-vessel)
Finland	2 VVER 440	■							FCVS is not feasible in VVER-440 due to the steel shell of containment that is vulnerable to sub-atmospheric pressures; EPR plant under construction will be equipped with FCVS
	2 BWR		●						
France	58 PWR			●					metal pre-filter inside containment, sand bed filter outside containment
Germany	7 PWR		●		●				DFM in 2 PWR units
	2 BWR		●						
Japan	24 PWR	□							PWRs: FCVS planned as “Specialized Safety Facility” ¹³ (no design decided yet) HSSPV and other scrubber system planned for BWRs. Additional FCVS planned as “Specialized Safety Facility” ¹⁵
	26 BWR	□	○						
Mexico	2 BWR	■							Hardened CVS from wet and dry well (Mark II) under implementation
Netherlan	1 PWR		●						

¹⁴ No FCVS designed for severe accidents implemented or FCVS planned but design not selected yet¹⁵ Refers to systems to suppress large releases caused by containment failure as a result of extreme external events

ds									
Romania	2 PHWR		○						HSSPV planned
Slovakia	4 VVER-400	■							Under assessment with other SAMM
Russia	6 VVER-440 11 VVER-1000	■							Under assessment for some VVERs after Fukushima. Not considered for other reactors (RBMK, ...)
Slovenia	1 PWR				●				DFM installed in 2013 in Krško NPP, used in passive mode with rupture disk
South Korea	19 PWR	□							Only Wolsong-1 Unit equipped with HSSPV. Other units are planned to be equipped with FCVS by 2018, development of a Korean system under consideration
	4 PHWR	□	●						
Spain	6 PWR	□							PWR: FCVS implementation is planned by 2016 BWR: Hardened venting available. Filter implementation is planned in 2017
	1 BWR	□							
Sweden	3 PWR					●			
	7 BWR					●			
Switzerland	3 PWR		●				●		HSSPV type at Gösgen F-MVSS type at Mühleberg
	2 BWR					●	●		
USA	69 PWR	■							Preparation of guidance documents on Hardened CVS for BWR Mark I & II. Implementation by 2018 or earlier ¹⁶ .
	35 BWR	■							

■ no FCVS □ planned but design not yet selected ● installed ○ planned

¹⁶ The rulemaking effort for containment vent filtration and accident management strategies is in progress. Implementation of an external filter is contingent on the outcome of the rulemaking effort.

5. FILTERED CONTAINMENT VENTING STRATEGIES IN EOP AND SAMG DOMAINS

5.1 Severe accident management

In managing the consequences of a nuclear accident, the overarching goal is always to protect people, both on-site and off-site, while bringing the reactor (and associated systems) back to a safe state. With the most likely accident scenarios, the most probable sequence of events can generally be predicted well in advance. For these design basis accidents, emergency systems can be installed beforehand to deal with specific issues and comprehensive response protocols can be implemented as part of an emergency operating procedure (EOP) or event-oriented procedure to stop the accident progression.

However, not all possible accident scenarios can be explicitly addressed, and even though EOPs are often sufficient to bring many accidents that are beyond the regular design basis back under control, there may be certain cases where severe core damage or large fission product releases can still occur. In these cases, SAMG provides a framework that helps to identify different actions that can be taken in response, to: (i) terminate the progression of core damage, (ii) maintain containment integrity, and (iii) minimize on-site and off-site fission product releases.

SAMG protocols have generally been developed for cases when regular EOPs have failed, and as such, they do not rely on any prior assumptions about the nature of the accident, or the events that led up to it. Rather, SAMG protocols are intended to address the accident on a symptom-by-symptom basis, including steps for comprehensive plant diagnosis and how to identify as many mitigating measures as possible. With more mitigating measures in place beforehand, the defence-in-depth will be more robust and the chance of reducing the overall severity of the accident will be improved. This is especially true for systems that require little or no operator intervention, that can operate passively without electrical power, and that are independent from other systems and common failure modes. FCVS is often used as part of a SAM strategy precisely for these reasons: it offers an extra means to reduce radioactivity releases to the atmosphere, regardless of the state of the reactor or the events that transpired to cause the accident.

For countries where it is employed, FCV reinforces the function of nuclear containment as last barrier for the release of radioactive products to the environment, minimizing radiological health consequences to the public, and preventing large amounts of land contamination. The overarching goal of the FCV is to prevent, in case of SA, the overpressure failure of containment and keep the containment pressure to acceptable levels. However, even though radioactivity releases to the environment would be largely avoided, the operation of FCV during an accident still requires clear instructions on when to initiate venting, integrated decision making with national authorities, and coordination with emergency responders on and off-site.

5.2 Strategies for FCV operation

In operating a FCV system during a nuclear emergency, the timing of when to vent is the single most critical decision. With venting initiated, the process of depressurizing the containment building can begin, but there are several different considerations that must be balanced.

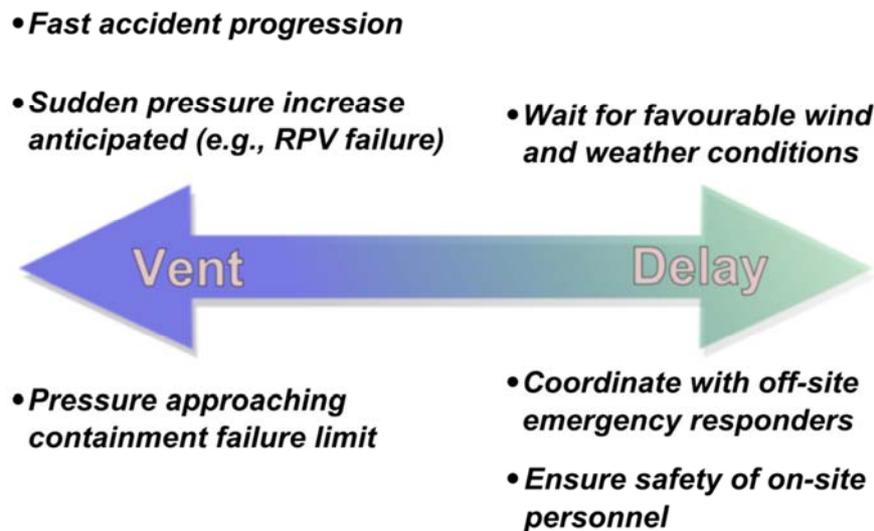


Figure 5.1 – Rationale for venting

- **Failure pressure of containment building:** In general, containment structures are strong enough to remain isolated during any design basis event. During a SA that has progressed beyond that, however, the pressure may become high enough to threaten the containment integrity. The design pressure is normally lower, by a certain safety margin, than the pressure at which the containment would be expected to fail, but filtered venting should still be initiated early enough to avoid that risk.
- **Containment pressurization and the speed of accident progression:** Depending on the nature of the accident, as steam and other gases are produced, the containment will pressurize. These gases will be generated over time, but specific events, like the failure of the reactor pressure vessel or molten corium-concrete interaction, could occur that would result in a fast spike in containment pressure. The pressurization rate and the potential for sudden jumps in pressure should be taken into account whenever filtered venting is being considered. Too long of a delay could result in the failure pressure being exceeded and FCV systems can only relieve pressure as fast as their designs allow. PWR, PHWR, and newer generation BWR containment designs have relatively large volumes, but during a SA, it is possible that the pressure in smaller volume containments, like the Mark-I and Mark-II BWR designs, could reach the limits of containment integrity sooner. Many of the countries that designed and installed FCVS in the 1980s are reevaluating their systems based on new lessons learned from the Fukushima Daiichi accident.

- **On-site emergency response and radiological protection:** Wherever possible, the decision to vent should be well coordinated, and should ensure that site, control room, and emergency response personnel are adequately sheltered and protected. This includes any personnel that are outdoors, as well personnel near the filtration unit or any vent lines. Shielding the FCV system should be something incorporated into its design, as the fission products that it collects would pose a radiation hazard.
- **Coordination with off-site emergency response:** The FCV systems would capture a large portion of the total activity carried by the gases being vented, but a certain proportion of aerosol-bound and vapour phase radionuclides would still be discharged, along with all of the noble gas species. As such, wherever possible, filtered venting should be coordinated with off-site emergency response personnel to ensure that any evacuation activities, sheltering, and distribution of potassium iodide tablets can take place in order to best protect the public. In some jurisdictions, venting must be delayed by 24 hours, at a minimum, to give adequate time for off-site preparations to be made.
- **Wind and weather conditions:** The dispersion and transport of any radionuclides emitted from the FCV system will depend on wind and weather conditions. Daytime venting during unstable atmospheric conditions will result in greater dispersion, but lower overall concentrations than, for example, night time venting under a stable atmosphere. Likewise, rainfall will greatly enhance the deposition of non-noble gas radionuclides, and create higher levels of, but more localized, ground contamination. Whenever possible, venting should be coordinated so that the prevailing wind directs contaminants away from population centres and other sensitive areas.

The decision of whether to vent is generally taken according to established procedures and criteria, and is almost universally part of the coordinated response with the responsible national authority. The operation of filtered venting system would, as applicable, be guided by EOPs for design-basis accidents and SAMGs for SAs. It should be underlined that, in the SAMG domain in particular, an assessment of the radiological consequences outside the plant is made, and the time and duration of containment venting is typically coordinated to minimize the potential impact on public health.

Once initiated, the FCV system will capture most of the radionuclides being emitted, and the containment pressure will start to decrease until, eventually, the pressure has dropped low enough that venting can be stopped. If the venting was initiated by the control room (as opposed to passively by a rupture disk on the vent line), then it can be actively cycled on and off as necessary if the accident continues to progress. Plant operators can monitor the progress of the accident in a proper way continuously. System instrumentation discussion is included in Chapter 10.

5.3 International Standards

The International Atomic Energy Agency has developed several safety standards that apply in the general context of SAM, as well as containment design and emergency response:

- NS-G-2.15, “Severe Accident Management Programmes for Nuclear Power Plants” [25]
- NS-G-1.10, “Design of Reactor Containment Systems for Nuclear Power Plants” [26]

- GS-R-2, “Preparedness and Response for a Nuclear or Radiological Emergency” [27]
- GSG-2, “Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency” [28]

The safety guide, NS-G-2.15 [25], outlines some of the essential component of a SAM programme, and provides a framework with which countries can develop their own systems and procedures. Among the top level objectives for any SAM programme, as stated in NS-G-2.15(2.6), are maintaining containment integrity for as long as possible, and minimizing releases of radioactive material. The document states numerous times that maintaining containment integrity is paramount, and in NS-6-2.15(3.67), suggests employing filtered venting as one of the engineered systems that would be very valuable for managing overpressure in the mitigatory accident management domain.

NS-G-1.10 [26] establishes many of the essential containment-related design considerations in order to respond to accidents. In NS-G-1.10(4.143) for design basis accidents, and in NS-G-1.10(6.16) and (6.20) for SAs, it states that wherever containment venting is employed, the discharge should be filtered in order to reduce radionuclide releases to the environment. In NS-G-1.10(4.224) and (6.30-6.32), the importance of having working controls and instrumentation in order to operate the FCV systems is underlined, including containment pressure and temperature, dose rate meters in the containment structure and attached peripheral buildings, and activity monitors in the stack to record atmospheric releases.

IAEA standards for the emergency response that would take place following a nuclear accident are presented in GS-R-2 [27] and GSG-2 [28]. GS-R-2 outlines the essentials goals and criteria for emergency response and emergency preparedness, as well as what should be in place to protect the public, and mitigate the consequences of a nuclear emergency. GS-R-2, on the other hand, gives specific criteria for taking action when either the projected or received doses are above a certain limit. Some of these criteria, for example, include:

- For acute doses, external doses above about 1 Gy (red marrow, or 0.1 Gy for a foetus) and, depending on the organ, internal doses above 0.2 Gy to 30 Gy (or 0.1 Gy for a foetus) require urgent protective actions, contamination control, health monitoring, and counselling;
- For mitigation of stochastic radiation effects, if a dose over 50 mSv is projected in members of the public in the first seven days after an accident, iodine thyroid blocking should take place, and sheltering, evacuation, contamination control, and food consumption control should take place if the 7 day projected dose is over 100 mSv. Likewise, if a dose above 100 mSv is projected over one year, temporary relocation should be considered in addition to these other measures.

The full criteria are given in GSG-2 [29]. Individual countries must determine their own criteria for emergency response and dose limits, but these are accepted international targets that can be used in deciding how best to respond to a SA, and whether or not to initiate venting.

5.4 Filtered venting strategies for PWR and PHWR containments

The containment buildings for PWRs and PHWRs are typically large, dry volumes that can withstand having considerable amounts of steam and other gases injected into them from a damaged reactor. Although different countries have different design and regulatory requirements over the implementation of FCV systems, one of the universal tenets within EOP and SAMG domains, however, are that the

containment envelope should remain sealed for as long as possible. Whether or not FCV is implemented, the decision to vent is generally delayed as long as possible to allow the containment structure to perform its function, but where FCV is available, the technology allows the decision to vent to be made at an earlier time while the risk of an uncontrolled containment breach is lower.

5.5 Filtered venting strategies for BWR containments

In contrast to PWR and PHWR containment designs, BWR containments rely primarily on large suppression pools to condense steam and keep the overall pressure down. At the present time, radiological release mitigation strategies and approaches for SAs at BWR plants are different depending on both the specific BWR containment type and the regulatory requirements of the particular country.

In the case of Mark I and Mark II containments, venting is done prior to the pressure exceeding the primary containment pressure limit (PCPL). Venting has long been recognized to be an important provision, where because of their small size, BWR containment designs are more susceptible to overpressure failure during SAs. Although hardened, non-filtered venting systems have been incorporated into the design in many cases, additional external FCV systems have in the past been seen as unnecessary or not cost-beneficial because the scrubbing effect of the suppression pool provides a good degree of filtration. Even so, venting from these older BWR designs has only been considered as an extreme measure to prevent core melt, or as a last resort to prevent the irreversible and unpredictable rupture of the containment which could otherwise lead to a large release. Figure 5.1 shows the difference between Mark I and Mark III containments types, as well as the corresponding venting pathways:

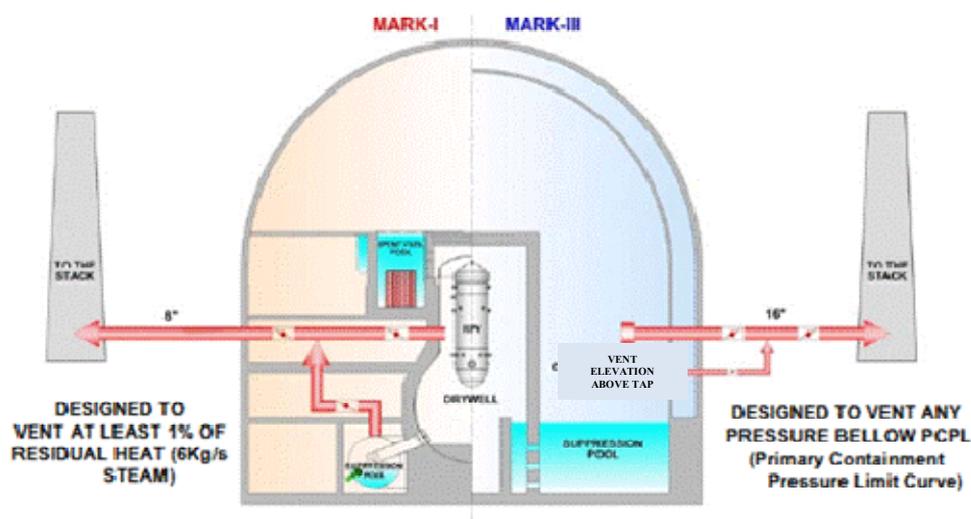


Figure 5.2. Comparison of Mark I and Mark III containment venting designs

The overall containment strategy for a Mark III reactor is significantly different than for a Mark I or II. At the present time, however, venting strategies still vary from country to country. In Spain, for example, containment venting is currently carried out by the Dedicated Venting System, which is a hardened vent, with no other external filter beyond the suppression pool. The containment venting is

considered both in EOP and SAMG domains. Depending on the countries, FCVS can be designed to operate both as part of early venting strategies, to control/manage the containment parameters in emergency situations (e.g., pressure, temperature, hydrogen content), as well as in later phases to protect the containment structures against high hydrogen concentrations, to act as a final heat sink in some reactors, and to make water injection to the containment and reactor possible through low pressure systems. In each plant at least one venting path is available to be operated locally in case of loss of support systems (e.g. electrical power, instrument air), and it is possible to close and re-open the venting line locally in case of loss of support systems.

6 DESCRIPTION OF DIFFERENT FILTERED CONTAINMENT VENTING SYSTEM TECHNOLOGIES

The currently installed containment venting filters use different filtration technologies involving more than one filtration medium. The ones which use water as the first filtration stage, so called, wet systems, are further equipped with other stages to eliminate droplets and fine aerosols releases, and even may additionally be equipped with a stage containing certain absorption media for filtration of gaseous iodine species. Other designs, based on deep bed filtration as the main retention stage, so called dry filters, use metal fibre or ceramic or sand bed filtration media for the aerosol filtration. The metal fibre dry filters are equipped with droplet separators and optionally with cooling tubes and an iodine species absorption stage.

6.1 FCVS with water scrubber – droplet separator/deep bed fine aerosol filter

Filtration of aerosol particles and gaseous fission products, (i.e., iodine species, ruthenium tetroxide), by pool scrubbing processes such as sparging aerosol-iodine species laden gas through a water pool, which is commonly doped with chemical additives, is an established technique. Water produces not only an effective filtration media for filtration of particulates and gaseous iodine and ruthenium species under prevailing conditions but also acts as a heat sink.

The degree of effectiveness of water scrubbers for removing aerosol particles and gaseous species depends on many factors such as: the type of the sparging device used, hardware introduced in the water column to improve the mass transfer of particulates and gaseous species, bubble hydrodynamics defining bubble sizes and residence time, etc. Several technologies using water as the main filtration media have been in use for many different industrial applications, including nuclear reactors.

The effectiveness of the heat sink capacity depends on first the amount of water available and its temperature as well as the extent of received thermal energy associated with the vent gas and the decay-heat generated by the filtered fission products.

As the water pool is initially cold, the steam condensation causes an initial increase in the inventory of the water pool, but later a decrease by boiling or evaporation depending on whether the vent gas is composed of 100% steam or less. Depending on the rate of water mass loss after the rather fast initial heat-up phase is over, the scrubber efficiency of water may diminish when the water level drops below a certain level, which necessitates the refilling of the water. The time until this state is reached should fulfil the regulatory requirement on the ‘Autarky period’, which defines how long the unattended passive operation of the venting operation should be accomplished. How much water should be in the filter vessel initially defines automatically the key filter vessel dimensions unless a separate water storage vessel is installed, which can provide make-up water on demand.

Other important processes affecting the vessel height are: increase in water volume by condensation, swell level by gas sparging, height needed to facilitate fall-back of droplets, which are generated by burst of gas/steam bubbles at the water surface, and certain vessel volume to accommodate room for housing a droplet separator/deep bed fine aerosol filtration stage.

There is a need for a droplet separator alone or in combination with a deep bed fine aerosol filter in order to avoid release of contaminated droplets which contain dissolved fission products and suspended particles. Another task of the deep bed fine aerosol filter is to remove fine aerosol particles to secure their filtration since the water stage cannot effectively remove submicron particles.

The aerosol load to the deep bed filter stage shall be limited to the values, which shall avoid critical clogging situation safely. The maximum aerosol load to the filter shall also consider the specific behaviour of different aerosol mixtures [29] including high moisture situations, if such conditions could not be excluded inside the filter media. Therefore, experimental verification of deemed permanent high aerosol retention efficiency with the pool scrubber stage during an extended venting operating period is essential to securely avoiding overloading of such downstream deep bed filter elements. Similarly, the amount of droplets reaching the droplet separator should be reasonably low and the efficiency of the droplet separator under all foreseeable conditions should be as high as possible for either eliminating droplet release from the filter vessel into the outlet piping or to secure entry of droplet free gas into the deep bed filter elements.

Removal of gaseous iodine fission products and retaining the iodine which is initially in salt and/or gaseous form is handled with water chemistry. This includes the use of chemicals for obtaining high pH, and reducing agents. However, caution should be given to the effective suppression of the thermal and radiolytic oxidation of iodine ions and reactions with organic materials (radical reactions) in the water pool [30]. A substantial amount of gaseous iodine release from the FCVS might be expected [31] if the following penalizing conditions prevail: low pH as a result of potential acid fume inflow into FCVS, and low concentration of reducing agent.

Removal of organic iodides by the water scrubbers has been a technological challenge [32]. Attempts have been made by research and FCVS technologies lately to reduce the organic iodide / elemental iodine release by incorporation of either zeolite based molecular sieve filters impregnated with silver as an add-on to the scrubber, or utilization of co-additives [33] with an aim to enhance the removal of gaseous organic iodine from the gas bubbles as well as fixing the iodide ions in the aqueous phase to suppress the re-volatilization. It is reported in the literature [34,35] that the use of some specific scrubbing liquid additives might also produce negative phenomena, e.g. foaming and filter burning although evidences against such arguments have also been presented [36].

The use of zeolite for adsorption of specific target molecules is common in industry. The benefits as well as the limits of the zeolite as the adsorption media are discussed in open literature. For instance adverse effects which might reduce the filtration efficiency of zeolite based absorption medias are low super-heated gas or wetting high face velocity [37], dose rate by iodine absorption and additional absorption of some noble gases [38], poisoning [39], hydrogen reactions [40,41] remobilizing iodine, etc. Water scrubbers provide inherent feature of gas pre-cleaning, which might reduce some of these adverse effects. An extensive qualification of these retention stages considering such adverse effects could therefore be recommended.

The design parameters of chemistry control or new add-on hardware depend on the iodine load, both aerosol bound and the gas phase species.

Solid deep-bed filter retention stages

Although at an early stage of the venting the aerosol filtration would take place in the filter bed, this phase is relatively short and the retention of the particles takes place primarily at the surface of the filter media, e.g. fibres, grains or other porous materials. The prevailing retention effects are driven by mechanism such as blocking, interception, impaction, Brownian motion, etc.

Deep bed filter retention stages could be used as single filter media or also as post-filtration stages, specifically for fine particles.

The principle function of the solid deep bed filtration used in the filtering method is among others based on the design principle of most homogenous distribution of the retained aerosols within the different filter layers and filter stages in order to avoid aerosol accumulation in certain filter layers, which could otherwise cause local clogging of the respective layer. The filter theory shows, that the aerosol retention/adhesion on filter media, in general depends among others on aerosol sizes and types, impaction forces produced by the momentum of the flow, temperatures, etc. Thus different aerosol sizes and types, flow velocities, gas densities, temperatures, dry or temporarily wet conditions, etc., influence the retention efficiency of each filter layer and could finally cause very homogeneous or even inhomogeneous aerosol distribution inside the filter layers. These effects are of importance if filters shall be designed as high capacity aerosol filters.

6.2 Metal fibre filter with sorbent retention stage

The metal fibre filter method is designed as a deep bed filtration and is generally composed of two or more stages, consisting of a wet filtration section, including water separation, followed by a dry filtration section. Inside the dry filter stages, very efficient aerosol retention of solid and soluble aerosols takes place within the fibre surfaces. These filter stages are equipped with different fibre layers down to fine fibres of 2 to 3 μm diameter. The dry operating conditions in the dry filtering section must be reliably controlled to avoid condensation which otherwise will dissolve the retained soluble aerosol by moisture or water droplets and their eventual mobilization [42].

The amount of fission product aerosols together with the inactive ones at the given gas velocity determine how long the filtration device retains capacity before the pressure drop over the filter increases due to high aerosol load. In the worst case, the aerosol load may lead to the filter clogging [43,44,45]. Therefore, the design parameter is the total aerosol load at the given face velocity which should not cause problems associated with clogging. The filter aerosol load of deep bed filter stages shall therefore be limited to values which avoid critical clogging situation safely. The maximum filter aerosol load values shall also consider the specific behaviour of different aerosol mixtures [29], including high moisture situations, if such conditions could not be excluded inside the filter media.

Filters, in which a few micron metal fibres constitute the filtration media, have very low heat absorption capacity due to the very low mass of the media and very low heat conductivity because of high porosity. In a post venting situation with no throughput, a large amount of active aerosol particles being filtered may produce a concern due to the accumulated fission product decay heat, which might cause the temperature of the aerosol cake to be high enough for filtered volatile fission products to re-vaporize [46] or undergo partial melting (e.g., at about 250-300⁰C caesium re-vaporization can occur when about 400

W/m² heat is deposited [44]). Re-start of venting afterwards may sweep the gaseous activity into the environment. Large filter surfaces, heat transfer to the ambient rooms or dissipation of the decay heat by some engineered means (e.g. forced fan cooling such as for the EDF sand bed) or aerosol filters with integrated cooling tubes, as presented in [47] may provide a solution for avoiding critical high temperature conditions inside the filter media.

Sorbents retention stages

The second or third filtration stage downstream of scrubbers or deep bed filters utilizes a zeolite based molecular sieve impregnated with silver for elemental and organic iodine retention. The efficiency of organic iodine retention of such filter media depends among others strongly on the residence time and the super heat condition [44]. The selected technical design and the operating conditions to be expected over the entire venting period shall enable the organic iodine retention as requested. Especially sensitive process conditions needs to be verified by adequate testing, e.g. as low super heating as expected at frequent start up or at lower containment pressures and decay heat transfer.

The same concerns introduced in the previous paragraph apply to the zeolite based filtration media, if such adverse aspects are not technically resolved. However, it has to be noted that due to the high collection efficiency of the primary filter, the aerosol mass and associated decay heat load to the secondary zeolite filter is significantly reduced, if no significant re-volatilization caused transport of volatile species occurs.

6.3 Sand bed filters

By their nature, rather thick sand beds clean the surface water as it drains through the bed before reaching the ground water. The industrial application needs a compact bed with a certain surface area, resulting in an optimized face velocity. The filter method is often designed as deep bed filtration and must be operated under dry conditions. Such a filter is equipped with different layers with different grain sizes diameter.

Similar to the dry filter stages of metal fibre filters, inside the dry sand bed, aerosol retention of solid and soluble aerosols takes place at the grain surfaces. The dry operating conditions in the dry filtering section shall be reliably controlled to avoid re-dissolution of the retained soluble aerosol by moisture or water droplets [45]. To avoid such effects means can be provided to pre-heat the filter section and efficient thermal insulation of the process for minimisation of the heat losses. As long as steam condensation could be avoided, filtration efficiency for aerosol particles of about 100 was experimentally determined in France in 1980s [48].

A metallic pre-filter, located in the containment upstream of the sand bed filter then increases the total aerosol filtration efficiency (decontamination factor) to 1,000. As the metallic pre-filters are prone to clogging [49], a provision is made to by-pass the pre-filter if the pressure drop across the filter is too high. This then reduces the overall filter efficiency to > 100 after filter clogging.

The net removal of the elemental iodine is a balance between adsorption and re-vaporization in the large surface area of the sand bed filters and upstream piping. It is stated that the sand bed filter has no effective filtration capacity for organic iodides since organic iodides retention by sand bed filters was not checked through testing. This will be done as part of the MIRE and PASSAM programmes [14].

6.4 General information available in the public domain

Nuclear Air Cleaning Conferences organized and sponsored by USNRC and DOE in late 1980 and early 1990s contain many papers presented on FCVS systems' research and development programmes conducted in late 1980s [50,51]. The OECD Specialists Meeting on FCVSs held on May 1988 [1] is the first forum where regulatory requirements as well as then available/developed FCVS systems were presented.

An OECD State of the Art Report on Nuclear Aerosols [52] introduces a history of the development of filtration systems, and describes the mechanisms of filtration by different filtration medias. The report contains a description of filters generally used in containments for normal operation and design basis accidents. Furthermore, it introduces a short description of the commercial venting filters developed in 1980's and very early 1990's and as well as provides brief details of the international (ACE tests) and one national (Switzerland) experimental efforts to test filtration efficiencies of model FCVS.

An EPRI Document entitled "Technical Foundation of Reactor Safety" [53] introduces the details of the ACE tests that EPRI managed. It specifically mentions the substantial uncertainties in the measured decontamination factors in the ACE project due to the extremely low aerosol concentrations at the exit side of the filters (in the range of $\mu\text{g}/\text{m}^3$) which are at the state-of-the-art of detection. The EPRI report emphasizes that direct one-on-one comparison of the filters' performance on the basis of decontamination factors is not meaningful due to their different design bases, assumed operating conditions, and test constraints.

6.5 Filtered containment venting systems

Currently, there are different types of FCVS installed in the NPPs. Applied venting system combinations could be categorized in three different retention technologies, FCVS using i) deep sand bed filter as used in French reactors in combination with metal fiber filter pre-filtration, ii) water as the scrubber as the first filtration media and other filtration stages for droplet/fine aerosol as used by AREVA, CCI-AG and Westinghouse and iii) metal fiber filter as the aerosol filtration stage with an additional sorption stage for filtering gaseous iodine species as used by Westinghouse¹⁷.

As a result of the outcome of recent research, e.g. Phebus FP programme, and accidents, e.g., Fukushima Daiichi, designers have further developed their FCVS performance for improved filtration of gaseous iodine species, e.g., high volatile organic iodine species as well as retaining high volatility species, e.g., caesium.

It is suggested that for each single retention technologies, as well as for the entire combinations used, the relevant recommendations given in Chapter 7 "Recommended design specification for FCVS" shall be taken into account.

Highlighting of any particular FCVS technology or product in this report is simply a reflection of the fact that such a system is currently available and information has been provided by the corresponding designer or vendor. Other systems are being developed and may be commercialized. Details of systems for

¹⁷ The EFADS system used for multi-unit stations in CANDU plants is not considered here because its use is primarily for design basis events.

which information was received from vendors can be found in the Appendices. Vendors have reported certain information on own experimental programmes carried out for the development and qualifications as well as key information about performances and other important aspects with varying degree of details:

Appendix 1: French sand bed with metal fiber pre-filter FCVS;

Appendix 2: Westinghouse;

Appendix 3: CCI-AG;

Appendix 4: AREVA.

7. RECOMMENDED DESIGN SPECIFICATION FOR FILTERED CONTAINMENT VENTING SYSTEMS

Accident management measures in case of SAs are in place in most of the OECD countries regarding early sheltering and/or evacuation, together with additional protection measures of the public in some countries, e.g., providing KI tablets [54,55,56,57]. These measures should protect the public from ionizing radiation as a result of inhaling the noble gases, gaseous iodine species, and airborne aerosols as well as from the exposure by ground contamination. Additionally, avoidance of consumption of contaminated food and water is a part of the management measures.

However, the effectiveness of the protection measures depends on many factors. FCVS with a dual goal of protection of the containment against failure at pressure and reducing the activity emission into the environment is a further means to improve the land and public protection, at least in the countries where FCVS are mandated. It should be noted that, typically, noble gases are not considered to be retained in FCVS.

Most of the design specifications for FCVS regarding the loads are very much plant specific although regulatory requirements are the target objectives. The performance of FCVS regarding filtration efficiencies of activity and retaining the captured activity should fulfil the national regulatory requirements, if in place, regarding the level of emissions determining the extent of the environmental consequences or fulfilment of the safety goals. Large variations exist in the definition of the safety goals in OECD countries [54,55,56]. They range from “no definition” to ambiguous definitions such as “as low as reasonably practical”; limiting the land contamination to a few kilometres from the site boundary, and limiting the long term health effects; they may be based on cost effectiveness of the risk reductions achieved by implementation of the FCVS, etc. The newest European Union (EU) proposal for Common Risk Target (CRT) for severe nuclear accidents based on existing specifications, e.g., IAEA Safety Objectives and Principles, is introduced in [56]. The extent of land contamination is one of the greatest concerns for many safety organizations, especially for the nuclear power plant sites very close to large population centres.

Nuclear power plant types and designs, operational characteristics, and how a SA progresses determine the thermal-hydraulics processes, generation and transport of aerosols and gaseous fission products, and the thermal and radiation chemistry leading to the source term in the containment, i.e., how much activity can be transported into the FCVS and its time evolution. The design and performance of the FCVS then define the level of the emission into the environment. Again, the noble gases are an exception, as they are not expected to be retained in the FCVS.

The design specifications shall consider objectives of the FCVS design and describe general design requirements and design rules, including triggering criteria and the vent duration, vent flow rate capacity, thermal-hydraulic boundary conditions, aerosols loads and characteristics, iodine loads, avoidance of re-suspension, recommended design margins, strategy for active or passive use, hydrogen load, radiological protection of workers and the public, FCVS use for multiple units, maintenance and inspection, and other specifications including equipment and functionality classifications.

7.1 General design recommendations and design rules for FCVS

There are two main objectives of a FCVS installation: one is to maintain the containment integrity by terminating its over pressurization by relieving its atmosphere directly into the environment; the second objective is to reduce the activity emission out of the containment (e.g. airborne active aerosol particles and gaseous iodine and ruthenium species) to the environment below a certain target value to avoid large land contamination and negative health effects by providing a reliable filtered venting function.

This could be provided by use of robust and verified retention process stages and complete systems designs to enable the reliable filtering in the different operating conditions to be considered.

General design rules to be considered for selection or design of a FCVS are as follows:

- Minimize the risk of potential re-suspension or re-volatilisation of filtered contaminants, e.g. caesium and iodine compounds;
- Use high temperature & radiation resistance materials, such as metallic or ceramic materials;
- Improve combustible gas safety, particularly:
 - o Investigate whether a combustion propagation from the containment could be excluded;
 - o Reduce the hydrogen ignition probability by ensuring high self-ignition threshold temperature inside the system;
 - o Pre-heat FCVS before the initiation of the vent operation to minimize risk of reaching deflagrable hydrogen concentration due to steam condensation;
 - o Investigate whether pressure boundary design (piping and housings) can cope with the H₂ combustion loads.

Although the qualification needs for demonstration of effectiveness of the process technology is country/utility specific, in general, it could be recommended that the testing and qualification, already existing or to be performed, should demonstrate sufficient justification of the filtration and retention performance under representative operating conditions in a small but representative scale or preferably in full scale filtration sections.

In this context robustness of the retention stages should be verified for the different operating conditions (full load, partial load, hot stand-by after previous operation, etc.), e.g. that they:

- Have sufficient loading capacities for the expected aerosol quantities¹⁸ including consideration of:
 - o Aerosols size distribution (fine and large);
 - o Aerosol types (hygroscopic, non-hygroscopic, moisture, etc.) ;
- Provide reliable decay heat transfer e.g.:
 - o Pool evaporation for scrubbers;
 - o Heat transfer to installation location for solid filters;
 - o Heat transfer out of the installation room to the environment;
- Control aerosol/iodine re-vaporization/re-volatilisation effects due to:
 - o Loading of the filter;
 - o High temperatures;

¹⁸ Overload capacities can be recommended for verification purpose with an aim to reduce the probability of filter clogging.

- Wetting, applicable to solid filter types (e.g. metal fiber filter, sand bed filtration, sorbents media, etc.)
- Provide a margin of safety to the self-ignition temperature of hydrogen inside any volume/surface of the filtration system.

Further Considerations

The design of the FCVS should fulfil other specifications, mostly defined by the utilities. These specifications could include:

- Requirements regarding redundancy and/or application of single failure criteria for the FCVS system downstream of the containment isolation;
- Robustness of FCVS (piping/filter units and associated axially systems) against site specific earthquake conditions;
- No loss of functionality during i) internal or external flooding, ii) extreme temperatures at the NPP site, iii) loss of partial of all of DC and AC power, iv) loss of plant pressurized air/nitrogen supply; v) loss of plant demineralised or normal water supply;
- Avoidance of build-up sub-atmospheric pressures in the containment and un-planned back flashing of the water pool of scrubber based FCVS into the containment;
- Design or protection against projectiles that could be generated by the wind, if applicable, internal explosion, falling aircraft risks;
- Safety classes of the mechanical and electrical systems¹⁹;
- Instrumentation and local/remote control of isolation valves;
- Location of the FCVS, inlet and outlet piping layouts, thermal insulation and shielding recommendations;
- Etc.

7.2 Main design rules and design recommendations for FCVS

7.2.1 Vent initiation

The initiation of the venting may be fully passive, if no operator intervention is taken to open the isolation valves, or active if the initiation commences by the operators opening the isolation valves. Whether the initiation is active or passive may depend on the regulatory recommendations. The venting initiation is typically determined by the containment design pressure or the pressure that the operators are instructed to vent. The initiation pressure may vary significantly in the range of about 2 - 9 bar (abs) depending on the plant type, containment size, and other considerations. Therefore, conditions for initiation

¹⁹In general practice so far, the safety classification of FCVS components downstream of the containment isolation is either assigned to be 'non-classified' (NC) for some operating or licensed plants or 'important for safety or safety related system' (IPS) for the others. The definition of the safety classifications has the objective to define conditions to be considered in the design of FCVS for reliable functioning and robustness when the FCVS goes into operation. This results in defining safety standards to be used for the mechanical design of the components, their fixtures, and design parameters/loads, for example: seismic (stability, integrity or even function), radiation, pressure, temperature, etc.

and termination of FCVS operation which affect FCVS loads and the absolute emissions from FCVS, are largely varying depending on the actual FCVS performance.

The closing and possible reopening of the isolation valves in the case of multiple venting cycles is also possible for some installations as a part of the accident management procedure with a goal to limit the load to the FCVS to as low a level as possible. The need for early venting – as early as some hours – or very late venting – beyond a few days –, clearly defines the available airborne aerosol activity in the containment, which determines the fission product load to the FCVS once the venting commences. Therefore, the range of the loads defined for existing installations varies considerably, and hence, no generic recommendations can be proposed regarding the plant type and conditions leading to the venting.

Currently, operation of FCVS is generally foreseen during slow pressurization transients in the long-term for PWRs and in the medium-term for BWRs to remove decay heat in the case of loss of heat sink. In either case, the operation is integrated in the SAMG. Potential integration of FCVS operation in the EOP domain (i.e., well before the progression of the transient into substantial core melt, or during fast pressurization scenarios including core melt leading to early venting) might require establishment of the goals of FCVS operation and/or re-evaluation of the FCVS designs and their integration in the procedures for such operations. The potential goals for operation of FCVS in EOP domain may be to attempt to reduce the oxygen concentration in the containment before any substantial hydrogen release occurs or to limit the containment pressurization before any significant radioactive releases due to core degradation occurs, these with an aim to provide margins to cope with rapid pressurization, etc., In other words, older FCVSs were designed for managing long-term pressure build-up in the containment whereas new FCVSs may be designed for new and perhaps more challenging conditions, regarding early-phase accident management. More details can be found in Chapter 10.

7.2.2 Vent flow rate capacity

One of the two objectives of FCVS is to stop further pressurization in the containment once FCVS operation is initiated, regardless in passive or active mode. The vent flow rate should discharge the amount of energy corresponding to the amount of steam and non-condensable gas generated during venting and to some fraction of containment atmosphere already existing at the vent initiation. The vent flow rate determines the depressurization rate of the containment and the depressurization rate determines when the desired final containment pressure is reached. In order to utilize the low pressure coolant injection systems available at the plant site as early as possible it may be that reaching a low enough containment pressure in a relatively short time without causing any adverse effects (e.g. flashing of water inventories because of the magnitude of the depressurization rate) may be desired. Another possible advantage of an optimum containment pressure reduction strategy is to generate sufficient margin to cope with sudden energetic reactions (e.g., hydrogen burns), and avoid challenge to the containment integrity. The latter was not considered in 80's and 90's as a specification, since the concept of FCVS considered only the slow pressurization of the containment caused by the molten corium concrete interaction (MCCI).

The total flow rate was defined in 80's and 90's for most of the currently installed FCVS as the heat removal capacity associated with the decay heat, which was in the range of about 0.5 to 1% of the total decay heat, depending on the NPP type [58]. What was considered additionally was the assumption of no sudden and very high energy addition to the containment atmosphere occurring during the venting.

The FCVS inlet and outlet piping dimensions and FCVS itself should be designed to cope with the specified flow rate and its thermodynamic conditions. What perhaps needs to be considered as a part of the evaluation of the FCVS performance in conjunction with plant safety studies is whether the designed FCVS flow rate capacity would still depressurize containment even if any energetic reactions, such as hydrogen burn, etc. occurs after the vent initiation, if relevant.

7.2.3 Thermal load

The thermal energy associated with the vent flow, defined by the vent flow rate, steam fraction, as well as pressure and temperature of the containment defines, in principle, the amount of heat to be absorbed by the filtration media. In addition, the heat losses in the inlet piping and from the FCVS boundary, e.g. as vessel or filter housings, etc., have to be taken into account. The required vent flow rate, as introduced above, is determined by the thermal-hydraulic conditions in the containment, e.g., steam and non-condensable gas generation, thermal power, pressure levels at which the venting is to be initiated, and the utility recommendations on how fast the containment should be depressurized once the venting starts. The heat load may be as high as several megawatts in total.

The second source of thermal energy to the FCVS is the decay heat of the fission products accumulated in the FCVS during filtration. Depending on the plant type and accident scenarios considered to require venting, large variations can be observed in the amount of decay heat ranging from a few kW to several 100 kW.

The selected FCVS technologies should safely handle these accumulated decay heats in a passive manner in vent and in post vent situations. In post venting situations critical temperature conditions caused by decay heat release inside the retention stages have to be avoided to provide a safe margin to re-suspension or re-volatilisation of the retained substances and avoid critical conditions which could cause aerosol melting inside the retention stage at high temperatures [46,52].

Design of scrubber stages must provide sufficient passive operating times without any need of water or chemical refilling, e.g., as often selected for > 24 h.

For the heat transfer method of solid filter stages similar values shall be considered (often no time limitation is requested by the process). If such process heat is transferred to the installation rooms, the temperature limitation of the room area has to be considered.

7.2.4 Aerosol load and characteristics

Fission product aerosols are expected to dominate the filter aerosol load for early venting scenarios, and mostly non-active aerosols formed by core-concrete interaction dominate the late (a few days) stage initiated venting. A couple of 10s of kilograms to several 100 kilograms may envelope the aerosol load.

In containments, aerosols may be characterized by agglomerates composed of different fission product and inactive materials. The composition may change depending on the accident progression and timing of the venting. The size of the particles, based on many research results, may cover a wide range. The most typical size entering the containment from the reactor primary coolant system is considered to be

1-2 μm . In the containment, the particles grow due to their hygroscopicity, agglomeration, and coagulation. However, the existence of particles smaller than 1 μm cannot be excluded. Such particle mixtures could be present in dry super-heated condition as well as under saturated condition and contain water droplets.

It is generally accepted that sub-micron sized particles are the most penetrating aerosol particles. The target size distribution of the particles leaving the filter is usually not mandated by the safety authorities, perhaps due to the difficulty of measuring the size distribution after the high collection efficiency of the filter modules. Attempts have been made by the FCVS designs to reduce the emission of the most penetrating sized particles by incorporating different retention techniques as well as by utilization of fine aerosol filters.

7.2.5 Iodine load

Before the Phebus FP tests, it was generally considered that a relatively small amount of gaseous iodine (few percent of the iodine core inventory) was present in the containment and that this fraction was mostly composed of elemental iodine. Recent Phebus tests [59,60] indicated the importance of organic iodide generation, regardless whether the containment sump is at high pH, and the potential effects of B_4C from the control rods on formation of volatile iodine. The effect of silver in trapping iodine in the sump is argued [59,60] although certain investigations show that radiolytic effects may hinder [61] the desired bounding effect of silver. Recent investigations also draw attention to the formation of iodine oxides [60] in aerosol form.

There are many factors affecting the generation and release of gas phase iodine in the containment. These include the type of the reactor, timing and speciation of the iodine release into the containment from the reactor coolant system [62], radiation and thermal chemistry in containment sump (PWRs and PHWRs) or pressure suppression pools (BWRs), as well as surface reactions with the painted surfaces, to name a few. Paint and gas phase (containment air) reactions may significantly change the level of airborne iodine concentration and its speciation.

The timing of the venting initiation will determine the amount of iodine load and its characteristics. Therefore, the total iodine load to the FCVS may be as small as a few grams or as high as one kilogram depending on the factors mentioned above. This figure includes iodine both in the aerosol form and in the gas phase.

7.2.6 The autonomous time for unattended FCVS operation

Once the FCVS operation starts, it is generally desired that the operation should be passive and should need no operator intervention to sustain the FCVS performance for certain duration. *e.g.*, no water refilling requirement of water scrubbers, no solid filter cooling or installation room (filter room) cooling. This period or “autarky time” was generally defined to be “24 hours” by the safety authorities, who already mandated the FCVS in the 1980-1990 period. Since autarky time in principle defines the amount of total energy load to FCVS, the heat absorption capacity of the FCVS must be sized accordingly. In the future FCVS applications, the autarky time may be specified to be much longer if it is technically and economically feasible.

7.2.7 Hydrogen load

If not consumed by the operation of recombiners or igniters, hydrogen will flow into the FCVS inlet piping, FCVS filter and from thereon into the outlet vent piping. The potential for hydrogen deflagration in the FCVS, including its piping, depends on the amount of hydrogen and air (if still exiting at appreciable concentration for containments not initially inerted) in the vent flow as well as on the existence of air in the FCVS, i.e., whether the FCVS is already inerted or not.

During start-up, significant steam condensation can occur in systems parts that are not pre-heated (inlet and outlet piping and the retention devices themselves) and could increase the relative hydrogen and air concentrations, thereby increasing the risk of deflagration in the gas space. In some plants, the off-gas flow from FCVS is mixed with exhaust-air flow from regular NPP building ventilation systems (exhaust air system) as no fully separate vent outlet piping is installed. Such configuration can produce additional risk for hydrogen deflagration challenging the functionality of the stack.

Considering the many different scenarios, even hydrogen flame propagation from the containment into the venting system cannot be excluded. It is generally accepted that hydrogen concentration above 4% in air atmosphere can burn. The amount of energy needed for hydrogen burn is not very high. The necessity of an ignition source for the initiation of the burn is not justified based on the experience from the accidents at Fukushima. As a first general measure to reduce the ignition risk inside the system it could be proposed to avoid or minimise ignition sources inside the system, e.g., avoiding reaching self-ignition temperature, static ignition.

Therefore, the main question is what the maximum allowed hydrogen concentration is in the vent flow for the cases when i) the FCVS systems is not pre-heated or initially inerted, ii) the FCVS is initially inerted and iii) the plant off-air flow, if operational, is mixed with the gas released from the FCVS in such plant configurations. Furthermore, plant specific analyses incorporated with the FCVS model and plant hydrogen management measures should evaluate the hydrogen risk in all FCVS components including piping for reference accidents scenarios. In case the off-gas piping of the FCVS is linked to the piping of other air ventilation systems, specific analyses should be performed to evaluate the hydrogen risk in the stack.

Carbon monoxide should be treated similarly since under the prevailing conditions it may also burn. The effect of burning in the FCVS on the mechanical stability and functionality of internals and filter vessel are the aspects requiring careful evaluations.

As a protective measure it could be suggested to consider loads (dynamic and static) due to hydrogen deflagration and combustion in the design of the pressure boundary (piping and housings) for guarantying the mechanical integrity of the FCVS system. If the flame propagation from the containment shall be considered, it may be beneficial to reduce or stop flame propagation and acceleration into the FCVS in order to minimize combustion loads by introducing special features, e.g., combustion quenching and arresting inside the system by utilizing different possibilities, such as hydraulic pools (liquid seals) or packed filters (sand beds, ceramic packed bed filters), or specially designed flame arrestors.

As a further protective measure a fully separate FCVS off-gas piping can be recommended in general for the future FCVS applications.

Multiple or single long term venting operations in the long term or with the concurrent accident management measures (e.g., spraying, flooding, etc.) might cause sub-atmospheric pressures in the containment. The FCVS system design or an additional special system should eliminate the build-up of the sub-atmospheric containment pressure, however, potential hydrogen risk as a result of atmospheric air inflow into the containment either through the FCVS components (if it is possible) or directly through the special system should be evaluated.

7.2.8 Radiological protection of plant workers

Most safety authorities define the maximum permissible radiation exposure to the plant workers under accident conditions. Potential retention of activity in the inlet piping, retention of activity in the FCVS filter and some activity deposition in the outlet piping defines the radiation source from the FCVS. Incorporated in the considerations is the activity due to the presence of noble gases in the whole FCVS. Expected attenuation in scrubbers due to the water may be properly estimated by considering the reduced absorption by the high temperature water (due to lower water density) and by voids (bubbles). In general practice, retention devices are located in remote protected locations, where the radiation is being absorbed by the concrete structures surrounding the filter, or special filter rooms are designed for active shielding.

Whenever possible, implementation of pre-filters or filters inside the containment building (as already existing in some NPPs) offers the possibility of retaining a large part of the activity due to airborne active aerosols inside the containment. Thermal and aerosols loads capacities of such filters should be considered for their design.

7.2.9 Radiological protection of public

Even if the emission, except the noble gases, from a 'perfect' FCVS does not produce any land contamination and long term health effects, the public must be protected from noble gas emissions, however this can be accomplished with relatively simple accident management (sheltering). The extent of the emergency preparedness needs (evacuation, KI tablets, sheltering, etc.) should be defined based on the qualified FCVS performance for retention of aerosols and iodine in order not to exceed permitted public exposure values.

7.2.10 FCVS Systems for multiple NPPs

In the past, due mostly to economic reasons and with the assumption that only one unit is likely to experience a SA, one FCVS unit served more than one NPP block at sites with multiple NPPs. Recent Fukushima Daiichi accidents questioned this approach. In design of the FCVSs for multiples units in the future, the possibility of occurrence of SAs in multiple units should be considered.

7.2.11 Further design aspects

The following recommendations should be considered for a FCVS design.

- General considerations:

- Start of venting should terminate containment over-pressurization and should immediately initiate the depressurization at maximum allowable/specified rate at prevailing conditions: containment pressure, containment atmospheric temperature (yielding maximum superheat), vent flow gas density;
- FCVS should provide a reasonable fast depressurization rate or time duration after which the target low containment pressure is achieved by considering the steam and non-condensable gas generation rates after the initiation of the containment venting;
- Accumulation of condensed water and aerosol deposition should not cause plugging of the inlet and/or outlet piping or excessive pressure drop affecting depressurization;
- Effect of restart of venting (multiple venting) on the droplet mobilization into the deep metal fibre filter, if used, should be quantified;
- Frequency and magnitude of vibrations in FCVS components and their potential effects on the fixations of components due to pressure pulsations as a result of strong condensation of steam (e.g., direct contact condensation in cold water pool, condensation in the inlet and outlet piping (water hammer) should be considered;
- Similarly, dynamic loads produced by sudden and very large flow velocities at the initiation of the venting due to large pressure gradient between the containment and the FCVS components including pipings should be considered in their design and fixations;
- The possibility of flow of large size airborne debris, e.g. insulation materials, in the containment into the FCVS inlet piping should be avoided in order to eliminate the risk of clogging of any FCVS piping and related components or decreasing the performance of filtration medias;
- Prototypicality/applicability of the filter performance (up-scaling) as determined in experimental programmes to the full-scale plant unit should be demonstrated;
- Technical basis for the deemed efficiencies of filtration and retention processes of the individual filtration stages under the plant specific FCVS operation conditions should be provided;
- Experimental, and where applicable, analytical model results should demonstrate that the plant specific boundary conditions for the FCVS operations should be at safe distances from the technical or inherent physical/chemical limitations of the filtrations medias for the deemed performances.

- Wet scrubber and wet scrubber/metal fibre bed based filters: the followings should be considered:

- Volume of the wet scrubber section of the FCVS vessel should accommodate:
 - the maximum increase in the water level by condensation without producing any danger of flooding the droplet separator/deep bed aerosol filter;

- the maximum swell level generated by vent flow rate composed of assumed 100% non-condensable gas, without causing entry of water into the droplet separator/deep bed aerosol filter;
- maximum amount of filtered aerosol mass eventually to be settled at the bottom of the vessel in order to eliminate possibility of sparger units being buried in settled aerosols;
- continuous swell level as a result of large fraction of non-condensable gas contribution in the total vent flow or sudden swell due to fast transition from non-boiling to boiling conditions (geyser effect) should not cause droplet separator and other components in the downstream be flooded with water;
- Hydrodynamic conditions in the wet scrubber should not produce excessive droplet generation and transport which would otherwise overload the droplet separator stage beyond its capacity;
- Droplet separator and/or deep bed filter should not be plugged by aerosols or should not cause excessive pressure drop endangering the depressurization of the containment;
- Fast and substantial pressure drop in all components downstream of the water pool should not exceed the static water head at the outlet of the drain line, which otherwise has the potential to flood the droplet separator and other components positioned in the downstream side with the contaminated water;
- Fulfilment of autarky time for single long duration venting cycle or multiple venting cycles should be demonstrated;
- The sensitivity of initial pH due to incoming acid fumes (hydrochloric acid, nitrous oxides, carbon dioxide) and its evolution should be considered;
- Reduction of and timing of the reduction in concentration of reducing agents used as a function of temperature, dose and pH should be considered;
- Stable aerosol, iodine and ruthenium filtration and retention efficiency with respect to the different operation conditions should be considered.

The sensitivity of the items introduced above to other conditions should also be considered. These conditions include:

- i) the sudden increase in containment pressure during venting as a result of occurrence of certain energetic reactions (H₂ burns, FCI, core concrete interaction resulting in sudden gas generation, sump or wet-well water flashing causing sudden and large steam generation, etc.);
- ii) the changing vent gas density or vent gas composition which may alter the volumetric flow rate very strongly;
- iii) adverse conditions at which filter performance should fulfil the utility/regulatory requirements (e.g., lowest and highest vent flow rate, hottest water, lowest water level, highest aerosol/iodine load, smallest particle size, maximum accumulated dose, lowest pH, lowest concentrations of chemical additives, if used).

- **Deep bed metal fibre filters: the following should be considered:**

- Stable aerosol removal and retention efficiency with respect to the different operation conditions (flow velocity, steam-condensation/moisture, particle size and concentration);
- Prohibition of filter clogging by margin with respect to the following clogging mechanisms:

- Clogging by large surface deposition of non-soluble and mixture of soluble and non-soluble aerosol;
- Formation of aerosol cake on the 1st filter layer surface;
- Clogging due to local aerosol accumulation in a specific layer;
- Overall aerosol load capacity;
- Consideration of penalizing aerosol characteristics:
 - Hygroscopic aerosols (increases the clogging potential);
 - Significant aerosol fractions of the same size/type (risk of clogging a specific filter layer);
 - Low melting temperature of aerosols (backing of an aerosol layers could e.g. be produced due to internal heat generation inside the layer by decay heat²⁰ and would cause a non-porous filter layer with high clogging probability);
- Decay heat dissipation
 - Characterization of associated decay heat levels and dissipation;
 - Effectiveness of passive heat removal, if any, as a function of heat loads induced by the captured aerosol and non-uniform depositions in the filter bed and boundary conditions (atmospheric temperatures in the filter room/containment);
- Avoidance of re-suspension of deposited aerosols, especially during i) long operational periods and ii) multiple venting cycles at operational conditions:
 - Dissolution of soluble aerosols by water droplets and further transport due to droplet mobilization;
 - In case of implementation of passive heat removal components the risk of condensate production at partial load has to be investigated,
- Avoidance of local temperature peaks (e.g. caused by hot spots in the fiber beds due to non-uniform aerosol deposition) in respect to the following undesirable phenomena:
 - Hydrogen self-ignition;
 - Aerosol melting;
 - Effect on the metal filters and on the mechanical integrity (e.g. loss of geometry and packing density of the fibres and on the resultant filtration efficiency and pressure drop characteristics of the bed).

Finally, the sensitivity of the behaviours described above should be examined with respect to the sudden increase in containment pressure during venting due to the occurrence of certain energetic reactions (H₂ burns, FCI, core concrete interaction resulting in sudden gas generation, sump or wet-well water flashing causing sudden and large steam generation, etc.), to the changing vent gas density or vent gas composition which may alter the volumetric flow rate very strongly.

- Deep sand bed filters, the following should be considered:

Deep sand filters with metal fibre pre-filter have been incorporated in French nuclear power plants. This FCVS type is not commercially available. However, to offer a complete coverage of considerations for all existing systems in this report, a few conditions have been included, may not be a complete list, which should have been already considered in the integration phase of these filters at French nuclear power plants:

²⁰ high filter temperatures may especially occur during hot standby phases between depressurization cycles because of absence of cooling vent gas flow.

- Similar considerations as suggested for the deep bed metal fibre filters;
- Additionally, effect of steam condensation, if hot gas heating is not available or not effective, in the sand bed on i) the pressure drop which may potentially lead to clogging, ii) aerosol and gaseous iodine/ruthenium filtration and retention in the bed;
- Assurance of bypass of metallic pre-filter if overloaded.

Similar to the other venting filter concepts, sensitivity of the filter performance, especially when the pre-filter is bypassed, should be demonstrated at similar challenging boundary conditions.

- **FCVSS using sorption media for removal of iodine species, the following should be considered:**

- Effect of condensation reducing/hindering absorption of organic iodides;
- Effect of exothermic reaction due to steam/moisture intake by the molecular sieves on the absorption process (inverse thermophoresis);
- Functionality of gas expansion by the throttling device in the upstream piping alone or in combination with gas heating to reach sufficient superheating excluding the possibility of steam condensation throughout the absorbent bed;
- Effect of local beta irradiation exposure from iodine radionuclides and noble gases (Kr) on potential degradation/destruction (amorphisation) of molecular sieve based absorption media, and hence potential remobilization of iodine species;
- Effect of potential poisons, acids, organic fumes, on absorption performance;
- Effect of condensation plugging pores and hence potentially reducing absorption performance;
- Effect of hydrogen that may strip of the iodine absorbed/chemically reacted.

- **FCVSS enabling removal of gaseous ruthenium species, the following should be considered**

Experimental results from fission products release tests (Candu fuel release programmes performed at AECL, PWR fuel release programmes VERCORS and VERDON performed at CEA) highlighted significant releases of ruthenium from the fuel under conditions causing fuel oxidation by steam or air. Ruthenium is known to form volatile oxides, notably RuO_4 at low temperatures (including containment conditions). The depletion and the potential re-volatilization behaviour of the gaseous ruthenium species in the RCS and in the containment are still being investigated. However, some organizations already consider gaseous ruthenium filtration as important, because of the high radio-toxicity of its two isotopes ^{103}Ru and ^{106}Ru while some other do not. For the organization considering the ruthenium release issue as important, we may list the following considerations although currently existing filters as described in Appendices 1 to 4 do not mention about the potential capacity of existing filters for ruthenium retention. The filtration process may be different for scrubbers than those based on dry fibre filters further equipped with sorption units or scrubbers additionally equipped with special sorbent units.

For wet scrubbers, where if the filtration is pool scrubbing based removal and reduction of ruthenium tetroxide:

- Reduction of and timing of the reduction in concentration of reducing agents if used as a function of temperature, dose and pH;
- Effect of operational parameters (water level, temperature, flow rate, etc.) on the filtration process;

- Any potential heat up of substantial deposits on surface or other filtration medias for aerosols/droplets;
- Re-suspension/re-volatilization from water pool.

Sensitivity of the similar operational conditions already introduced for the wet scrubbers should be demonstrated.

If the FCVS would be equipped with additional sorption unit or the use of the existing one for the removal of gaseous iodine species would be used, we would suggest to consider the same considerations as introduced above.

- FCVSs using special media for removal of noble gases, the followings should be considered:

Currently there is no process or filtration media with potential use for FCVS applications. However, research activities might continue to develop a suitable one. We have listed a few important considerations when such processes or filtration media are to be integrated in a FCVS concept:

- Stable filtration and retention efficiency at different operation conditions (flow velocity, steam-condensation/moisture, accumulated dose, etc.);
- Retention efficiency at multiple venting cycles;
- Effect of potential poisons, acids, organic fumes, on filtration performance;
- Robustness of the filtration medium regarding hydrogen/CO deflagration;
- Long term management of the vessel(s) containing the filtration media due to internal decay heat production and activity level.

Sensitivity of the filtration and retention performance at dynamic conditions (due to occurrence of certain energetic reactions (H₂ burns, FCI, core concrete interaction resulting in sudden gas generation, sump or wet-well water flashing causing sudden and large steam generation, etc.), and to the changing vent gas density or vent gas composition which may alter the volumetric flow rate very strongly).

7.3 Recommendations for qualification of FCVS

Recommendations for qualification of FCSV behaviour and demonstration of its performance for filtration and retention of captured activity may be country/utility dependent, however, general qualification rules can be recommended addressing many different issues as introduced in 7.2.11 under general headings, 'Thermal-hydraulic behaviour', 'aerosol filtration and retention performance', 'and gaseous iodine filtration and retention performance' for each of three main classes of existing FCVS introduced in Chapter 6 "Description of different venting systems".

The qualification may mean producing proof of experimental evidences, that already exist or to be generated or additional data to be generated to justify the deemed FCVS performances under the main headings introduced above. Furthermore, analytical assessments using established and assessed methodologies should be presented to demonstrate other FCVS performances that cannot be generated by experimental efforts, such as containment depressurization characteristics. The conditions, under which the performance of the relevant FCVS system should be presented, shall represent the anticipated SA

conditions, e.g., containment pressure, temperature, gas composition, initial vent flow rate, etc., as specified by the utility, together with their variations.

Based on these tasks, extensive national and international qualification tests have been performed to investigate the efficiency of the different systems retention technologies under the relevant operating conditions, including the single retention stage technologies already implemented or foreseen to be implemented, e. g. such as scrubbers (Venturi's, and others), solid filters (deep bed filters as metal fibre or sand bed, etc.), specific iodine traps with and without cooling devices) etc.

International ACE test programme

Presumably the most extensive international test programme for Venting Systems conducted so far is the Advanced Containment Experiments (ACE) Phase A, which took place in 1989-1990 [52,53].

Companies, institutions and associations from more than 15 countries contributed to the test programme. The atmospheric tests carried out by EPRI through Westinghouse at Battelle Pacific North-West Laboratories in Richland/USA as part of the international filter comparative tests for different filter process solutions were performed under standardized test conditions. The test programme included among other dispersed mixed aerosol, hydrogen iodide (HI), fine aerosols (DOP) and re-volatilization test with pre-loaded filters.

During this independent third party testing some significant findings were observed:

- Very high retention factors for metal fiber and specific sand bed deep bed filter devices;
- Clogging/transient differential pressure increase as a result of non-uniform loading at certain filter layers;
- Scrubbers without fine aerosol filtration stage featured a high re-suspension of soluble aerosols (e.g. Cs);
- Significantly higher penetration of fine aerosols through metal fibre filters in comparison to the larger mixed aerosols;
- Etc.

General verification recommendations

In general all relevant requested design features important for the reliable FCVS operation given in chapter 6 and 7 and especially 7.1 should be verified using representative process sections and simulating the representative operating conditions.

The experimental evidences should be generated using i) preferably a full size component sections or ii) an appropriately scaled-down model of the FCVS or iii) laboratory scale setups of certain components if scaling down of such components is not possible due to the nature of the process/phenomena, especially for the chemistry aspects under the consideration of the right level of radiation and time duration, when the radiation affecting the chemistry must be considered.

Based on the experiences collected during the different test programmes, the following specific qualification testing could be recommended in general, e.g.:

- Large mixed aerosol situation (for early venting situation);

- Simulation of core-melt aerosol mixtures (including Cs, I, etc.)
- Penetrating fine aerosols;
 - Simulation of late venting situations and down-stream wet-well
- Industry standard filtration tests using DOP or DEHS;
- Re-suspension/re-entrainment tests;
 - Simulation of effects of long term operation with soluble and insoluble aerosols, ideally conducted at the respective minimum and maximum temperature and maximum pre-existing aerosol loads of the respective FCVS system;
- Simulation of high aerosol loads/ clogging tests, under dry and wet (considering water sealing effect) conditions and partial flow conditions;
- Behaviour /sensitivity of filter medias and devices under conservative operation conditions, e.g. as strong radiation conditions, extreme temperature, dry/wet peak, overload scenarios (e.g. twice the containment design pressure), etc.;
- Retention and storage capacities under the prevailing pressure and temperature operating conditions, e.g. as:
 - Atmospheric pressure;
 - Over-pressure or sliding pressure operation.

Verification of the relevant process operation conditions and determination of the retention of the sections, considering flow variations, start-up conditions and the relevant design specifics, e.g. as heat losses and heat transfer devices. If the retention method requests superheating of the gas flow, these values should be determined.

7.4 In summary

There is no generic design specification for FCVS. Design specifications for each installation are defined by the expected bounding loads (fission products, inactive aerosols, thermal load, and hydrogen) and the required performance of the FCVS as mandated by the safety authorities. In the 80's, two levels of decontamination factors were defined by the safety authorities: 1000 for the aerosols and 100 for elemental iodine. In France, the required decontamination factor for elemental iodine was 10.

Specific PSA Level 3 analyses have not been generally conducted to elaborate the effectiveness of the FCVS in the context of PSA (i) to fulfil the requirements on the level of the protection of the environment, (ii) to avoid health effects, and (iii) to guide the emergency preparedness. It seems also to be an issue, whether this analysis should be done on deterministic or probabilistic basis, especially after the Fukushima accident experience.

8. SOURCE TERM EVALUATIONS IN VIEW OF FILTERED CONTAINMENT VENTING SYSTEMS

This section provides some examples of source term evaluations which were performed in various countries in relation to the FCVS use as a SAMM. These evaluations are performed either to support the definition of FCVS design requirements in particular the expected filtration efficiencies for aerosols and gaseous iodine species or to assess radiological consequences resulting from their use for postulated SA scenarios. In some cases, radiological consequences analyses are performed to check that the FCVS comply with the required limitations of radioactive releases if any, i.e. to levels allowing efficient and manageable protection measures for the population on-site and off-site and reduced extent of land contamination.

Examples of source term evaluations presented in this chapter are limited to countries which have done specific evaluations in view of FCVS performance and provided detailed information. These source term evaluations generally involves SA integral code (such as ASTEC, MELCOR, MAAP...) calculations for "conservative" accident sequences providing the most challenging conditions in terms of "in-containment source term" (in-containment thermal-hydraulic and suspended radioactive species concentrations conditions) and in terms of filtration capacities and efficiencies. They are, in general, part of level 2 Probabilistic Safety Analysis (PSA) which are mandatory in many countries and which have not been discussed in detail here.

Some considerations regarding economic impact analyses in relation to FCVS use performed in France and the US are also reported.

8.1 General considerations for source term evaluations with FCVS

When performing source term evaluations related to the use of FCVS, radioactive releases from a deliberate filtered venting are generally compared with releases which would arise from a containment failure several hours or even days after the start of the accident, depending on the timing of venting. In other words, consequences of a controlled filtered release have to be compared with consequences of an uncontrolled release of radioactive products from the containment atmosphere. For an early venting, releases of radioactive products from the degraded fuel in the reactor core is the predominant contributor; for late venting, re-suspension processes from the RCS, from the walls and water pools in the containment and releases from melt/concrete interaction with or without water also have to be considered. An uncontrolled release would occur through an opening of the containment at an undefined location and with an undefined leakage rate.

Deliberate venting can be used to mitigate radioactive releases in case of unforeseen containment leakages (*e.g.*, containment walls and penetrations leak-tightness degradation under SA conditions) or of a containment base-mat melt-through during a SA. Moreover, it may prevent any consequence of the pressure rise in the containment resulting from the cooling of the hot corium by water. This also has to be considered in the comparison of source term evaluations.

Deliberate venting should prevent containment failure due to slow over-pressurization, allow a controlled release of the containment atmosphere and can even stop a release, if required.

A limited and delayed release of radioactive products from the containment allows for further radioactive decay and further decrease of the radioactivity in suspension in the containment atmosphere.

Existing FCVS designs cannot retain noble gases. Aerosols are initially retained by the filter with a retention factor greater than 10 or 100 or more depending on the design of the filter and on the considered accident sequence and type of aerosols to filter. This should result in a significant reduction of the extent of long term land contamination by the retention of long-period radioactive isotopes, notably Cs isotopes. The existing FCVS can also retain elemental iodine, and to a lesser extent organic iodides depending on the design, thereby further decreasing the short term radiological consequences from radioactive iodine isotopes on the population and environment.

Deliberate filtered venting capability should allow optimized releases strategies during an accident as long as radiological consequences of the venting can be properly evaluated. In this respect, best-estimate validated tools for source term evaluations, reliable prognostic source term evaluations for well-selected bounding accident scenarios, as well as SA capable instrumentation in the containment and in the vent line would be important tools to guide optimized venting strategies for the management of an accident.

8.2 In-containment source term and filters loading assessment for source term evaluations

As mentioned in Chapter 7, the amount and the nature of the material that will reach the filters of the vent line depend very much on:

- The reactor type, power, and the number of reactors to consider (when the vent line is common to two reactors or more). These parameters determine the radioactive products inventory in suspension in the containment atmosphere that may accumulate on the filter during venting (aerosols masses ranging between 10 and 100 kg, aerosols of various sizes and composition and some gaseous iodine fractions are generally considered to arrive on the filter);
- The containment size and design pressure or the venting operating pressure. These are determinant for the timing and duration of venting;
 - o It is generally considered that large containment venting (PWR, PHWR) is used to keep the containment pressure below the design pressure value for slow pressure build-up and is delayed as long as possible (usually for more than a day after the accident initiation). This delay results in a significant decay effect on the radioactive products concentrations in suspension in the containment. It is however considered in some ST sensitivity studies that accidents with pressurized reactor pressure vessel failure or with energetic events in the containment (DCH, hydrogen combustion, FCI) may result in much earlier venting, notably when the FCVS is passively actuated;
 - o For BWRs, earlier venting is generally considered than in PWRs, due to their smaller size leading to shorter-term pressure build-up and in some situations hydrogen accumulation. Earlier venting may result in a larger decay heat on the filter and possible larger amount of material than in PWRs depending on the venting flow rates and duration and on the assumed retention due to pool scrubbing for wet-well venting. However, it is considered in some source term studies that BWRs with large suppression pools or flooded reactor cavity pit may efficiently condense steam and lower the containment pressure and that venting in these cases may be delayed for more than a day as for PWRs;

- For late or long-term venting, suspended radioactive materials due to re-suspension and re-volatilization processes from the RCS, walls and water pools in the containment (notably due to some energetic events) and releases from melt/concrete interaction have to be considered and R&D programmes are on-going or foreseen to improve the assessment of the contribution from such processes;
- The accident scenario considered, including assumptions regarding the availability or recovery of safety systems used for core and containment cooling, and of the SAM measures taken, which greatly impact the vent timing and the radioactive products amount in suspension in the containment at the time of venting. Bounding scenarios usually assume prolonged failure of safety cooling systems; long-term station black-outs are typical scenarios considered in ST studies. Different bounding scenarios are often considered for the same type of reactor in source term evaluations, yielding different in-containment source terms and venting times (for instance, consideration of pressurized vessel at the rupture time or not, consideration of pressure spikes resulting from energetic events such as H₂ combustion, direct containment heating, fuel-coolant interaction);
- The fuel degradation scenario itself is generally chosen to be bounding in terms of integral radioactive releases from the fuel (complete core melts and eventually corium-concrete interaction). Considerations of the effects of oxygen potential and of control rod materials in the core and the RCS on fission products chemistry and transport can provide detailed evaluations of the nature of the species to be filtered: aerosols of different sizes and composition (all elements except iodine and, in most recent French evaluations, ruthenium for oxidizing scenarios, are considered to be present only in aerosol form; iodine is assumed to be partially in gaseous form as molecular iodine, organic iodides and in most recent French evaluations as IO_x particles resulting from radiolytic processes in the containment atmosphere). Most source term performed evaluations consider the filtration of aerosols, molecular and organic iodides;
- In-containment processes such as:
 - Pool scrubbing effects for BWR's. For BWR's, wet-well venting is preferred to dry-well venting (when available) to take advantage of the retention by scrubbing through the suppression pool. Dry-well venting is only considered as an ultimate measure when wet-well venting is not possible anymore. Source term evaluations performed for BWRs usually consider significant retention by pool scrubbing. Different models with different level of validation are used in SA codes to assess pool scrubbing retention for source term evaluation. They treat pool hydrodynamics with some level of detail but they generally do not treat in detail chemical effects;
 - Pre-filtration on metallic pre-filter for French PWRs (reduces the amount of material to be tackled by the sand bed filter);
 - Iodine reaction with paints which determines the organic iodides fraction. Formation processes depend on the type of paint used in the containment;
 - Iodine radiolytic reactions in the containment atmosphere which determines the iodine oxides particles concentrations in suspension.

To summarize, even for a given reactor type, various accident scenarios, processes and hypothesis may need to be considered to assess the in-containment source term and filters loadings, both of which are inputs for environmental source term evaluations. For instance, there is a strong variability in the venting times (a few hours or more than a day after vessel rupture) both for BWRs and PWRs which results in a strong variability of the in-containment source term to consider. Some countries (Sweden and Belgium) performed sensitivity studies assuming very early containment ventings. The definition of relevant bounding accident scenarios (in-containment thermal-hydraulics and source terms, timing and duration of venting) for source term evaluations is thus of crucial importance.

Further, considerations of the nature of the materials to be filtered differ from one country to another. For instance, evaluations performed to date in some countries focus primarily on the impact of the global reduction of aerosols releases in view of reducing long term land contamination (reduction of Cs isotopes release) even if some retention is considered for gaseous iodine species. Other countries are further concerned with the reduction of gaseous iodine species release in view of implementing appropriate measures for the protection of the population and reducing the radiological impact on the population and the environment on the short term.

The knowledge base for assessing in-containment source term resulting from fuel degradation in the reactor core and transport in the RCS for core melt-down accidents is rather extended, see for instance [13,30,63,64,65] (with Phebus FP, ISTP, OECD BIP and THAI programmes completed recently) even if programmes are still on-going for specific aspects related to iodine and ruthenium in-containment source terms (OECD STEM, BIP2 and THAI2 programmes).

The knowledge base for assessing delayed containment source term resulting from re-suspension and re-volatilization processes from the RCS, walls and water pools in the containment and releases from melt/concrete interaction is not as extended and deserves to be completed. Re-suspension and re-volatilization processes from the RCS and the containment walls, involving iodine and ruthenium species, will be examined as parts of the OECD/STEM, MIRE and PASSAM programmes.

The knowledge base to assess retention by pool-scrubbing in containments or by scrubbing FCVS systems is also rather extensive [52] (ACE, EPRI, GE, SPARTA, JAERI, LACE, UKAEA; POSEIDON, ARTIST programmes for pool scrubbing, specific testing performed for scrubbing systems) but it could be completed to more thoroughly evaluate the effects of the evolution of the pool hydrodynamics, radiological and chemical conditions with the progression of the accident. Pool scrubbing models that are implemented in major SA codes used for source term evaluations have to be further validated, notably for iodine species filtration efficiency under SA conditions. This issue will be examined as part of the MIRE and PASSAM programmes.

8.3 Assumed decontamination factors for FCVS

Emission from FCVS largely depends on FCVS design and performances. As seen earlier, three types of systems with considerable differences in terms of design are presently implemented in NPPs: water scrubbers combined with droplet separator and fine aerosols filtration, metal fibre filter combined with molecular sieve, sand bed filter combined with a metal pre-filter.

Noble gas filtration is not considered in existing filtration devices. Some discussions are underway to assess the interest of capturing noble gases on-site to avoid too high doses for interventions on the site during the accident and facilitate the accident management. The technical feasibility of such a filtration, its advantages and possible drawbacks have to be further assessed.

Aerosols decontamination factors for FCVS are usually considered to be high in source term evaluations, of the order of 1,000 in most countries (best-estimate or required values). These decontamination factors concerns all radioactive isotopes with the exception of the gaseous species (iodine, and for France, ruthenium for oxidizing scenarios).

A lower DF (DF = 10) is considered for wet-well venting in some US source term evaluations made for BWR Mark I reactor since it is assumed that suppression pool scrubbing retains in-containment most of

the aerosol (thereby already providing effectively some degree of decontamination often in the range of few tens to few hundreds) except the aerosol types that are generally not efficiently retained by filtration (sub-micron particles).

Molecular iodine DFs are assumed to lie between 10 and 100. DFs of 100 are generally assumed for scrubbing Venturi systems and DFs of 10 for other types of filtration systems.

Organic iodides DFs are assumed to be lower than molecular iodine DFs; they are given to lie in between 2.5 and 10 for some commercial systems (HSSPV type). Organic iodides are generally considered not to be retained by other filtration systems. Conservatively, it is generally considered in existing source term evaluations that organic iodides are not filtered by FCVS.

Iodine oxide aerosols considered in most recent French source term evaluations performed by IRSN are assumed to be 0.1 μm size particles (based on preliminary experimental observations). Considering the efficiency retention curves obtained from the metallic pre-filter and the sand bed filter for French FCVS, a DF of 500 for these particles was assumed in the most recent French source term evaluations. Characterizations of iodine oxides particles is underway as part of on-going research programmes (OECD/STEM) in view of providing more accurate assessment of DF values for these particles as they may dominate the in-containment iodine source term for some accident scenarios.

Gaseous ruthenium (as RuO_4) is considered in recent French source term evaluations performed by IRSN to possibly contribute significantly to the source term and short and long-term radiological consequences for oxidizing conditions. As mentioned in Chapter 7, experimental results from fission products release tests highlighted significant releases of ruthenium from the fuel under conditions causing fuel oxidation by steam or air. The depletion and the potential re-volatilization behaviour of the gaseous ruthenium species in the RCS and in the containment are still being investigated.

The knowledge base to assess retention by FCVS systems has to be completed to consider the cumulative effects of SA conditions and long term operation on the global retention of radioactive products. Also, the qualification of FCVS with respect to gaseous fission products retention, notably that of organic iodides has to be extended. These aspects will be examined as part of the on-going MIRE and PASSAM programmes [14]. These programmes also consider the testing of innovative systems (scrubbers and filters with new material and new combinations of filters, acoustic agglomerator, electrostatic precipitator) to propose new technical solutions with increased filtration efficiency for aerosols and gaseous species in view of offering the possibility to reduce further radioactive releases during a SA. They also address the possible release and filtration of ruthenium tetroxide.

8.4 Examples of source term evaluations performed

Belgium

The minimum requirements in terms of FCVS decontamination factors (DF) for aerosols, molecular iodine and organic iodides were based on a supporting source term evaluation which was performed considering:

- Integration of the FCVS in the global SA strategy (considering interaction with other SA mitigation systems such as reactor cavity pit injection and alternate containment sprays);

- Definition of SA scenarios which are representative and bounding in terms of containment pressurization rate and fission products releases. These scenarios:
 - o consider complete station blackout with the loss of all internal and external power sources leading to vessel failure;
 - o consider unavailability of steam generator auxiliary feed-water system including the turbo-pump;
 - o bound the probabilistically representative sequences leading to a SA with high containment pressure;
 - o take into account the interaction with dedicated post-stress tests measures that will enhance the strategy applied to prevent and mitigate SA (i.e. alternative mean of containment spraying and water injection into reactor cavity pit);
 - o consider situations with core relocation in dry or wet cavity, i.e. venting gases are either mainly non condensable gases or mainly steam;
- Calculation of these SA scenarios was performed with MELCOR 1.8.6;
- Calculation of the speciation of iodine in the containment and the mass of iodine released to the FCVS was performed with ASTEC/CPA code;
- Evaluations of radiological consequences (i.e., total effective dose and thyroid dose at ground level) due to the use of FCVS in the defined scenarios were assessed for a range of decontamination factors.

The noble gases which cannot be filtered yield a base dose value which cannot be decreased. The doses are calculated for increasing DF values. The minimum DF requirements are set to DF values for which the relative benefit in terms of dose limitation of considering higher DF values becomes small. Using this approach, the following minimum DF requirements were set:

- DF for aerosols: 1,000;
- DF for molecular iodine: 100;
- DF for organic iodides: 10.

It is required that these DF should be guaranteed on the whole pressure range for which the FCVS could be used and for the whole venting periods. The FCVS design shall ensure that fission products are retained permanently in the filters considering several venting periods and that the decay heat is evacuated over the long term.

France

Since the TMI2 core meltdown accident in 1979, many assessments and various research activities have been conducted in France in order to acquire a better knowledge of radiological consequences of a SA occurring on a PWR. Both underground (liquid) and atmospheric radioactive releases were considered. Because it impacts the accident consequences, efforts have been made to quantify the amount and chemical speciation of all radionuclides released in the environment through filtered or uncontrolled leakages of the containment.

In France, the utilities have the responsibility to establish the Source Terms that are associated to a facility. IRSN, acting as technical support for the French Safety Authority has nevertheless contributed significantly to develop technical basis needed for these source term evaluations.

The assessments of SAs for French reactors led to define three source terms representative of three accident categories assuming a complete core meltdown:

- S1 corresponding to accidents for which an early failure of the containment occurs leading to large early releases;
- S2 corresponding to accidents leading to large non filtered releases one day after the beginning of the accident;
- S3 corresponding to accidents with late filtered release (after 24 hours).

Historically, the source terms assessment concerned firstly the S1, S2 and S3 representative scenarios and preliminary results established in the late seventies using US assessments (essentially from the WASH 1400 report [12]) after adaptation to French reactors.

In the early eighties emergency plans for on- and off-site were formulated. For the French PWRs sites, it appeared that it would be possible to evacuate the population within a 5 km-area around the plant and to confine it up to 10 km. These protection measures have to be effective before any radioactive release.

The comparison between the consequences of these emergency measures and the postulated releases shows that the S3 source term corresponds approximately to the level of consequences that can be correctly accommodated by the off-site emergency plans. Therefore, all accidents leading to higher releases should be practically eliminated.

The ASTEC code is used by IRSN to assess the radioactive releases resulting from an accident sequence with a best-estimate approach. Sensitivity analysis can help in assessing the related uncertainties. The results obtained are used to update the initial reference source terms (S1, S2, S3) derived from the WASH 1400 report. In addition, the development of Level 2 PSAs resulted in source term calculations for a large number of scenarios.

To highlight the progresses made in the continuous re-assessment of source terms, the following key dates can be considered:

- 1970s: first evaluation of the S3 source term to provide a technical basis for off-site emergency plans;
- 1990: update of the S3 source term to take into account the implementation of the U5 procedure (FCVS);
- 2000: detailed reassessment of the S3 source term by IRSN; IRSN L2 PSA for 900 MWe PWRs including source term calculations with a similar technical basis to that in previous evaluations (new R&D knowledge was however included), but applied to a large number of scenarios;
- 2010: IRSN L2 PSA for 1 300 MWe including source term calculations using an updated technical basis (new available R&D knowledge).

The main objective of the study led by IRSN [66] in 2000 was to calculate a “reasonably” conservative S3 source term for the French 900 and 1 300 MWe PWRs. The selected accident scenario was a LB-LOCA accident with a total failure of the safety systems (safety injection and Containment Heat Removal System) and a late containment failure by over-pressurization and base-mat penetration

Available additional R&D knowledge was taken into consideration concerning the modelling of FP release during in vessel core degradation (from VERCORS and Phebus FP tests results), the modelling of MCCI, the modelling of iodine behaviour and associated chemical species in the RCS and the containment.

Some results are presented in Table 8.1. The 2000 assessment distinguishes between iodine species (particulate, gaseous organic or non-organic) and more precisely evaluates the aerosols releases. These releases are significantly lower in the reassessment mainly due to the in-containment retention modelling.

Table 8.1 shows:

- a significant decrease of release of aerosols due to an updated modelling of aerosol deposition in-containment and of FCVS filtration efficiency;
- the importance of the organic iodine contribution to the total release in the 2000 assessment. This contribution is due to the iodine interaction with containment paints;
- a higher contribution of gaseous iodine for the 1 300 MWe series; this is due to a lower quantity of silver in the control rod for these reactors; iodine is less efficiently trapped by silver in the containment sump (the pH of the sump is acidic in the scenarios considered due to the assumption of CHR5 failure).

Table 8.1 : Examples of results obtained by IRSN for the S3 source term evaluation in 2000

Fractions of initial core activity released in the environment				
Fission Product	Representative Isotope	900 MWe PWR		1 300 MWe PWR
		S3 (1990)	S3 (2000)	S3 (2000)
Noble gas	Xe ¹³³	7,5E-01	9,5E-01	9,5E-01
Particulate iodine	I ¹³¹	-	4,2E-05	4,5E-05
Gaseous iodine (I₂)	I ¹³¹	-	2,5E-07	2,2E-03
Non organic iodine (I₂ and particulate I)	I ¹³¹	3,0E-03	4,5E-05	2,2E-03
Organic iodine	I ¹³¹	5,5E-03	4,2E-03	2,2E-02
Cesium	Cs ¹³⁷	3,5E-03	3,5E-05	3,5E-05
Actinides	Pu ²³⁹	5,0E-05	9,75E-08	1,0E-07

It was nevertheless concluded that these numerical results needed some further validation due to remaining uncertainties

A second update of the source term evaluations was completed in 2010 by IRSN mainly in the context of the L2 PSA developed for the 1 300 MWe PWRs [66].

The 1 300 MWe PWRs have a two-walled containment, and a ventilation system (EDE) which extracts air continuously from the secondary building (annulus zone) in order to:

- establish and maintain a low pressure in the annulus zone (below atmospheric pressure);
- avoid direct transfer of contaminated air outside the secondary reactor building;
- ensure purification (iodine filtration and trapping) of contaminated air leaking in from the internal containment before release to the environment.

The main update of the modelling for the fission product modelling concerned:

- New modelling of the fission products release from fuel

The models were revised based on the interpretation of the VERCORS and Phebus FP programmes. New kinetics of release have been adopted for the following four classes of fission products:

- fission gases and volatile fission products: Kr, Xe, I, Cs, Br and Rb along with Te, Sb and Ag;
- semi-volatile fission products (Mo, Ba, Y and Rh);
- low-volatile fission products (Sr, Nb, Ru, La, Ce, Eu and Np) ;
- non-volatile fission products (Zr and Nd).

- New modelling of iodine behaviour

Based on experimental programmes on iodine behaviour in the RCS and the containment (Phebus FP, ISTP, OECD/BIP, CAIMAN), the main updates or new models concerned the following items:

- the fraction of gaseous iodine released from the RCS (higher values were considered based on Phebus FPT3 results);
- the production of organic iodides in the gas phase of the containment from iodine adsorbed onto paints;
- the iodine oxides (IO_x) formation and destruction in the gaseous phase by the reactions between I₂ or organic iodides with air radiolysis products.

- New modelling for the ruthenium behaviour

The amount of ruthenium produced by nuclear fission is important and increases with the fuel burn-up. Ruthenium has a high specific activity and a high radio-toxicity compared to other released fission products. Canadian and French experiments have shown that a large ruthenium release from fuel under high oxygen potential is possible (air and steam-rich scenarios). Ruthenium oxides formed at high temperature rapidly deposit on RCS surfaces and ruthenium may then be re-volatilized as ruthenium tetroxide at a later stage. That is the reason why in France (ISTP, OECD/STEM), Hungary and Finland, some experimental programmes include specific investigations on ruthenium re-volatilization from RCS surfaces. These programmes help develop knowledge and new modelling of ruthenium behaviour in the RCS and the containment.

In the assumption defined for L2 PSA source terms assessment, the gaseous form of ruthenium (ruthenium tetroxide) is considered as a non-filtered species. Even if not exactly identical, a L2 PSA scenario close to the S3 scenario (SA with a late FCVS) is compared to the re-evaluation performed in

2000 in Table 8.2. It must be underlined that the release of ruthenium tetroxide does not appear in the comparison but is considerably higher in the L2 PSA 2010 assessment for this type of scenario.

Table 8.2 : Comparison of source term calculations: L2 PSA 2010 / S3 (2000)

Fission products	Ratio L2 PSA (2010) / S3 (2000)	IRSN L2 PSA 2010 Explanation of differences
Aerosols	5	<ul style="list-style-type: none"> • Higher leak flow rate of internal containment • No ventilation of secondary containment
Particulate iodine (including iodine oxides)	1.8	<ul style="list-style-type: none"> • The new modelling of iodine oxide production in L2 PSA increases the quantity of iodine in particulate form
Gaseous iodine	0.02	<ul style="list-style-type: none"> • Gaseous iodine oxidation (production of iodine oxide in the L2 PSA modelling that was not considered before)
Organic iodine	0.01	<ul style="list-style-type: none"> • Radiolytic destruction of organic iodine in the new L2 PSA modelling
Noble gas	0.5	<ul style="list-style-type: none"> • Later containment venting in the L2 PSA scenario (activity decrease)
Ruthenium	-	<ul style="list-style-type: none"> • Higher in the L2 PSA modelling.

Because of the gaseous iodine oxidation, the radiolytic destruction of organic iodine in gaseous phase of the containment and a higher leak flow rate of internal containment, an aerosol form of iodine, iodine oxide, is one of the major parts of the iodine releases with the updated FP models. The L2 PSA deposition model of iodine oxide takes into account a higher deposition rate at the accident beginning due to agglomeration phenomenon which can occur with other particles in the containment atmosphere. In the latest phase of the accident, deposition of iodine oxide particles is slower (no agglomeration with other particles). Thus, with the updated FP models, iodine oxide is the major iodine species in the containment and the diameter of iodine oxide particles (0.1 µm) seems to coincide with the diameter for which the filtration efficiency of the FCVS is the lowest. This topic will need further consideration. It should however not be forgotten that the characteristics of iodine oxide particles are still subject to uncertainties (characterization of these particles is part of the OECD/STEM programme).

As explained above, new chemical reactions have been taken into account to model the ruthenium and iodine behaviour. Figure 8.1 presents the radiological impact of the different considered species for L2 PSA accident scenario with late containment venting. It shows that, with this new modelling, the ruthenium releases contribute significantly to the consequences due to the additional release caused by the ruthenium oxidation in the RCS (re-vaporization due to oxidation). However, this result is considered to be significantly overestimated, in particular, because it does not take into account the RuO₄ decomposition into the containment atmosphere. This is the reason why the modelling of the ruthenium behaviour in the containment has to be consolidated by on-going R&D programmes including the on-going OECD/STEM.

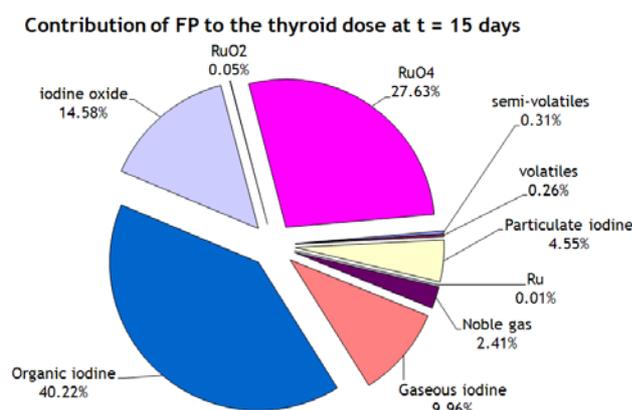


Figure 8.1: Radiological impact of the ruthenium and iodine on L2 PSA (1 300 MWe PWR) accident sequence with containment venting (and failure of active safety systems)

The filters integrity and efficiency (for radioactive gas and particles) is an important issue to limit the accident consequences. Both the filters of the annulus ventilation system and the filters of the FCVS are concerned. Increase of the filtration efficiency is desirable.

Sweden

Source term evaluations are performed as part of accident analyses and reported in Safety Analysis Reports. In addition to calculations of basic design scenarios, i.e. station blackout, sensitivity studies are performed where a number of accident sequences leading to early venting are analysed, for instance actuation of the system, via bursting of the rupture disc, at the time of melt ejection from the reactor pressure vessel.

For the postulated event with loss of all AC power in BWRs, the pressure in the containment will not reach the design pressure within 8 hours and therefore the actuation of independent containment spray at this time will significantly delay the over-pressurization of the containment for more than 24 hours. At a certain level of pressure, the FCVS is assumed to be actuated manually, but in the absence of manual actions, the FCVS will be automatically actuated through the bursting of a rupture disk when pressure in the containment exceeds the rupture disk set point

In the design scenario for PWRs, pressure in the containment will reach the design limit pressure typically after 4-6 hours. Since no manual actions are credited during the first 8 hours, the FCVS will be automatically actuated through the bursting of the rupture disk and will reduce the containment pressure through filtered venting. After 8 hours the independent containment spray is available which will reduce the containment pressure and thus reduce the transport of radioactive materials to the scrubber

In the source term evaluation analyses, the decontamination factor (DF) for the filters is assumed to be 500 for BWRs (design DF is 100) and 1,500 for PWRs (design DF is 500). These “best estimate” DFs are based on experiments and analysis of Multi Venturi Scrubber systems performed in the 80s (DFs measured in testing were much higher). The removal of aerosols in the containment by various deposition mechanisms is calculated by the MAAP or MELCOR code.

Evaluations are made to check that the requirement to mitigate the design scenario so that the releases, except noble gases, shall be limited to maximum 0.1 % of the reactor core content of ^{134}Cs and ^{137}Cs in a reactor core of 1800 MW thermal power is fulfilled.

United States

The systematic approach for regulatory assessment of accident management options, followed by NRC, consists of: (1) selection of dominant accident sequences based on probabilistic risk analysis and informed by relevant past studies; (2) accident source term calculations using NRC's accident analysis code MELCOR, taking into account various accident prevention and mitigation measures; (3) consequence calculations (health consequence and offsite property damage) using the MELCOR Accident Consequence Code System, Version 2 (MACCS2); (4) assessment of risk (and risk reduction) corresponding to various prevention and mitigation measures; and (5) regulatory cost-benefit analysis of various accident management options including FCVS. The industry has a similar approach, in particular, for source term and consequence calculations.

The above approach was used by NRC to support regulatory cost-benefit assessment of FCVS for a boiling water reactor (BWR) plant with a Mark I containment, and to form the technical basis in support of the recommendation for the containment filtered venting strategy. In particular, NRC performed a large number of source terms and consequence calculations for a wide spectrum of selected accident scenarios. The calculated consequence results were used to perform cost-benefit analyses of various accident prevention and mitigation options. The results are documented in detail in SECY-12-0157 [22]. EPRI, on behalf of the industry, also performed source terms analysis using MAAP [67].

The selection of accident scenarios considered for MELCOR analysis was informed by the recent state-of-the-art reactor consequence analysis or SOARCA [68] and also by the recent Fukushima study [69]. Specifically, two accident scenarios were selected for MELCOR analysis: long-term station blackout (LTSBO) and short-term station blackout (STSBO) as defined in the SOARCA study, both initiated by a seismic event. The LTSBO results in a loss of offsite power (LOOP), failure of onsite power, and failure of the grid. All systems dependent on alternating current (AC) power are unavailable. The turbine-driven reactor core injection cooling (RCIC) system is available for a finite duration after the accident and for the current study it is assumed that the high-pressure coolant injection (HPCI) system is not available. For STSBO, it is further assumed that the RCIC is initially not available.

The primary focus was on the LTSBO scenario and a large number of MELCOR cases were run simulating different possible outcomes (e.g., containment failure by over-pressurization, dry-well liner melt-through, and main steam line rupture). These cases considered RCIC operation and a combination of one or more mitigation features such as core spray, containment spray, and venting. The cases with venting included the option of vent cycling.

Table 8.3 below summarizes a few selected LTSBO cases. All cases reported in the table were run for a 48-hour transient duration.

Table 8.3: Matrix of Selected MELCOR Cases for Containment Venting Study

MELCOR Case Description (LTSBO)	Case 2	Case 3	Case 6	Case 7	Case 14	Case 15
RCIC with 16-hour duration	X	X	X	X	X	X
Wet-well venting at 60 psig, vent open		X		X		
Wet-well vent cycling, open at 60 psig, close at 45 psig						X
Core spray after RPV lower head failure			X	X		
Drywell spray at 24 hours					X	X

MELCOR is an integrated system-level computer code for modeling progression of SAs (i.e., accidents resulting in severe core damage, possibly melting of the core, leading to release of radioactivity) in nuclear power reactors. The scope of accident progression modeling includes:

- core uncover (due to loss of coolant), fuel heat-up, candling, clad ballooning, clad oxidation, fuel degradation (loss of geometry) and core material melting and relocation;
- heat-up of reactor vessel lower head from relocated core materials, subsequent failure of the lower head from thermal and mechanical loading, and release of molten core debris to the reactor cavity;
- molten core-concrete interaction in the reactor cavity and ensuing aerosol generation;
- in-vessel and ex-vessel hydrogen production, transport, and combustion;
- fission product (aerosol and vapour) release from the core, transport and deposition in the containment, and ultimate release into the environment; and
- containment loading from high-pressure melt ejection, over-pressurization from non-condensable gas generation including hydrogen, or other mechanisms (e.g., hydrogen burning, thermal attack of liner), and subsequent failure of the containment.

Of particular interest for the FCVS study is the assessment of source terms (i.e., timing, quantities, and chemical/isotopic forms of fission product species which contribute largely to health consequences and land contamination). Table 8.4 below summarizes MELCOR results for the selected cases in table 8.3.

Table 8.4: Selected MELCOR Results

Selected MELCOR Results	Case 2	Case 3	Case 6	Case 7	Case 14	Case 15
Debris mass ejected (1,000 kg)	286	270	255	302	267	257
In-vessel hydrogen generated (kg-mole)	525	600	500	600	614	650
Ex-vessel hydrogen generated (kg-mole)	461	708	276	333	327	276
Other non-condensable generated (kg-mole)	541	845	323	390	383	270
Iodine release fraction at 48 hrs.	2.00E-02	2.81E-02	1.70E-02	2.37E-02	5.41E-03	1.86E-02
Caesium release fraction at 48 hrs.	1.32E-02	4.59E-03	3.76E-03	3.40E-03	1.12E-03	3.01E-03

The MELCOR code provides input to MACCS2 for the analysis of radioactive material dispersion in the environment and the consequences of this dispersion. The code models atmospheric transport and dispersion, emergency response actions, exposure pathways, health effects, and economic costs. MACCS2 estimates consequences in four steps:

- (1) Atmospheric transport and deposition onto land and water bodies;
- (2) The estimated exposures and health effects for up to 7 days following the beginning of release (early phase);
- (3) The estimated exposures and health effects during an intermediate time period of up to one year (intermediate phase);
- (4) The estimated long-term (e.g., 50 years) exposures and health effects (late-phase model).

The assessment of offsite property damage in terms of contaminated land and economic consequences uses all four parts of the modelling. Land areas contaminated above a threshold level can be calculated in several ways. The simplest is to report land areas that exceed activity levels per unit area for one or more isotopes. This is the approach used to report contaminated areas following the Chernobyl accident (i.e., land areas exceeding threshold levels of ¹³⁷Cs activity were reported). Currently, MACCS2 estimates such areas based on the Gaussian plume segment model for atmospheric transport and deposition.

The results of the consequence analyses are presented in terms of risks to the public, population dose, land contamination, and economic costs for each of the cases. All consequence results are presented as conditional consequences (i.e., assuming that the accident occurs), and show the risks to individuals as a result of the accident (i.e., LCF risk per event or prompt-fatality risk per event). Table 8.5 summarizes the consequence results obtained by MACCS2.

Table 8.5: Summary of MACCS2 Results for the 50-mile Radial Distance

Consequence Attribute	Case 2	Case 3 Unfiltered <i>Filtered DF = 10</i>	Case 6	Case 7 Unfiltered <i>Filtered DF = 10</i>	Case 14	Case 15 Unfiltered <i>Filtered DF = 10</i>
Population dose @ 50-mile radius per event (rem)	580,000	460,000 <i>180,000</i>	310,000	240,000 <i>37,000</i>	86,000	280,000 <i>43,000</i>
LCF risk @ 50-mile radius per event	4.8×10^{-5}	3.3×10^{-5} <i>1.3×10^{-5}</i>	2.5×10^{-5}	1.6×10^{-5} <i>2.2×10^{-6}</i>	6.4×10^{-6}	2.1×10^{-5} <i>2.7×10^{-6}</i>
Contaminated area (km ²) exceeding 15 $\mu\text{Ci}/\text{m}^2$ per event	280	54 <i>8</i>	72	34 <i>0.4</i>	10	28 <i>0.3</i>
Total economic cost @ 50-mile radius per event (\$M-2005)	1,900	1,700 <i>270</i>	850	480 <i>18</i>	120	590 <i>20</i>

Neither MELCOR nor MACCS2 mechanistically model the decontamination effect of an external filter for the wet-well or dry-well vent path. Instead, a prescribed DF value is assigned to represent the external filter. This DF is applied to the portion of the environmental source term released that would flow through the filtered vent and is not a noble gas.

For consequence calculations, a decontamination factor (DF) of 10 is assumed for an external filter downstream of the wet-well. As mentioned earlier, this low DF value accounts for the fact that suppression pool scrubbing retains most of the aerosol except the aerosol types that are generally not efficiently retained by filtration (sub-micron particles).

The relationship between the DF value and the reduction in environmental consequence (e.g., land contamination) is nonlinear. A DF of 10 does not usually translate to a 10-fold reduction in consequence. Depending on the accident sequence under consideration and the consequence metric being evaluated, the effect of a DF can be modest to significant.

Generally speaking, the MELCOR/MACCS2 analyses show the beneficial effect of an external filter with regard to population dose, LCF risk, land contamination, and economic consequence. To put the source term analysis in context, the MELCOR/MACCS2 results were used to estimate risk reduction achievable (relative to a baseline case) when considering various containment vent filtration and accident management strategies. The baseline case here refers to the reliable hardened vent per the order EA-12-050, whereas the options refer to the SA capable hardened vent without and with external filters. The results of risk analysis showed that the implementation of SA capable vent and other accident management measures, supplemented by an external filter, contribute to a net reduction of risk. However, the relative contribution of an external filter to overall risk reduction is modest when the filter is implemented at the wet-well vent, whereas the contribution is quite significant when the filter is implemented at the dry-well vent.

The work summarized herein was performed, as already mentioned elsewhere, to form the technical basis for SECY-12-0157. The Commission subsequently directed the NRC staff to implement the SA capable vent option in the short term which resulted in the order EA-13-109, while performing additional analysis to support a future rulemaking option for containment vent filtration strategy. This additional analysis of source terms, consequence, and risk is currently in progress.

Canada, Finland, Germany, Korea, Switzerland

Source term evaluations were performed assuming FCVS functioning according to their design specifications (including required DFs). These evaluations were generally performed to define or check minimum requirements in terms of FCVS DF. No detailed information was provided on these evaluations.

Other countries

No source term evaluations related to FCVS were performed to date in countries that are presently considering the implementation of FCVS. Evaluations are generally planned to help in the definition of the FCVS design requirements, notably DFs values.

8.5 Summary and identified recommendations in relation to source term evaluations for FCVS

Source term evaluations are factored into accident analysis in different countries. It is recognized that source term evaluations are important for FCVS regulatory assessment and as a guide for design and operation requirement of FCVS.

For a given reactor type, different bounding accident scenarios with different venting times and in-containment source terms are considered for environment source term evaluations using FCVS. The definition of relevant bounding scenarios for each type of reactor appears to be of crucial importance (bounding venting times, bounding in-containment source term).

Despite variability in bounding scenarios, consequence analyses show large reductions of radiological consequences on the short (health effect) and long term (land contamination) using FCVS systems. This is exemplified by recent comparative source term evaluations lead in France for a S2 (unfiltered release at 24 hours) and S3 (filtered release at 24 hours) scenarios for PWRs and in the US for unfiltered and filtered release scenarios for Mark I BWRs.

Economic analyses performed recently both in France [70] and in the US (Table 8.5) also show a significant reduction of the costs due to the radiological impact of the accident when considering the use of FCVS (reduction of perimeters of contaminated land). Even if French and American costs evaluations for the accident differ by about an order of magnitude (estimated to be ten times higher in France when comparing only the radiological costs; this difference is not surprising since the studies concern different reactor types), both studies conclude that the use of FCVS systems would reduce the cost due to radiological consequences by about an order of magnitude.

In most countries, calculated reduction of radiological impacts appears sufficient to consider that FCVS are beneficial for SAM. In the cost/benefits studies performed in the US, these benefits are offset by the low probability associated with accidents where the FCV option would be useful.

Present environment source term evaluations for FCVS essentially treat Cs aerosols (long term effects, ground contamination) and gaseous molecular iodine (short term effects, health effects) in assessing the effects of filtration. Recent R&D results indicate that other species that may significantly contribute to the short and long term radiological consequences have to be further considered for FCVS filtration: organic iodides (RI), iodine oxides particles resulting from air radiolysis processes (IO_x), and possibly gaseous ruthenium tetroxide (RuO₄). If RI are already partly filtered by some existing systems,

improvement of FCVS filtration efficiency for such compounds may still be desirable to reduce short term radiological consequences.

Despite large attenuation of Cs isotopes release when using FCVS (considered DF of 1,000), consequence analyses show it may be still desirable to increase the efficiency of radioactive aerosol filtration by FCVS for SA conditions and for all classes of aerosols. Preliminary R&D results suggest that IOx particles are sub-micron particles. DFs larger than 1,000 for all classes of aerosols could be a target value.

The effects of the evolution of conditions in FCVS during a SA on the filtration efficiency and possible re-suspension/re-volatilization from deposits in the filters have to be further assessed (evolution of thermal-hydraulic, chemical and dose rate conditions) both for liquid and solid filtration technologies.

Progress seems still necessary to improve in-containment source term evaluations with respect to delayed in-containment source term (re-volatilization and re-suspension in RCS and containment) and attenuation by in-containment pool scrubbing during a SA (further consideration of chemistry in the pool in SA conditions).

The interest of developing systems for rare gases retention could be further assessed even if rare gases are not considered in consequence analysis. Rare gases retention may be of interest to facilitate short-term on-site interventions.

SA capable instrumentation in the containment and in the vent line (e.g. measurement of radioactive species concentrations in suspension in the containment and in the exhaust of the FCVS line) could be developed to guide, in parallel to reference environment source term evaluations and inform FCVS release strategies.

9. SUMMARY OF BENEFITS EXPECTED FROM FILTERED CONTAINMENT VENTING AND POSSIBLE ADVERSE ASPECTS

9.1 Purpose of filtered containment venting

The overarching goal of the FCVS is to prevent, in the event of a SA, overpressure failure of the containment and keep the containment pressure below its design value while minimizing radioactivity releases to the environment. This is achieved by venting in a controlled manner through a filtration system to prevent large releases that could occur from either unfiltered venting or containment failure. In addition, a FCVS can be used in some cases as an additional means of hydrogen risk reduction and, in the case of smaller BWR containments, of decay heat removal. Thus, an FCVS reinforces the function of nuclear containment by minimizing radiological health consequences and preventing large amounts of land contamination. That said, it is worth emphasizing that the FCVS is not the only available system in NPPs to ensure containment integrity in the event of a SA.

Following the Fukushima accident, there is renewed interest in some countries in evaluating the necessity and the consequences of installing engineered filters for use during SAs. In particular, studies and analysis are ongoing in the United States, as part of the regulatory assessment, to determine whether FCV is indeed a viable cost-beneficial mitigation strategy. Such an analysis will differentiate between densely and sparsely populated areas in which plants are located. Each country should draw its own conclusions about the cost-benefit ratio of a FCVS taking account of the specific characteristics of individual sites.

The expected benefits and possible adverse aspects, discussed in the next two sections below, should be analysed as part of the decision-making process to install a FCVS at a particular nuclear power station and within a particular country's regulatory framework. Ultimately, though, FCV is a viable technology which can help mitigate the consequences of a SA and this option should be considered when developing a SAM strategy.

9.2 Expected benefits

Overpressure protection and confinement of radioactivity

Venting is an effective mitigation measure to avoid containment failure due to over-pressurization in the case of a core-melt accident. Venting can also reduce the likelihood of penetration failure and containment leakage. An integrated FCVS offers a clear advantage as a means of reducing the radioactivity release to the environment. In some countries, this consideration alone appears to be sufficient to formulate a recommendation for implementing a FCVS with an external filter as an essential feature.

Hydrogen risk reduction

Venting the containment in a timely manner can reduce the migration of hydrogen to the reactor building or any other adjacent areas. This, in turn, can reduce the risk of any hydrogen explosion as reportedly occurred in Fukushima. Note that the extent of hydrogen migration will depend on pressure reduction due to venting as well as on the effluent flow rate. A high effluent flow rate, while reducing the hydrogen build-up in the reactor building, may temporarily lead to an increase in hydrogen concentration in the vent line, possibly increasing the risk of hydrogen combustion in the line.

BWR-specific benefits

Early venting prior to core damage is being explored as a means to keeping the RCIC available for a longer period of time in BWRs with a Mark I containment to optimize the operation of the reactor core injection cooling (RCIC). With the RCIC running for an extended period, core degradation and vessel failure can be delayed.

Venting can also remove decay heat more effectively than other methods of heat removal from smaller BWR containments. Some BWRs have the provision for dry-well and wet-well venting. Generally, for BWRs, wet-well venting with the suppression pool temperature below saturation is the preferred option when there is a breach of the RCS because it provides an additional benefit of scrubbing fission products. Prior to breaching of the RCS, dry-well venting may provide better heat removal from the upper dry-well and be of benefit for dry-well head seal leakage concerns.

Venting steam from a boiling wet-well in a BWR accident with complete loss of heat removal from the wet-well is another benefit. In German BWRs, such a strategy is implemented for BDBA before any core degradation is reached.

Venting before failure of the reactor pressure vessel is another strategy that may have some associated benefits, particularly for BWRs. Such a strategy would concern accident scenarios with no initial or induced break in the RCS. Nevertheless, it seems challenging at this time to predict with any accuracy the timing of vessel rupture which can occur quite rapidly after core melt.

Radiological consequences and accident management

The most important benefit of a FCVS with respect to radiological consequences, when compared to a hardened vent only, lies in the fact that a FCVS can significantly reduce such consequences – both on-site and off-site - in the case of a disaster at a nuclear power plant. In particular, caesium and iodine releases can be expected to be much less with filtration when compared to a situation with unfiltered releases. Thus, a FCVS can facilitate on-site accident management as well as limit radiological impact on the population in the short term. FCV can also reduce the extent of land contamination and perhaps simplify treatment of contaminated land in the long term. In this way, installation of FCVSs may also lead to higher public acceptance of nuclear power plants.

Filtration inside the containment itself can be of high value by limiting to a large extent the amount of radioactive aerosols exiting the containment. In BWRs, wet-well venting and in other reactors, pre-filters or filters placed inside the containment (e.g., for French reactors and some of the FCVSs for German reactors) offer this possibility. When available, such filtration would reduce the challenge to any external

filtration placed downstream in terms of aerosols and reduce out-of-containment dose loadings even if the filtration is coarse.

9.3 Possible adverse effects

Unintended release of radioactivity

The FCVS hardware and procedures (i.e., operator actions) can have the desired effects only if the systems are designed and operated as intended. For example, timing of and criteria for vent opening are important with regard to the potential and mode of containment failure. Delayed venting at high containment pressure (e.g., in excess of design pressure or primary containment pressure limit) may increase the likelihood of penetration failure and for BWRs, head flange leakage. Furthermore, delayed venting may fail to prevent more catastrophic containment failure. Early venting at low containment pressure, on the other hand, may lead to unintended early release of radioactivity prior to implementing adequate protection measures for the population. Therefore, for radiological consequences to remain acceptable, early venting should be considered only when the radioactivity levels in the containment are low enough (i.e., prior to any significant core degradation) and/or if the FCVS is adequately qualified for efficient reduction of releases.

Potential for containment function impairment

Venting can create, in the event the vent cannot be closed, a negative or back pressure in the containment which may lead to structural instabilities or inflow of air. Moreover, venting may have the unintended effect of de-inerting an otherwise inert containment as the inert gas will be purged in the process as well. The combined effect of de-inerting the containment and condensation of steam is likely to create a condition that is very conducive to hydrogen combustion if there is inflow of air due to vent opening.

Qualification against external events

An external filtering device should be qualified for relevant external events dependent on the NPP site location and the relevant specific risks there. A system which is not seismically rugged may contribute to the risk of containment impairment in the case of an earthquake. Likewise, a system which is not designed for and/or protected from other external hazards such as high flood level, external fire, or extreme meteorological events, may contribute to the risk of containment impairment in the case of such hazards occurring.

Hydrogen risk

Hydrogen in the FCVS (vent piping, stack, etc.), if present in sufficient quantity, can form combustible mixtures in the presence of oxygen (due to air ingress from vent actuation). This situation can be aggravated by steam condensation (if the vent line is cold) and pose a risk when a FCVS has not been initially designed to withstand the dynamic loadings that would result from hydrogen combustion (if the latter has not been excluded by other means). If a common vent line is used, as in some German PWRs

where the vent line ends in a common collecting space in the building exhaust system or in the entrance to the chimney, the possibility of hydrogen combustion there cannot be excluded and hence, should be analysed.

Operation mode and operator exposure

The requirement that the venting procedure should be terminated as foreseen in the permitted procedure raises the question of whether an automatic start of the venting procedure by failure of a rupture disc at a certain containment pressure level is the preferred option. Such an automatic start would involve an automatic termination or manual termination. The automatic termination seems to be highly risky in the case of a SA as instrumentation logic and power sources for such action may not be available. This may lead to a long-lasting and uncontrolled open containment which has to be avoided at all cost. On the other hand, the Fukushima accidents showed that manual operation of the FCVS may be required in a prolonged SBO accident. The mandatory requirement for manual termination would, in turn, require physical accessibility of equipment and proper protection of the operators.

The operation of FCVS undoubtedly puts an additional burden on the operators, in particular, if the system has to be operated in a manual mode. Furthermore, the operation of a FCVS may have an impact on the operation of other important safety systems, though ideally these two operations should be independent of each other.

Filter loading

There are different vent procedures under discussion, continuous or intermittent venting, and venting systems in some countries capable of operating up to 72 hours. Also, depending on the reactor type, accident scenario and SAM procedures, the venting can be started a few hours to more than a day after the reactor vessel ruptures. Early and/or long term venting might lead to some constraints for the filters, related to the risk of overloading the filtering media with radioactive products which can diminish the filtering efficiency and reduce the venting rate.

10. IDENTIFICATION OF POSSIBLE IMPROVEMENTS OF CONTAINMENT VENTING SYSTEMS/STRATEGIES

10.1 Venting strategies

Venting strategies considered in various countries have shown different timings for vent initiation (a few hours up to a few tens of hours after reactor vessel rupture) and a range of pressures at initiation (between 2 and 9 bars) depending on the reactor type, the containment type and size, and SAM procedure. One challenge to implementing such a strategy is to be able to realistically assess the actual margin to containment failure. Factors that should be considered in such an assessment include penetration failure in SA conditions, leakage through concrete walls at pressures above the design pressure, opening (often reversible) of flanges, hatches, and other structural components, and the possibility of sudden pressure escalation due to energetic events in the containment.

If there is no early challenge to containment integrity, it is desirable to maintain the containment closed as long as possible to maximize the benefit from activity deposition in the containment and the extra time it offers for evacuation and off-site protection measures. The success of such a strategy will depend on the effectiveness of long-term accident management actions based on outside means (e.g., portable diesel generators to start up safety systems, etc.). Learning from the Fukushima accident, incorporation of a pressure limit – e.g. slightly above the design pressure of the containment - should be considered at which the filtered venting starts automatically.

If venting initiation is required early during the accident, it has implications for aerosol loading of the filter since activity deposition in the containment would be limited in the early period. It is desirable, whenever possible, to use some kind of pre-filtration inside the containment to limit the amount of radioactivity exiting the containment (e.g., wet-well venting in BWRs and pre-filtration or filtration inside the containment for dry containment venting). In this respect, it is important to ensure that the FCVS effectiveness is not compromised by, for instance, clogging of the filter. Also, measures are needed to maintain the aerosols within the filters after the FCVS use is terminated.

Generally, to determine the efficacy of the venting strategies, it is important to analyse, in a systematic manner the accident progression in the reactor pressure vessel, containment, reactor building, and all release pathways, taking into account the mitigative effects of venting. The main parameters to be analysed are thermal hydraulics (temperature, pressure, fluid level, etc.), condensable and incondensable gas inventories, and fission-product distribution in various volumes. Recent documented analyses in the U.S. for BWRs with a Mark I containment have shown an obvious impact of the vent process on the accident progression as well as the mode and timing of failure.

It is understood that venting should only be initiated if, at the time of opening, there are no challenging conditions for the system termination that might not be overcome. Then there is the question of whether manual venting operation is acceptable at all due to the risk to the workers. There should be provisions to reduce these risks (dose, high temperature, etc.) as much as possible. These provisions

include radiological protections, operations from a remote location, and limited duration maintenance operations over a prolonged period. The option of having redundant systems to make the venting termination more reliable should be investigated.

Presently it seems nearly impossible to exclude the risk of hydrogen combustion in all possible conceivable conditions occurring in the course of a SA, but efforts should be made to minimize such risk as far as possible. In the case of early venting, the risk of hydrogen combustion in the FCVS can be high for de-inerted containments or containments that may not be inerted to start with. New systems should be designed and operated so as to ensure that flammability limits of gases passing through the system are not reached; on the other hand, they could be designed to withstand dynamic loadings resulting from hydrogen combustion. Specific solutions already exist in some plants to reduce the risk, e.g., inerting of the vent line (requiring inert gas supply), heating of the line to prevent steam condensation (requiring power supply), or a separate exhaust line up to the exit of the chimney. If recombiners are installed in the containment, the risk of hydrogen combustion in the FCVS will be reduced as less oxygen would be available. Also, the vents can be designed to minimize the potential for hydrogen gas migration and ingress into the reactor building or other buildings. It may be desirable to avoid sharing a FCVS between two or more units.

Finally, to reduce the risk of failure of the overall venting process, it should be investigated if there is an advantage implementing more than one vent line (possibly connected to different containment locations). In general, redundancy of such systems should be further assessed.

10.2 Filter systems

With respect to the filter performance, more than 99.9 % (DF > 1,000) retention for aerosols and 99 % (DF > 100) for molecular iodine was considered sufficient when the first FCVS were implemented in the 1980s and 90s (such DF values were set as target values by some regulators). With the possible evolutions of FCV strategies (notably if FCVS are considered for the management of early phases of an accident, with fast pressurization as well, and for prolonged use in long-term phases of an accident), and given the wish in some countries to further reduce an accident's radiological consequences (see WENRA recommendations for new reactors), higher DFs may be desirable (DF > 10,000 for aerosols). Existing technologies may already perform to such levels.

However, there is a concern that the filter efficiencies of certain filter types as quoted by filter vendors may not be independently validated by data, notably for a wide range of aerosol sizes and for a wide range of thermal loadings. In particular, performance of existing and innovative filter technologies in more challenging conditions needs to be validated with regard to their claimed efficiency.

Retention of organic iodine compounds is less than 80 % for some existing systems (DF < 5), and there is an interest in having higher organic-iodide retention since, as recent research results have shown, these compounds may dominate the in-containment gaseous iodine inventory. There is undoubtedly a lack of qualification of the filtration technologies for these compounds. Work is in progress in the MIRE/PASSAM projects to gain additional knowledge on organic iodide filtration. In addition to investigating potential enhancement of existing filtration systems, the PASSAM project is also looking at new and innovative filtration technologies with regard to their efficiencies.

Another perceived deficiency of the current filtering technology relates to filtration of noble gases which could be beneficial both in easing on-site interventions and in reducing population and environment exposure during the accident. Some investigations were performed on the adsorption of noble gases on

different filtering media (see for instance [71]). There is presently no requirement concerning noble gases retention. It might, however, be of interest to investigate further potential retention of these species for various filtration technologies. The benefit of reducing their releases to the environment has, however, to be balanced with drawbacks that could result on-site from radioactivity accumulation in the system designed for their retention.

In core-melt accidents when conditions are oxidizing (where pure steam can be considered sufficiently oxidizing here), ruthenium re-volatilization from RCS deposits could result in significant gaseous ruthenium tetroxide fractions inside the containment which may contribute significantly to radiological consequences. Current filtration technology does not appear to provide the capability to filter ruthenium and its various chemical forms. Work is in progress in OECD/STEM programme to gain knowledge on ruthenium re-vaporization and in MIRE/PASSAM to gain knowledge on gaseous ruthenium tetroxide filtration [14].

The impact of high dose rates and thermal loads on the filter effectiveness in the course of the venting process needs careful evaluation. The impact of certain energetic events that could occur in the containment on the filter effectiveness also requires careful evaluation. In particular, detailed phenomena concerning migration of radioactive species for high loadings and prolonged or intermittent use in SA conditions should be investigated.

10.3 Others

Efforts should be placed to harden the availability of power sources for FCVS operation. These power sources could then require implementation with diverse redundancy.

For effective accident management, it is desirable to have a specific instrumentation dedicated to measurements of hydrogen, radioactive aerosols and iodine concentrations in the containment and in the FCVS exhaust line. Such instrumentation must provide the operators and decision makers with reliable information even in the worst conceivable conditions.

Finally, it is recommended that the FCVS be seismically qualified so that it does not contribute to the risk of containment impairment in the event of an earthquake. Also, provisions should be made so that it does not threaten the proper functioning of other important safety systems in such situations.

11. CONCLUDING REMARKS

The main objectives of the present Status Report on FCVSs in OECD countries, as defined by WGAMA, were to:

- Compile the status on the implementation of FCVS for Light Water (both boiling water (BWR) and pressurized water (PWR) types) and Pressurized Heavy Water Reactors (PHWR) including systems already installed and contemplated;
- Describe the national requirements on the implementation of venting systems and the filtering strategies;
- Describe the different filtered venting systems available as well as their performance;
- Describe design specifications for FCVS;
- Discuss possible disadvantages of containment venting, e.g., inadvertent opening, risk of under-pressure;
- Identify, from an accident management perspective, if there is room for improvements to both the hardware and the qualification of the systems; and
- Summarize the status of containment venting strategies as currently implemented, especially the strategies that require interfacing with decision-making processes to actuate containment venting.

The present Status Report fulfils most of the above-listed objectives, with two exceptions. First, some information concerning the existing filtration systems performance is proprietary and was not disclosed by FCVS designers; second, limited information could be obtained from the various countries concerning venting strategies, particularly concerning the description of the interface with the decision-making process. It should be stressed that for each country the decision-making process is highly dependent on the organization for the emergency response.

All contributing countries recognized through this work the potential benefits of FCVS for emergency response (reduction of on-site and off-site doses), reduction of the extent of land contamination and health effects and increased social acceptability. FCVS should, however, be considered in conjunction with other SAM strategies, e.g., no large benefit is expected for containment by-pass scenarios which have to be managed by other SAMM.

FCVSs implemented before Fukushima were primarily to manage long-term pressure build-up in the containment; new FCVS may be designed with perhaps more challenging conditions (management of early phases of an accident, cycling or long-term use in SA conditions). The robustness, the safe use and the reliability of FCVS for such conditions should be further assessed either to improve existing systems or to propose upgraded design requirements for future systems.

APPENDIX 1

Technical description of French FCVS

A sand bed filter containment venting line is installed on every operating French PWR.

A.1.1 FCVS design and qualification tests

Before implementing the FCVS systems, the licensee EDF conducted a R&D programme to design a FCVS essentially based on a massive sand bed filter that should be “as simple as possible”, that should not interfere with any other safety systems, should not induce additional safety risks of impairment of the containment isolation except for the pipe penetration and associated isolation valves and should work with a minimum electric power [72].

Experimental programmes were led by IPSN (former name of IRSN) in its Cadarache facilities in the 1980's, in cooperation with EDF to design the sand bed filter (geometry and flow conditions) and assess its behaviour under transient conditions:

- PITEAS programme (1982-1986):
 - small scale laboratory tests were performed with a sand bed filter of 20 cm diameter containing a 80 cm thick sand bed (1982 to 1985);
 - larger scale tests were performed with a sand bed filter of 1 m diameter containing a 80 cm thick sand bed (1985 to 1986).

PITEAS was essentially aimed to determine the sand characteristics (particle diameter of 0.6 mm with a maximum standard deviation of 2) and the velocity of the vented gas through this sand (which should not exceed 14 cm/s, tests were performed with velocities ranging from 7 to 14 cm/s) to meet the filtering efficiency criterion (a minimal decontamination factor of 10 for the aerosols and a maximum pressure load of 10^4 Pa in the filter).

- FUCHIA programme (1990): scale 1 of the U5 FCVS system without pre-heating and aerosol pre-filter. FUCHIA tests showed that the filtration efficiency for aerosols in the sand would exceed the minimal required efficiency of a factor of 10 for aerosols and reach efficiency of a factor larger than 100 when the velocity of the gas mixture would be below 12 cm/s²¹.

The system has finally been designed firstly with the following characteristics (that allow meeting the thermal-hydraulics criterion of velocity of the gas mixture in the sand below 10 cm/s):

- a containment pipe through the containment wall equipped with two manual isolation valves on the outside wall of the containment (the pipe was already existing and used for initial and periodic pressure tests of the containment);
- a fan that blows dry air in the parts of the downstream part of the FCVS under normal operation to avoid corrosion and sand moistening;

²¹ Aerosols with an AMMD of 1 to 2 μm , lower than the considered AMMD of 5 μm , were used in the aerosol filtration tests (retention efficiencies are expected to be significantly lower for this class of size).

- an orifice plate downstream of the manual isolation valves to expand to the atmospheric pressure and to superheat the vented gas before it reaches the sand bed filter;
- a cylindrical sand bed filter of volume 167 m³ filled with 65 tons of sand (grains size 0.6 mm and thickness of the sand bed of 80 cm), maximum pressure drop 10⁴ Pa;
- a device to measure the radioactivity level downstream of the sand bed filter;
- a pipe that connects the filter to the plant effluent chimney..

For the PWR 900 MWe plants, two neighbouring plants share the same sand bed filter and downstream bed filter equipment. These devices have been implemented on the existing plants from 1987 to 1989. The sand bed filter has been installed on the top of an auxiliary building and the impact of seismic loads was considered to choose this implementation (for one specific plant (Fessenheim), the sand bed filter has been installed at a different location).

FUCHIA experiments contributed to improve the accuracy of the prediction of the behaviour of this FCVS in real accidental conditions. Two experiments have been performed to evaluate the filtration efficiency regarding caesium aerosols and molecular iodine under mixed air and steam conditions (35%/65%). The filtering efficiency for caesium aerosols was measured to be more than one order of magnitude higher than the criterion of 10. Different trapping efficiencies have been measured for molecular iodine in the different phases of the two experiments; but for the fully heat-insulated filter that was finally implemented in the installations the decontamination factor was larger than 10. Very long term re-volatilization experiments have also been performed under air condition and by slowly decreasing the temperature to mock-up the residual power lowering. These experiments did not show any significant re-volatilization. With the knowledge obtained in the FUCHIA tests on gaseous iodine retention in the sand filter and considering that iodine may also adsorb on the FCVS line, studies led by IRSN and EDF in 1995 concluded that for all French PWR's gaseous molecular iodine decontamination factors would all the time be larger than 10 in the FCVS. However, potential effects of radiations in the FCVS on iodine deposits stability and especially the effect of air radiolysis products that can react with trapped species have not been accounted for. Researches to quantify such effects are on-going.

Research also continued after the devices implementation on two safety-related issues:

- the risk of hydrogen combustion in FCVS lines in cases of venting: on opening the FCVS line, the steam could condense in the pipes in contact with cold air leading to an enrichment of the gas mixture in hydrogen and thus to an increase of the explosion risk. To limit this risk, in the early 1990s, a heating system was added to the fan that blow dry air through the FCVS line to limit steam condensation. Heating should be started before insulation valves opening;
- the risk due to the high level of radioactivity due to trapped radioactive aerosols in the sand bed filter that would limit the possibilities of intervention in the plant site after FCVS use. There is also the necessity to limit the residual heat power in the sand filter. The only solution found was to reduce by a factor of 10 the amount of aerosols that would be transported through the venting line to the sand bed filter by adding a metallic pre-filter inside the containment. A metallic pre-filter has thus been designed to trap both hygroscopic and non-hygroscopic aerosols (characteristics of two different phases of the accident). When this pre-filter clogging leads to a pressure drop of one bar, a passive valve is opened to bypass the pre-filtering line. Two experimental programmes aimed to assess the efficiency of this pre-filter were performed in 1990-1991; they showed that the required efficiency can be reached under containment SA conditions and that for hygroscopic

aerosols the filter clogging occurs suddenly whereas for non-hygroscopic aerosols the pressure drop increases slowly to 1 bar.

A.1.2 FCVS description

Sketches of the FCVS as implemented and then complemented with the pre-heating system and the pre-filtering system are provided on figures A1.1 to A1.3.

Pre-filter

A pre-filter with metallic cartridges has been added to the initial device of every French PWR between 1992 and 1995. It is located in the reactor building at the venting inlet. The filtration medium, manufactured by the PALL society includes [73]:

- 92 cartridges made of sintered-consolidated stainless steel fibres, each one containing two types of filtering layer;
- An outlet connected to the venting line;
- A duct allowing to evacuate the residual heat generated by the radioactive deposits in the filter;
- Four inlets for the gaseous fluid to the filter.

The pre-filter basic design criterion is to allow for efficient trapping of the aerosols (i.e. to avoid aerosol clogging) for at least 7.5 hours during a SA. Calculations showed that this duration is sufficient to decrease the activity in suspension in the containment by a factor of 10. After this time lapse, if the pressure drop through the filter due to aerosol clogging exceeds 1 bar, the pre-filter is by-passed by a remotely controlled check valve located in the reactor building. Then the gas goes directly to the sand filter without pre-filtration.

Containment penetration, valves and orifice plate

The containment penetration was existing before the FCVS implementation and used for pressure tests of the containment. It is equipped with two manual isolation valves located outside the containment, as close as possible to it. Manual isolation valves are used since the opening of the FCVS is only envisaged after 24 hours following a slow containment pressure increase. Passive opening (via a rupture disc for instance) was excluded to avoid early uncontrolled off-site radioactive releases in case of containment pressure peaks resulting from energetic events in the containment, e.g. hydrogen combustion.

The orifice plate located downstream the manual isolation valves ensures venting gas expansion and super-heating before it reaches the sand bed filter.

Pre-heating and conditioning system

The pre-heating and conditioning system is connected downstream the orifice plate and is made of a fan and an electrical heater; it sweeps the downstream part of the containment venting system, including the sand bed filter, with 500 m³/h of dry air coming from the nuclear building ventilation system. During normal operation, the air is not heated and the fan operates to avoid corrosion and moistening of the sand bed filter. During a SA, the heater is switched on as soon as the criterion that leads to start the actions of

the SAMG is reached²². The heating of the FCVS line well before its opening intends to avoid steam condensation at its opening and reduce the hydrogen combustion risk in the FCVS line.

Sand bed filter

The sand bed filter, patented by EDF, is a thermally insulated cylindrical tank made of 316L stainless steel. It is a vertical axis cylinder with tori-spherical upper and lower ends. It is placed on the roof of a nuclear island building and is common to 2 twin units for 900 MWe PWRs. Its main dimensions are: inner diameter 7.3 m, height 4 m, volume 167 m³, filtering area 42 m², empty weight 12 tons, operational weight 92 tons, sand weight 65 tons.

The sand bed is 0.8 m thick, supported by layers of light weight concrete and expanded clay. The gas is homogeneously distributed through the filter by a constant-mesh Kevlar lattice enveloping the sand bed. After the sand bed, the gas is collected by a network of stainless steel strainers located in the expanded clay and is transferred in a rectangular collector torus at the filter periphery. The filter is designed to withstand a pressure drop of 500 mbar.

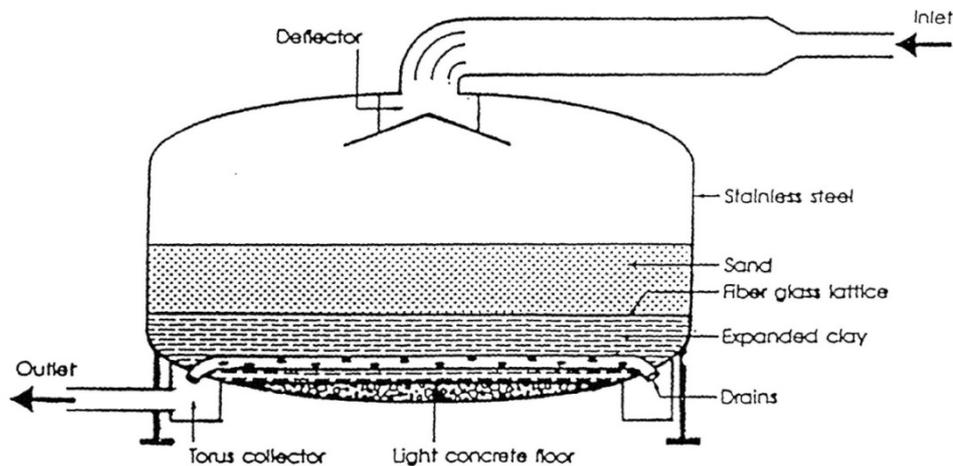
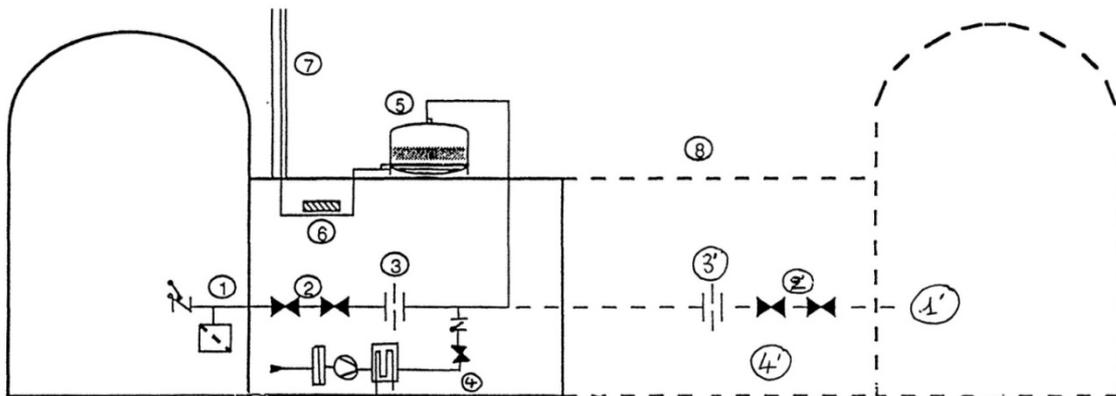


Figure A1.1: sketch of the sand bed filter of the FCVS system

²² The main criterion is when the gas temperature at the core exit exceeds 1100°C.



Figure A1.2: picture of the sand bed filter as implemented in the PWR 1300 MWe of Nogent sur Seine



LEGEND:

- | | |
|---|--|
| <p>1. Pre-filter;
Existing penetration, 300 mm diameter for 1300MWe plants, 250 mm diameter for 900 MWe plants.</p> <p>2. Manual valves, operated by reach rods from behind shielding.</p> <p>3. Pressure letdown orifice.</p> | <p>4. Filtered dry air supply during normal operation / Preheating for "H2 risk" in case of SA</p> <p>5. Sand filter.</p> <p>6. Radiation monitor</p> <p>7. Plant stack, with small vent stack</p> <p>8. Arrangement for twin units (900 MWe)</p> |
|---|--|

Figure A.1.3: sketch of the FCVS in French PWRs

Evacuation duct

A 0.4 m diameter independent evacuation duct is installed inside the regular plant effluent stack, in order to avoid climatic loadings (especially winds) and also to dilute the releases from the filter in the air flow exhaust from the nuclear island buildings. The duct provides sufficient air velocity to avoid condensate accumulation in the stack bottom under established operating conditions.

Radioactivity measuring device

When the FCVS is operating, the released fluid radioactivity is measured by a device located downstream from the sand bed filter. This device comprises a probe fixed on the connecting pipe between the sand bed filter and the plant stack, and a mobile detector. It uses a gamma-spectrometer with automatic energy calibration, allowing separate measures of the rare gas, iodine and caesium released activities.

Thermal insulation

The sand filter and the connecting pipes are insulated by 8 cm thick panels of mineral wool, mechanically protected by stainless steel sheets; the evacuation duct is not insulated. The condensate accumulation in the plant chimney during steady-state operation is avoided by the equipment thermal insulation and also by the expansion of the gases and super-heated steam at the orifice plate.

Safety classification

The containment isolation valves and the pipes between the penetration and the valves are safety classified, given their containment isolation function. The other parts of the system are neither safety classified, nor calculated to withstand seismic loadings. However, the civil engineering structures supporting them are designed to keep their integrity under seismic loadings: this is the reason why the sand bed filters were installed on the roof of a nuclear island building.

A.1.3 Venting procedure

From a safety perspective, it is of prime importance to maintain the containment function as much as possible during a SA. This principle should not be put into question by the existence of a FCVS which allows, as an ultimate emergency measure, a controlled opening of the containment if this becomes the only means to preserve its integrity. Thus, the opening of the venting should be postponed as much as possible.

The plant manager, in coordination with the local and national authorities in charge of the crisis management, is responsible for the opening of the FCVS [72i]. The venting procedure can be started when the following criteria are met:

- at least 24 hours have elapsed since the beginning of the accident — more precisely, 24 hours after entering the actions of the French GIAG (SA Intervention Guide)¹³;
- the internal containment pressure exceeds 5 bar abs., which is the average containment design pressure;
- the containment pressure is rising steadily, and thus is not related to a pressure spike.

When the containment pressure slowly reaches its design value (around 5 bars), the conditioning fan and the pre-heating are firstly stopped and the corresponding valves are closed. The two containment isolation valves are then opened manually. The operators follow the pressure and temperature evolutions inside the containment as well as the released activity during the venting. The venting is expected to be

manually stopped by closing the two isolation valves when an alternative safety system is recovered inside the containment to evacuate the residual power or when the pressure has decreased to a safe level for the containment. The end of the procedure is decided by the crisis management teams according to the evolution of the accident.

This filtering system has thus been developed with the support of an important research and development programme including the large scale FUCHIA experiments.

A.1.4 Remaining issues for the sand bed FCVS

Filtration efficiencies

Source term R&D programmes conducted in the last two decades has shown that iodine oxide particles, gaseous organic iodides and gaseous ruthenium tetroxide may contribute significantly to the environment source term in case of venting [66]. The filtration efficiency of the sand bed FCVS for these species was not investigated in the testing performed in the 80's and 90's. Also, the potential re-volatilization of the various deposited iodine and ruthenium species on the different parts of the FCVS has to be further assessed for conditions representative of a SA (pressure, temperature, gas composition, dose rates, flow transients).

In addition, the filtration efficiency of the metal pre-filter for these species, as well as for molecular iodine, is not established and thus not credited in current source term evaluations.

These issues will be addressed in the MIRE and PASSAM programmes [14].

Other issues in relation with the EU stress tests

The resistance to hazards of the FCVS, notably to seism, has to be further assessed since seism was not initially considered for the system design.

The consequences of venting on site accessibility, including that of the control room and emergency premises, has to be further assessed for simultaneous venting of two reactors (notably 900 MWe reactors).

The risk of hydrogen combustion has to be further assessed notably in the evacuation duct.

APPENDIX 2

Technical description of Westinghouse FCVS

Westinghouse currently proposes three different containment filtered vent products; a dry filter system, commonly referred to as “DFM” and two wet scrubber systems commonly referred to as “Filtration-MVSS” and “SVEN” (Safety Venting). The offering of a select choice of products allows for a better adjustment to the specific constraints and needs of each nuclear power station that is planning for the installation of such a system. A brief description of the three containment filtered vent products is provided below.

A.2.1 The Dry Filter Method (DFM)

A.2.1.1 Working principle and key components

In the course of containment venting under SA conditions, an air-steam mixture containing airborne fission products is released from the containment so that containment pressure is reduced to acceptable values. The function of the containment filtered vent system is to retain airborne radioactivity in aerosol and gaseous forms from the venting gas flow. To fulfil these functions, the DFM consists of a series of modular filter stages (Figure A.2.1). For aerosol filtering and gaseous iodine retention, two different types of filters are applied.

In a first step, aerosols are filtered from the venting gas flow using a specially designed deep bed metal fibre filter. The filtering principle of the aerosol filter is mechanical filtering of particles. It consists of a multistage design containing metal fibres which decrease in diameter over the depth of the filter. The metal fibres in the initial filter stages have relatively large diameters whereas the later filter stages are composed of smaller metal fibres. Most of the aerosol mass load is retained within the first filter stages, while the last filter stages achieve the overall high filtering efficiency.

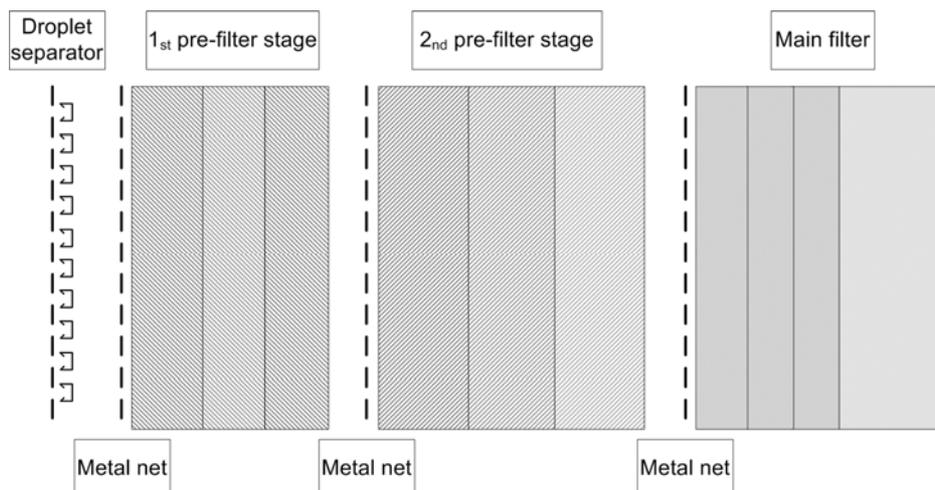


Figure A.2.1: Aerosol filter stages in the DFM aerosol filters

In addition to the aerosol filtering, gaseous iodine (both elemental and organic) is retained in a second step by a special iodine filter located downstream of the aerosol filter. The iodine filter or “molecular sieve” contains a silver-doped zeolite. Zeolite is a micro porous ceramic material with a high inner porosity. Ordinary zeolite is commonly used as an adsorbent in industrial applications. The filtering principle inside the zeolite filter is based on the chemical reaction between iodine (both, elemental and organic) and the silver doping, which is called chemical sorption.

In order to optimize the retention efficiency for gaseous iodine, the venting gas flow is expanded in a fully passive manner to eliminate the humidity of the steam and superheat the venting gas (drying effect) before entering the iodine filter. This is done by means of an expansion orifice. Another function of the orifice is flow control of the venting gas. The location of this orifice depends on the actual system design.

The DFM containment filtered vent product has been applied to 5 PWR’s in Germany and was installed in 2013 in the Krško NPP in Slovenia where it is used in passive mode with a rupture disk. Additional applications, mainly to PWR’s are expected over the coming years.

A.2.1.2 Performance of the DFM filters

Efficiency of the aerosol filter

The metal fibre filters contained in the DFM system for FCV filter radioactive aerosols from the vent stream with realistic decontamination factors of up to 3,000,000. This has been obtained for controlled conditions in international test programmes and laboratory tests.

For each manufactured aerosol filter unit, the filter efficiency is factory tested, using a small quantity of the test aerosol uranine in order to confirm a removal efficiency of at least 99.99 %, corresponding to a decontamination factor of at least 10,000. Uranine has a very small particle size distribution (AMMD $\sim 0.16 \mu\text{m}$) compared to realistic aerosols size distributions expected under SA, thus providing conservative results when considering the aerosol size parameter.

Efficiency of the iodine filter

The filter efficiency for gaseous elemental and organic iodine has been found to be essentially dependent on the residence time of the gas inside the zeolite bed and the distance of the gas temperature to the dew point of the steam contained in the gas mixture. The venting gas is expanded in a fully passive manner by a pressure reducing expansion orifice, leading to an increase in dew point distance and superheated steam. At higher containment pressure, a larger dew point distance can be achieved. At lower vent pressure, the distance to dew point will go down and hence the apparent efficiency of the iodine filter will be reduced. This effect is, however, fully compensated by the lower flow rates at lower containment pressure and the resulting longer residence times of the gas molecules inside the filter bed. Hence, the efficiency of the iodine filter can be guaranteed over the full range of flow and pressure of the complete venting cycle.

Typically designed decontamination factors for the iodine filter of the DFM are 1,000 for elemental iodine and 40 for organic iodine. The depth of the zeolite bed can be designed to achieve higher or lower DF for gaseous iodine. For each production batch of silver doped zeolite, the retention efficiency for gaseous iodine is measured individually under specified conditions in certified laboratories.

The zeolite filter is kept inert under nitrogen during stand-by conditions. Regular sampling of zeolite material from installed DFM systems in German NPPs has demonstrated that after standby periods of more than 20 years, no degradation of zeolite has taken place. The initial loading of zeolite is still in service without any decrease of retention efficiency.

A.2.1.3 Design of the DFM venting filter system

The DFM filter system is designed in a modular way for easy adaption to plant configuration as well as system functional requirements. Besides the key components of the system, namely the aerosol filter, the iodine filter, and the expansion orifice, typical components of the system include

- an intake for the venting gas flow;
- a containment penetration with containment isolation according to functional and regulatory requirements;
- an outlet for the filtered venting gas flow, and;
- connecting pipe work.

If possible, existing containment penetrations (e.g., spare penetrations or penetrations used for containment pressure testing) can be used. Westinghouse proposes a fully passive configuration of the DFM system. Actuation of the system can be performed manually by opening of two containment isolation valves. Alternatively, the venting process is passively actuated at a defined containment pressure by means of a rupture disk. Passive system provisions that will assist in protecting the containment vessel against the development of under-pressure can also be provided.

Therefore, the DFM does not require any external power source or make-up media even for long term operation.

DFM system configurations

Because of the modular design, different configurations of a DFM system are possible. Depending on the location of the aerosol filter, two configurations are generally distinguished:

- Inside containment configuration (aerosol filter inside containment and iodine filter outside containment);
- Outside containment configuration. (aerosol filter and iodine filter outside containment).

The DFM system has a compact and modular design, allowing a flexible installation of one filter unit as well as of several units of filter modules in existing buildings, in a new building outside or in a standard shipping container, which can be placed outside or on the roof of existing buildings, e.g., the auxiliary building. If available space is limited, the small size of the filter modules contributes to this installation flexibility.

Figure A.2.2 provides a schematic overview of the “inside” containment configuration of a DFM system. The aerosol filter is located inside the containment, whereas the iodine filter is placed outside of the containment, mostly in an existing auxiliary building.

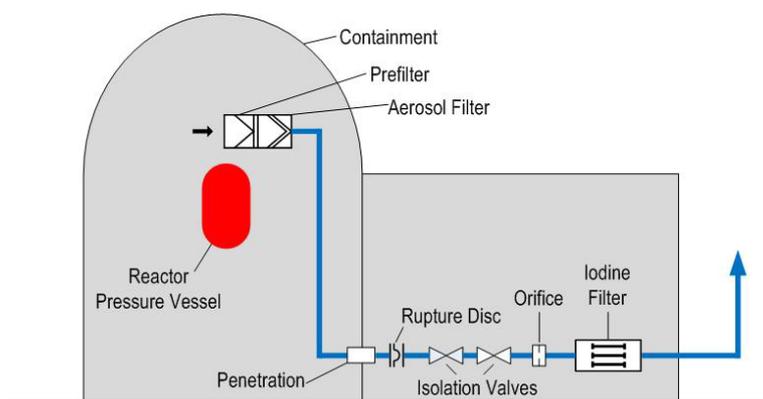


Figure A.2.2: Schematic view of the Dry Filter Method for containment filtered venting with aerosol filter inside containment

In this design configuration, the aerosol filter consists of several modules which are connected in parallel but can be arranged individually inside the containment. Typically, 3 aerosol filter modules are installed in a large German PWR.

The venting gas flow first passes the aerosol filter modules and leaves the containment via piping through a containment penetration. From there it passes the iodine filter. Finally, the cleaned gas is released to the environment, preferably by means of a dedicated vent stack. In this configuration the expansion orifice is located downstream of the containment isolation valves just before the iodine filter. Figure A.2.2 also shows the configuration for passive actuation of the system by means of a rupture disk in combination with two normally opened isolation valves during stand-by operation.

A major benefit of the inside containment design is the retention of long-lived radioactive particles inside containment by the aerosol filter and the fact that in this configuration the construction of additional shielding for the aerosol filter will not be required.

In the outside-containment configuration, the aerosol filter is arranged outside of the containment. Aerosol and iodine filter can be integrated into a common housing, which can be installed inside of existing building structures, a newly dedicated building, or even outside of any existing building in a standard shipping container.

For the outside-containment configuration, the aerosol filter and the iodine filter are mostly integrated into a combined filter unit. Inside the filter unit, the venting gas flow passes first through the aerosol filter modules and then through the iodine filter modules. The filter modules are compact, fully metallic and therefore inherently seismically rugged.

Critical FCVS design aspects

A relevant parameter to consider in any filtered venting system is its capability to avoid filter clogging under any expected aerosol load and particle size distribution carried with the venting flow.

Through independent, third party test laboratories, a variety of tests covering the full range of particle sizes and characteristics as well as temperature and pressure conditions have been performed. For instance, the following aerosols were used to test the aerosol loading capacity: wet and dry BaSO₄, mixed BaSO₄ and TiO₂, BaSO₄ micro, SnO₂, CsOH, CsI, MnO. Test results have demonstrated that the DFM design practice with filter sizing based on very penalizing test aerosols like SnO₂ provides large margin against filter clogging of the aerosol filter for the venting process. This DFM design includes two increasingly dense pre-filter stages before the main filter that retain most of the solid particles carried by the flow.

Another key design aspect of the DFM is its ability to handle fission product heat load on the filter mats retaining the aerosols and the zeolites retaining the gaseous iodine. As for the existing systems in German power stations the design heat load was quite low, additional testing and filter housing design changes have been made to increase the system's capacity for handling fission product heat loads. As a result of these changes, the filter units can now handle fission product heat loads representative of those expected on most pressurized water reactors while maintaining a reasonable construction volume.

A.2.1.4 Benefits of the DFM Westinghouse venting system

The DFM offers a number of significant advantages:

- Designed to achieve high filter efficiency. Typical retention efficiencies obtained in testing for aerosols are higher than 99.99 % (DF > 10,000), are 99.9 % (DF > 1,000) for elemental iodine, and 97.5 % (DF > 40) for organic iodine. The retention efficiency for gaseous iodine can be increased or decreased by modification of the zeolite filter, as required;
- The configuration with the aerosol filters inside containment provides the significant benefit that all long-lived radioactive aerosols are retained directly in the containment;
- Neither emergency AC or DC power nor any auxiliary systems are needed for a safe and proper operation of the system. The DFM decay heat is removed by cooling through natural convection of the filters. Therefore, the DFM system has the ability to operate in a fully passive manner for extended duration;

- The DFM requires little maintenance. There is no need for chemistry control, heating systems or water make-up systems. The periodic testing requirements for the filter system are very limited (system leak test every 4 years and zeolite efficiency testing every 5 years on small test sample). As the containment isolation valves are part of the containment they have to be inspected and tested according to containment requirements (typically, functional tests are performed once per year);
- The DFM is of flexible modular design. The aerosol filters can be positioned either inside or outside the reactor containment and all filter modules can in most cases be adapted to site-specific spatial constraints. Installation of the filters in existing rooms and buildings is possible as the filter housing is a bolted construction that can be assembled in situ. Alternatively, the filters can be located in a single location outside in a new building or a shipping container. Because of its simple and robust metallic construction, the DFM system can be adapted to stringent seismic requirements;
- With respect to the potential for hydrogen deflagration, the DFM, and in particular the in-containment configuration, has a low potential for condensation of a steam-inerted gas mixture thereby minimizing hydrogen deflagration risks.

A.2.2 The FILTRA-MVSS scrubber system

A.2.2.1 Working principle and key components

The FILTRA-MVSS Venturi scrubber unit is a wet containment filtered vent system that uses multiple Venturises to create an interaction between the vent gases and the scrubber media allowing for removal of aerosols and gaseous iodine in a very efficient manner. The FILTRA-MVSS Venturi scrubber is jointly proposed by Westinghouse and Alstom and is based on the design that is currently installed on all operating Swedish NPP's as well as the Mühleberg BWR station in Switzerland. The aerosols are essentially captured by suspension in the scrubbing media and the gaseous iodine is eliminated as a result of reactions with chemicals added to the scrubber water. Sodium thiosulphate is used to capture the elemental iodine, and partly the organic iodine. Sodium carbonate is used to control the pH.

In the individual Venturises, the particle-laden vent gases are accelerated in the throat whereas scrubber media that is atomized to fine droplets in the Venturi throat is accelerated at a later stage in the Venturi and acts as a quasi-stationary filter cloud catching the aerosol particles (inertial particulate separation).

The Venturises are organized in a unique arrangement that provides constant DF independent of the total flow rate. This innovative Venturi and header design as shown in figure A.2.3 was awarded the prestigious Swedish Polhem Prize as a high-level technological invention.

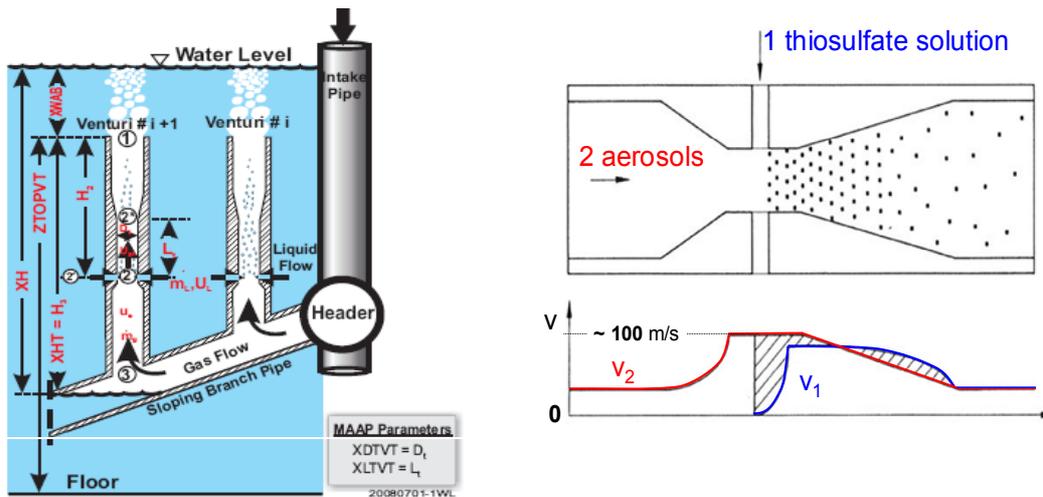


Figure A.2.3: Venturi and flow distribution header configuration of FILTRA-MVSS

In addition to the Venturi tree, the FILTRA-MVSS pressure vessel contains a moisture separator followed by a bank of sintered metal fibre filter cartridges. The moisture separator, of “Knitmesh” type and located in the upper part of the vessel, collects water droplets entrained by the gas. Downstream of the moisture separator, sintered metal fibre filter cartridges are located with as main function to provide for additional retention of extremely small aerosol particles $<0.8 \mu\text{m}$. The filter medium is manufactured from very fine, short stainless steel fibres that are sintered together at their points of contact to produce a very uniform, strong, multilayer filter medium. The filter layers are co-optimized with the Venturi system to produce maximum filtration capacity.

FILTRA-MVSS requires neither operator action nor water addition or electrical power for at least the first 24 hours of operation. The duration of this initial passive period can easily be matched to customer requirements and can be increased, e.g. by increasing the scrubber volume.

FILTRA-MVSS is delivered to site as one complete unit with all necessary lifting arrangements to facilitate the erection procedure. FILTRA-MVSS may also be delivered in sections if local conditions make this the preferred alternative. The FILTRA-MVSS consists of the following main items:

- Pressure vessel
- Venturi scrubber system
- Moisture separator
- Sintered metal filter
- Support systems

The pressure vessel is designed as a stainless steel pressure vessel with gas inlet and outlet nozzles. Furthermore, there are connections to the auxiliary system for inerting, make-up water supply, drainage, periodical circulation, internal heat exchanger and chemical addition. It is also equipped with local measurement of pool water level and temperature, so that the ventilation process can be monitored remotely from the central control room. Service and inspection of the vessel can be carried out through a manhole. For inside access, an internal platform and a ladder is mounted above the water level.

Figure A.2.4 illustrates the basic design of the FILTRA-MVSS containment filtered vent and the position of the different main elements of construction of the assembly.

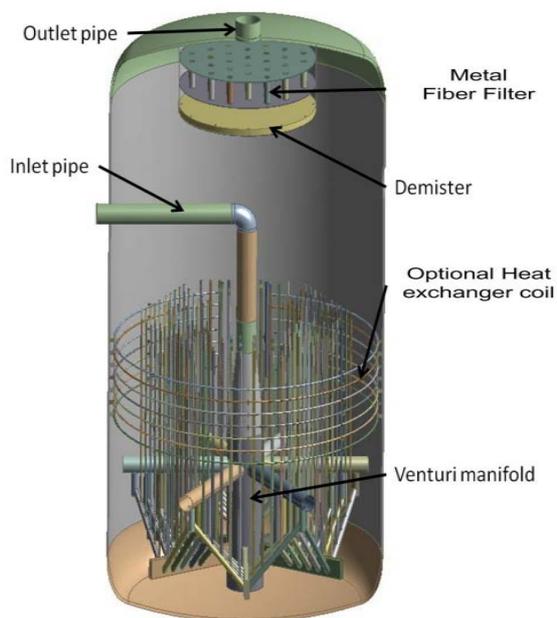


Figure A.2.4: Integrated FILTRA-MVSS scrubber module

It is noted that the generation 2 FILTRA-MVSS as depicted in Figure A.2.4 requires a significantly smaller construction volume than, e.g., the first generation of FILTRA-MVSS Venturi scrubbers currently installed in Sweden.

A.2.2.2 Performance of FILTRA MVSS

Efficiency of the venturi scrubber

The Venturi scrubber of the FILTRA-MVSS captures airborne aerosols in the vent stream with high efficiency. The decontamination factors achieved in the Venturis will depend on the MMD (Mass Median Diameter) of the aerosols. For a particle size with a MMD of 1.5 μm , the DF's in the wet fraction of the Venturi scrubber is higher than 1,000, thereby significantly reducing the aerosol load and associated decay heat load on the filtering elements downstream of the venturi tree. Considering the additional scrubbing effect of the water pool in the scrubber and the high efficiency of the sintered metal fibre filter directly upstream of the outlet nozzle, the total DF for aerosols offered by FILTRA-MVSS is more than 10,000. Extensive tests have been carried out to verify integrated system (Venturis, demister and metal fibre filter cartridges) performance.

The Sodium Thiosulfate dissolved in the scrubber water captures the gaseous elemental iodine (I_2) with DF's exceeding 10,000 and also offers a DF of approximately 2 for organic iodine (CH_3I). Higher DF's for elemental and organic iodine can be achieved by the addition of a molecular sieve downstream of the scrubber unit. Westinghouse provides two alternative molecular sieve designs depending on operating conditions. The molecular sieve can be placed either as an integrated part on top of the wet scrubber or as an individual module downstream the outlet from the wet scrubber. The exact location is plant specific. If the suitable location for the molecular sieve is away from the exhaust point (for example, in the reactor building), the molecular sieve designed for a higher discharge pressure is suitable. With this design

pressure drop to maintain vent flow to the exhaust can be maintained as well as sufficient superheating in the inlet gas.

A.2.2.3 Design of the Filtra-MVSS filter system

The FILTRA-MVSS containment filtered venting system is typically located outside containment in a separate building providing the proper radiation shielding. The system can also be installed in a suitable existing building, and be modularized for installation in enclosures with limited space, such as e.g. BWR containments. For cases where existing civil plant features can be used, the Venturi configuration can be adapted to non-circular form to suit the available space. A successful example of such a configuration is the system currently installed in the Mühleberg BWR station.

A typical, simplified system configuration of FILTRA-MVSS is shown in Figure A.2.5. The scrubber inlet nozzle is connected to a (mostly existing) containment penetration and different valve configurations can be conceived upstream of the FILTRA-MVSS inlet nozzle. The use of a rupture disc is recommended to allow for fully passive system activation.

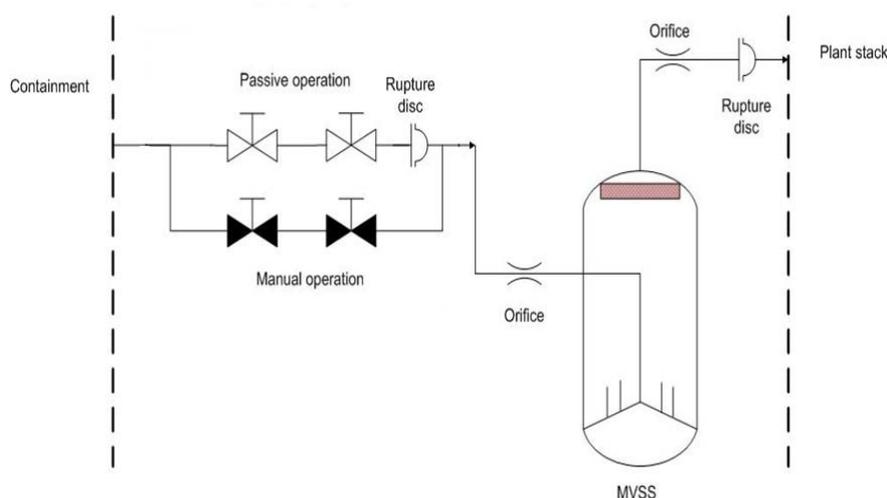


Figure A.2.5: Simplified System Configuration of the FILTRA-MVSS Venturi scrubber

A.2.2.4 Benefits of the FILTRA-MVSS containment filtered venting system

FILTRA-MVSS offers a number of attractive design features as summarized below:

- Designed to achieve high filter efficiency. Typical retention efficiencies obtained in extensive testing of integrated system (Venturis, demister and metal fibre filters) are higher than 99.99 % (DF > 10,000) for aerosols. Typical iodine retention efficiencies are 99.99 % (DF > 10,000) for elemental iodine, and 50 % (DF \approx 2) for organic iodine. The retention efficiency for gaseous iodine, in particular organic iodine, can be increased though the addition of a zeolite filter, if required;

- High decontamination factors for aerosols in the first filtration step as a result of the unique, highly efficient Venturi design. As a result of the highly efficient first filtration step, the aerosol and decay heat load on the sintered metal fibre filters is minimized resulting in optimal performance of the sintered metal fibre filters;
- High and consistent decontamination factors irrespective of flow rate through the Venturi scrubber. The system does not require any form of active flow control, as the unique flow distribution header will automatically activate the required number of Venturis;
- Ability to handle high aerosol and fission decay heat loads as the water contained in the scrubber can easily be dimensioned to contain sufficient scrubbing media for essentially any design condition;
- Robust and seismically rugged design, with all essential features for passive scrubber operation contained in a single pressure vessel;
- Neither emergency AC or DC power nor any auxiliary systems are needed for a safe and proper operation of the system for the designed duration of passive operation (typically 24 hours);
- Routine maintenance of the FILTRA-MVSS is minimal, and operating experience has shown that adjustment of thiosulphate and pH-control has been required only once in 20 years of operation;
- Suitable for a large variety of containment filtering requirements as observed on any type of light water reactor. For PWR service, steam inertia of the system in standby conditions will eliminate any concern of steam condensation during operation of scrubber and thereby eliminate the hydrogen deflagration concern;
- Can be applied for feed & bleed operation to handle decay heat removal in the long term following a SA;
- Extensively qualified under international test programmes such as the ACE test.

A.2.3 The SVEN scrubber system

A.2.3.1 Working principle and key components

SVEN is a wet scrubber system based on a sintered metal fibre filter separation technique. Aerosol filtering and retention of gaseous elemental and organic iodine is performed in 5 consecutive steps, see figure A.2.6.

Particulate aerosols are filtered in four stages. In the first stage the ventilated flow is routed through sintered metal fibre filter cartridges (step 1) which are submerged in a scrubber liquid inside a pressure vessel. The ventilated flow forces the liquid out from the manifold and the cartridges. The majority of aerosols (>99%) in the vent flow are removed by the submerged filter media as the vent flow flows from the inside of the cartridges to the outside through the filter media. Decay heat from captured aerosols is cooled by the scrubber liquid. The vent flow then pass a liquid volume where the large interfacial area between gas and liquid lead to scrubbing of the gas flow from aerosols (step 2). The scrubber liquid consists of sodium thiosulphate ($\text{Na}_2\text{S}_2\text{O}_3$) and sodium hydroxide (NaOH) dissolved in de-mineralized

water. During this bubbling phase elemental iodine is removed by a very fast chemical reaction with thiosulphate solution. Iodide ions created in the reactions are soluble in water. Sodium hydroxide (NaOH) is added to the liquid to increase the pH level to 13. This high initial pH value is provided to maintain the pH level above 7 during venting, which is necessary to prevent re-volatilization of iodine that is possible in acid environment. The ventilated gas flow typically contains chloride, due to burning or irradiation of cables. Chlorides forms NaCl and lowers the pH level.

Above the scrubber liquid, a splash shield and a demister to remove moisture from the vent flow are installed (step 3). The demister design is of Knitmesh type, with a wire size of approximately 250 μm . Knitmesh is a knitted fabric of interlocking asymmetrical loops of stainless steel. In this demister design, the droplets from the vapour stream are removed by impingement. The vapor takes the open path through the mesh, while the greater inertia of the liquid droplets projects them in a straight line to impinge on the wires. The demister prevents release of aerosols due to re-suspension when aerosols encapsulated in liquid droplets follow the gas flow from the scrubbing volume.

A DF for aerosols $>1,000$ is already obtained by Step 1,2 and 3, but the vent flow exiting the scrubber may still contain small amounts of fine aerosol particles. A second set of HEPA rated metal fibre filters is therefore provided in the upper part of the SVEN tank, designed to capture a smaller load of aerosols with MMD 0.3 μm (step 4). The amount of aerosols which these fine filters encounters is small (typically $<0.1\%$ of the total). Correspondingly, the associated decay heat, which will be generated by radioactive aerosols retained, is also small. Decay heat of captured aerosols is removed by convection.

Organic iodine retention in the bubbling phase is moderate, about 50% (DF \approx 2). The gas exiting from the SVEN tank may therefore contain small amounts of organic iodine (CH_3I). To achieve a specified guaranteed DF for organic iodine (CH_3I), an optional molecular sieve, consisting of beds of silver impregnated zeolite beads through which the vent flow is routed, is provided. The molecular sieve beds are housed in a separate housing downstream of the SVEN tank (step 5). Westinghouse provides two alternative designs for the molecular sieve depending on operating conditions. The molecular sieve can be placed either as an integrated part on top of the wet scrubber or as an individual module downstream the outlet from the wet scrubber. The exact location is plant specific. If the suitable location for the molecular sieve is away from the exhaust point (for example, in the reactor building), the molecular sieve designed for a higher discharge pressure is suitable. With this design pressure drop to maintain vent flow to the exhaust can be maintained as well as sufficient superheating in the inlet gas.

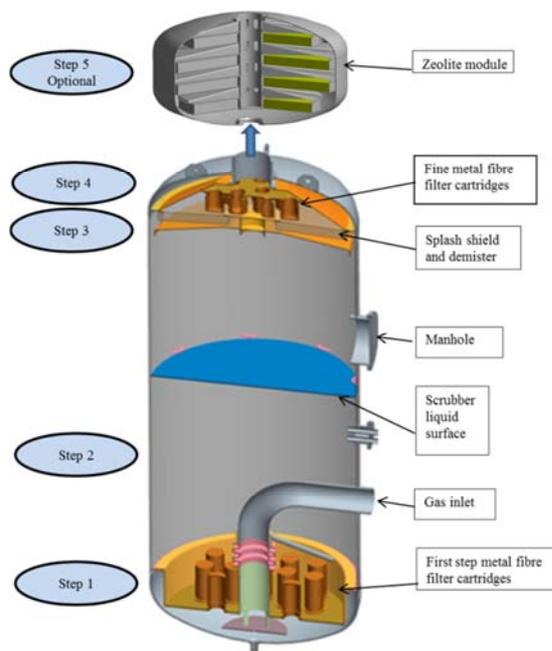


Figure A.2.6: Integrated SVEN filtered containment vent system

The SVEN design is suitable for scenarios resulting in total aerosol deposition corresponding to a generated decay heat of up to 500 kW per SVEN unit. The resulting temperature increase of the filter media relative to the steam temperature in the tank is designed to be less than 10 °C, implying a filter media well below the melting temperature of CsOH (342 °C.)

SVEN requires neither operator action nor water addition or electrical power for at least the first 24 hours of operation. The duration of this initial passive period can easily be matched to customer requirements and can be increased, e.g. by increasing the scrubber volume.

SVEN is delivered to site as one complete unit with all necessary lifting arrangements to facilitate the erection procedure. SVEN may also be delivered in sections if local conditions make this the preferred alternative. The SVEN consists of the following main items:

- Pressure vessel
- Metal fibre filter cartridges
- Moisture separator
- Support systems

The pressure vessel is designed as a stainless steel pressure vessel with gas inlet and outlet nozzles. Furthermore, there are connections to the auxiliary system for inerting, make-up water supply, drainage, periodical circulation, internal heat exchanger and chemical addition. It is also equipped with local measurement of pool water level and temperature, so that the ventilation process can be monitored remotely from the central control room. Service and inspection of the vessel can be carried out through a manhole. For inside access, an internal platform and a ladder is mounted above the water level.

A.2.3.2 Performance of SVEN

Efficiency of the scrubber

Extensive verifying tests of the SVEN scrubber system has been performed using the pressurized test rig outlined in figure A.2.7. In the lower portion of the vessel, a sub-scale size submerged metal fibre filter cartridge was installed. In the upper portion of the vessel, a demister and sub-scale size fine metal fibre filter cartridge was installed. Air or steam flow was supplied to the pressure vessel and temperature and pressure of the gas stream recorded at various locations in the rig.

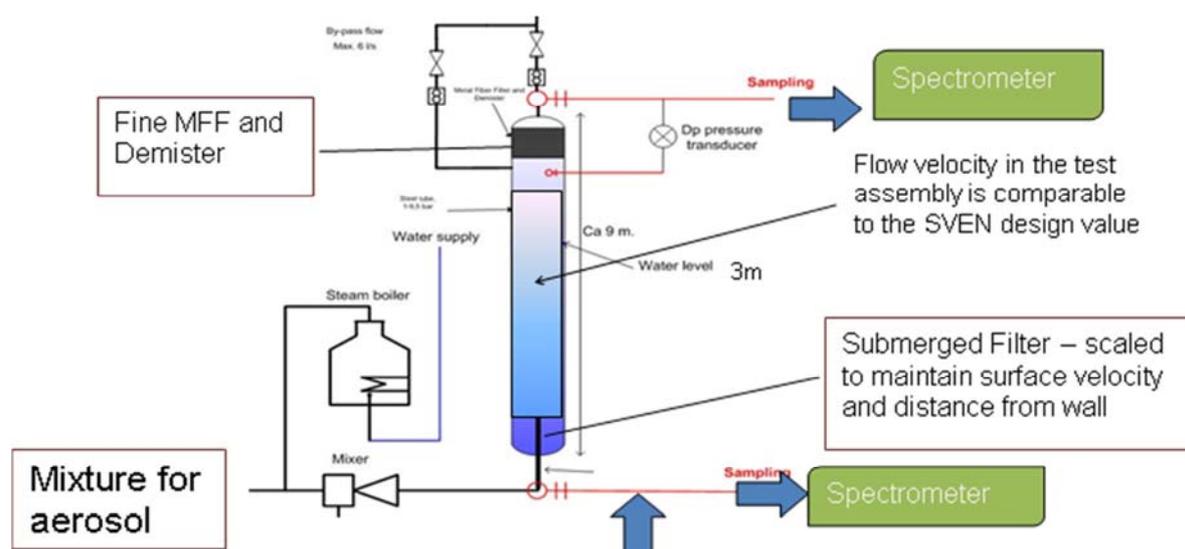


Figure A.2.7: Test rig for integrated aerosol tests of SVEN

To verify the filter efficiency, a well-defined concentration of aerosols, BaSO_4 aerosol with $0.3 \mu\text{m}$ MMD, was added to the flow stream being supplied to the filters. A minimum guaranteed retention efficiency of 99,9 % ($\text{DF} = 1000$) for submerged metal fibre filter, liquid and demister (step 1-3) was verified. Measurement of filter performance at $0.3 \mu\text{m}$ ensures that the filter performance is also guaranteed for particles size distribution centred on a bigger size (for example, $0.5 \mu\text{m}$ MMD). Extensive tests for a range of aerosol size fractions have proven that the integrated DF for the complete system always exceeds 10,000 for all vent conditions.

To determine the effectiveness of sodium thiosulphate in removal of elemental iodine, several preliminary tests by bubbling through a pool have been conducted. The gas in the test set up was discharged through a sparger with hole-sizes of 8 mm. All DF values during tests resulted in a $\text{DF} > 3000$. The SVEN submerged metal fibre filters have micro size pores and therefore, initial bubble size (before coalescing) will be smaller resulting in a larger surface to volume ratio. The chemical reaction between iodine and thiosulphate is fast and the removal of elemental iodine hence limited by the diffusion rate at the interface between gas and scrubber liquid. Having a smaller initial bubble size with a larger interface area increases the removal rate. Therefore, the preliminary bubble test results provide a conservatively low DF for the elemental iodine in SVEN. Extensive large scale testing in a test rig similar to figure A.2.7 is currently designed to confirm an expected larger DF for elemental iodine.

Efficiency of the molecular sieve

The organic iodine module filtration efficiency depends on dew point distance and vent gas residence time in the zeolite beds. The design is tailored to the chosen DF, typically 50, based on the conditions of the specific installation. Several qualification tests are done in order to qualify a specific zeolite batch to be used in the SVEN molecular sieve module. The zeolite material is tested at various air/steam mixtures, and at various superheating values (distance from dew point) and retention efficiency for various residence times is determined.

A.2.3.2 Design of the SVEN filter system

SVEN is a compact unit housed in a stainless steel tank and is connected to the primary containment vessel by the containment vent piping. Although typically located outside containment in a separate building, providing the proper radiation shielding, the system can also be installed in a suitable existing building, and be modularized for installation in enclosures with limited space, such as e.g. BWR containments.

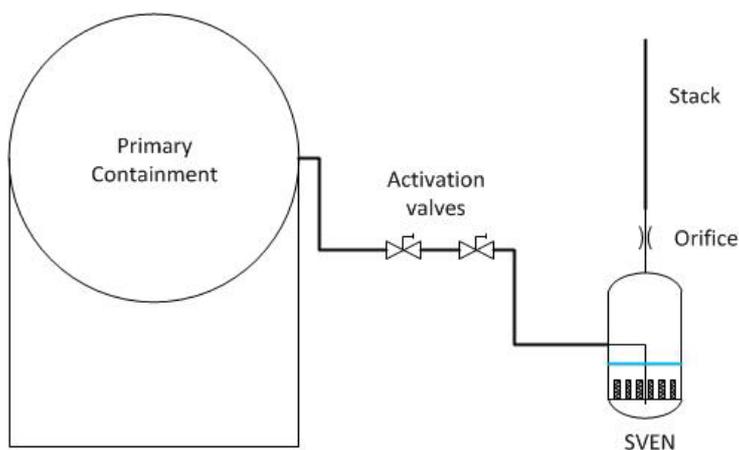


Figure A.2.8: Simplified System Configuration of the SVEN scrubber

A typical, simplified system configuration of SVEN is shown in Figure A.2.8 for a design without passive activation. The scrubber inlet nozzle is connected to a (mostly existing) containment penetration and different valve configurations can be conceived upstream of the SVEN inlet nozzle. A parallel activation line including a rupture disk is recommended to allow for fully passive system activation.

A.2.3.4 Benefits of the SVEN containment filtered venting system

SVEN offers a number of attractive design features as summarized below:

- Designed to achieve high filter efficiency. Typical retention efficiencies obtained in extensive testing of integrated system are higher than 99.99 % (DF > 10,000) for aerosols. Typical iodine retention efficiencies are expected to be larger than 99.99 % (DF > 10,000) for elemental iodine. Retention efficiency for organic iodine is tailored to the NPP need using one of Westinghouse zeolite modules and typically correspond to DF=50.
- High decontamination factors for aerosols in the first filtration step due to the efficient submerged metal fibre filter cartridges. As a result of the highly efficient first filtration step, the aerosol and decay heat load on the second set of HEPA rated metal fibre filters is minimized resulting in optimal performance;
- Verified flow stability and swell performance resulting in stable DF for all venting conditions;
- Ability to handle high aerosol and fission decay heat loads as the water contained in the scrubber can easily be dimensioned;
- Robust and seismically rugged design, with all essential features for passive scrubber operation contained in a single pressure vessel;
- Neither emergency AC or DC power nor any auxiliary systems are needed for a safe and proper operation of the system for the designed duration of passive operation (typically 24 hours);
- Routine maintenance of the SVEN system is minimal due to simple and rugged design. Operating experience from the Westinghouse FILTRA-MVSS system has shown that adjustment of thiosulphate and pH-control is required only once in 20 years of operation;
- Suitable for a large variety of containment filtering requirements as observed on any type of light water reactor. For PWR service, steam inerting of the system in standby conditions will eliminate any concern of steam condensation during operation of scrubber and thereby eliminate the hydrogen deflagration concern;
- Can be applied for feed & bleed operation to handle decay heat removal in the long term following a SA.

APPENDIX 3

Technical description of CCI FCVS

A.3.1 General remarks

The CCI venting system has been originally designed to cope with conditions set by Swiss ENSI (Former HSK) in reference [74]. The aim was to depressurize the containment during a SA in a reasonably short time, and, at the same time, to limit the release of gaseous species and aerosols by producing reliable, sustainable and reproducible high decontamination factors.

The CCI system installed in Swiss NPPs has been designed to achieve the decontamination factors (DF) shown in Table A1 under the specified operating conditions given in [74]:

Table A1: DF achievable by CCI Filter installed in Swiss NPPs and ENSI requirements [74]

	Installed CCI Filter System (Gen I)	ENSI Requirements [74]
Aerosols	> 10,000	$\geq 1,000$
Elemental iodine	> 300	≥ 100
Organic iodine	Approx. 5	N.A

As can be seen from Table A1, the DF for aerosols, elemental and organic iodine achievable in CCI Filter, is significantly higher than the values requested by ENSI. It must be pointed out that these systems belong to the first filter's generation (Gen I). This means that only Sodium Thiosulfate (THS) has been used in the systems as chemical additive. For achieving a further reduction of iodine release, it is possible to upgrade these systems by adding tanks filled with chemical additives aimed to improve Iodine DF, thus becoming second filter's generation (Gen II).

A.3.2 Description of CCI filtered containment venting system

A.3.2.1 General description of containment venting filter system concept

CCI Containment Venting Filter Concept is shown in Figure A.3.1

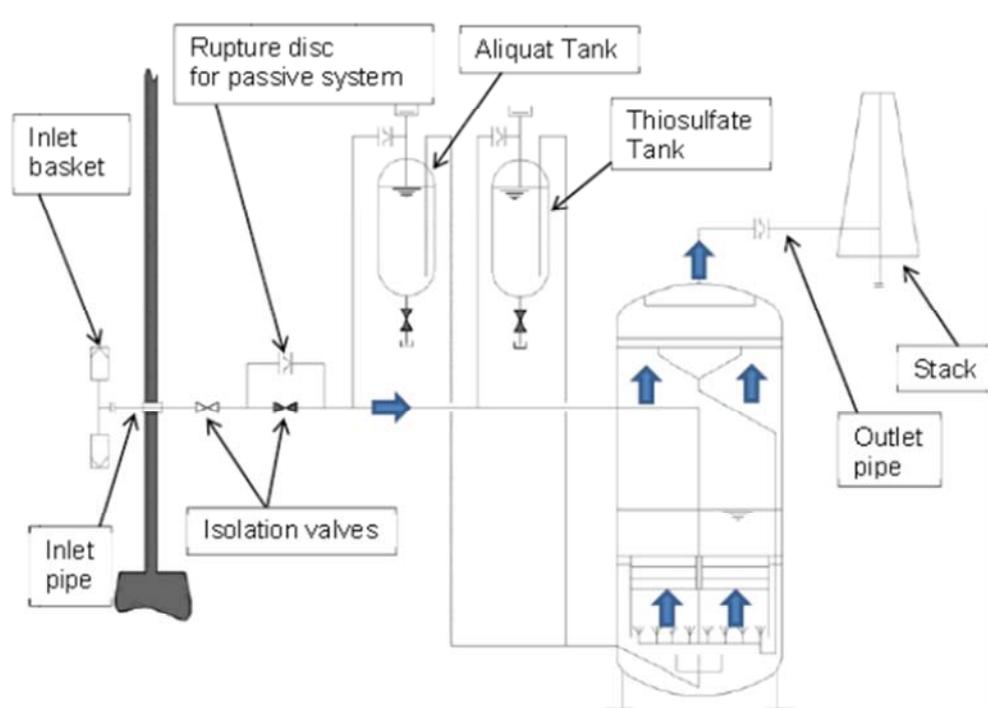


Figure A.3.1: CCI FCVS concept

The system consists of:

- Inlet basket inside the containment, aimed at avoiding that large debris pieces enter the inlet pipe;
- inlet piping between the containment penetration and filter vessel, including containment isolation valves;
- filter vessel and its internals;
- clean gas piping;
- auxiliary systems; instrumentation and control systems.

A.3.2.2 Description of the containment venting filter system main components

Containment venting filtration tank and internals

The CCI containment venting filter vessel (Figure A.3.2) consists of a stainless steel vessel with a three stage filtration system:

- Stage 1: water pool section of the wet scrubber;
- Stage 2: mixing elements, recirculation zone and gas space above the wet scrubber;
- Stage 3: separation unit consisting of a three stage moisture separator.

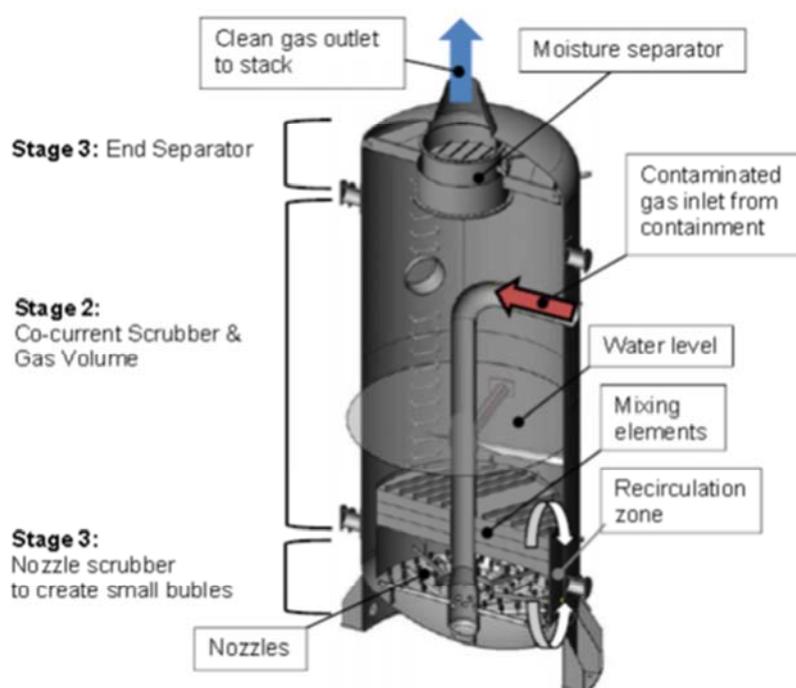


Figure A.3.2: CCI containment venting filter vessel

Stage 1: Wet scrubber

The wet scrubber is aimed to remove, with high efficiency, the gaseous and particulate effluents from the gas flowing from containment. Its design is based on an Air Lift Reactor system and the principle behind is explained shortly in the following.

The contaminated gas, coming from the containment and flowing through the inlet pipe, passes through a large number of nozzles settled inside a riser, which is surrounded by an annulus region bounded by the vessel wall and the riser itself (see Figure A.3.3). The gas pushes the water upwards, thus establishing a water circulation between the riser (upward direction) and the annulus (downward direction). This motion enables the gas bubbles to be entrained. The sustained bubble recirculation enhances bubble residence time, thus improving the total mass transfer of dissolved gas the in bubbles and particulates into the water pool, resulting in high Decontamination Factors (DF).

A brief description of the several components of the Stage 1, such as gas sparger system and mixing elements, will be given in the following.

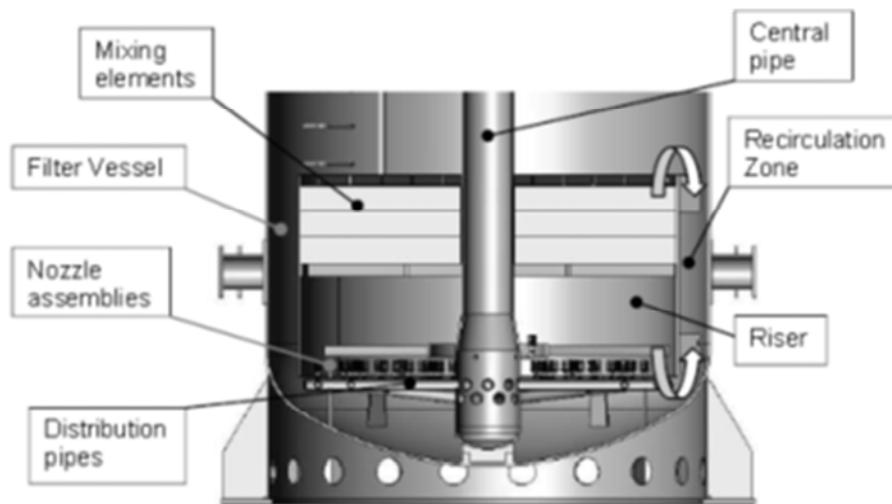


Figure A.3.3: Wet scrubber of CCI FCVS

The sparger system is composed of a large number of nozzles. The size and the number of the nozzles are dependent on the required flow rate to be able to depressurize the containment in a reasonable time in a reliable way.

As can be seen in Figure A.3.4, every impact nozzle is equipped with an orifice and a gas jet deflector aimed at disintegrating the gas jet.

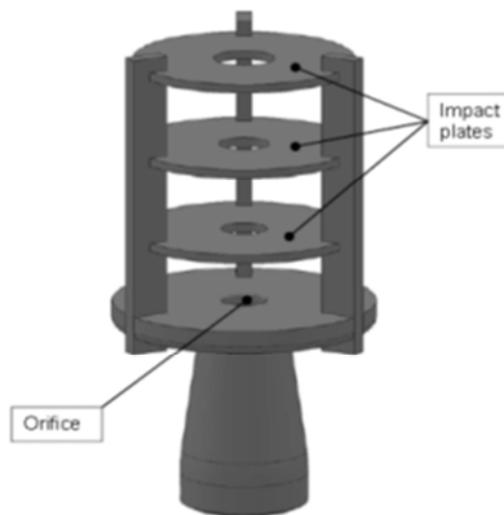


Figure A.3.4: CCI FCVS impact nozzles

The gas jet deflector is mounted above each orifice and is made up of three circular impact plates. Every plate has a hole in the centre, which is specifically sized.

The distances among the plates and between the first plate and the orifice, as well as the holes size of the plates are optimized to maximize the flow turbulence. The turbulent flow, together with the action of the chemicals, which modify the bubbles' surface tension, leads to the gas jet disintegration into very small bubbles. This system is suitable for high pressure ratios as well as at lower ones.

The upper section of the Stage 1 houses three layers of structured packs, called "mixing elements" (see Figure A.3.5), which are also widely used in the chemical industry in distillation, mixing and gas absorption columns. The design of these mixing elements enhances again the turbulence, thus disintegrating further the gas bubbles into smaller ones.

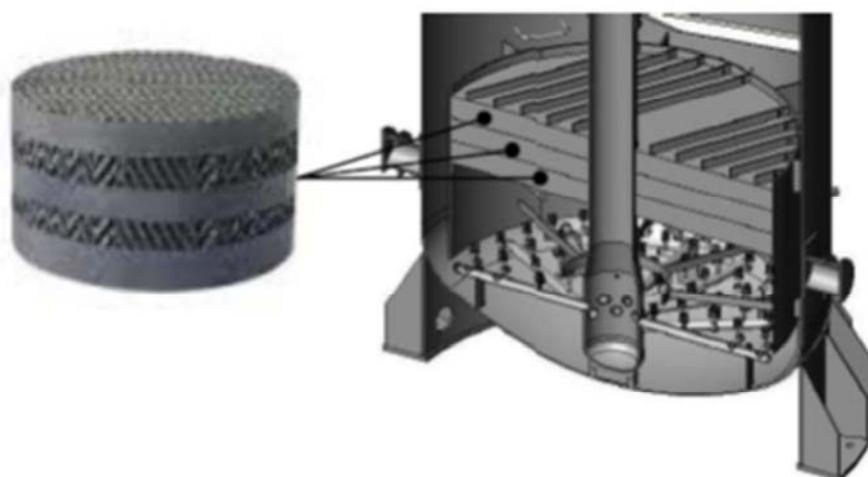


Figure A.3.5: Mixing elements

In order to avoid clogging due to the debris captured, the mixing elements are equipped with wide openings.

Riser dimensions (diameter and length), annulus cross sectional area and the water pool height above the exit of the riser are designed to enable sufficiently high gas and water velocities, thus improving very effectively the mass transfer of particulates and soluble gas components from the contaminated steam and non-condensable gas to the water inventory of the filter vessel.

Stage 2: Gas space above the water pool

The gas space is designed to accommodate the water level increase due to steam condensation, which takes place during the initial venting phase. In addition, this space contributes to increase the filter performance thanks to its natural filtration capability. In fact, since the gas velocity is relatively low, the larger droplets generated by the bubble bursting at the water surface, fall down in the water and hence do not enter into the final separation unit.

Stage 3: Moisture Separation Unit

The aim of the final separation unit is to remove any size of droplets that might be generated at the water pool surface due to bubble rupture and to remove remaining aerosol particles in the gas stream (Figure A.3.6).

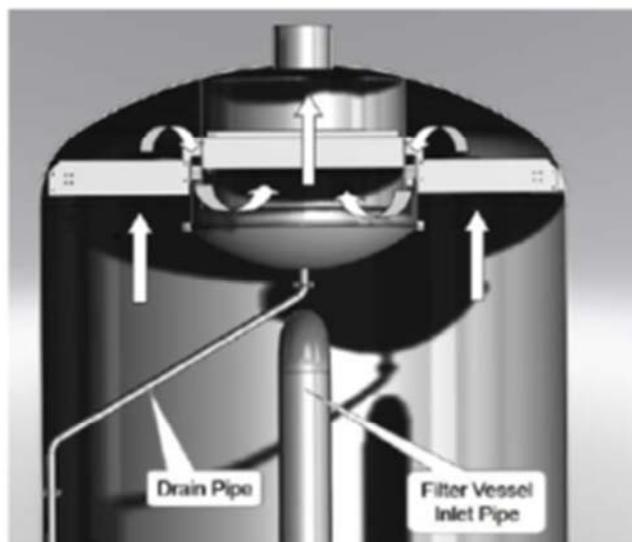


Figure A.3.6: Moisture separation unit

The Moisture Separation Unit contains three special mixing elements, which force the flow to turn 180°. The first mixing element unit is aimed at removing large droplets which might fall back to the water pool, as previously explained. The second unit, due to relatively high gas velocity within the unit, removes very fine droplets and particles because of the element geometry, which allow intercepting them and impingement occurring in the fine flow passages. The third unit removes completely any kind of remaining droplets.

The water separated from the particles is collected at the bottom of the moisture separator and drained to the wet scrubber section.

Filter water pH control and chemical addition

The main features of the Gen II FCVS are described briefly in the following.

Demineralized water is used in the filter vessel.

Two different chemical agents are added to the water in the filter vessel during the commissioning phase:

1. Sodium hydroxide (NaOH), whose function is to maintain the solution at high pH, in order to achieve a high iodine decomposition rates;
2. Sodium Thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$), whose function is to reduce elemental and organic iodine, thus enhancing their retention.

In addition, another chemical additive, Aliquat®336, is stored in a separate vessel and is added to the solution in case of venting operation.

Aliquat®336 is a phase transfer catalyst aimed at enhancing the organic iodine decomposition and therefore at improving the decontamination factor for iodine. The vessel is partially filled with gas and this gas space is connected through a pipe to the inlet piping.

The connection pipe does not contain any active elements like valves or pumps. The build-up pressure in the inlet pipe, caused by the beginning of the venting operation, let Aliquat®336 be injected in the inlet pipe. The filling and emptying connections of the Aliquat®336 tank may be sealed for any unintentional opening. It must be pointed out that the amount of the chemical agents, as well as the size of the vessel and additives tanks depends on the site specific specification. At least they must contain enough liquids to cover the so called “autarky time “, which is usually defined at 24 hours venting operation without any refurbishment.

Instrumentation

The status of the system (pressure, water level and temperature) is monitored, during the standby and the venting phases, from the filter building’s local control room with dedicated instrumentation.

All devices and visual displays are considered as passive systems and work without electric power. They are not equipped with recorders because there is usually no need to transmit the data to the main control room or to the emergency control room. Therefore, there is no interface with the existing plant instrumentation.

The indications in the local control room are the following:

- Water level in filter vessel

The water level inside the filter vessel may be checked by the operator during the periodical supervision in the standby phase. During containment venting phase, the water level indication constitutes the basis for water refilling into the filter vessel.

- Pressure measurement

Three devices monitor the pressure in several part of the vessel, such as:

- PI-1 that indicates the pressure in the filter inlet pipe at the venting phase;
- PI-2 that indicates the pressure in the lower part of the filter vessel also acting as redundancy for the water level indication;
- PI-3 that indicates the pressure in front of the isolation valve resp. the rupture disc

- Water temperature in filter vessel

This device indicates the water temperature

Auxiliary systems

The following auxiliary systems are provided for the different phases:

- refilling system: it is possible to refill the water inventory in the standby phase (if necessary) and at the venting phase after the autarky time. A pipe connecting to the external water supply is foreseen to refill the filter vessel if the water level decreases below the lower limit;
- pipe connection for draining the filter vessel for waste management after venting operation.

A.3.3 Venting operation

The only intervention needed to put the FCVS into operation, in case of a SA, is the manual opening of the containment isolation valves that allows starting the containment venting. After reaching the desired containment pressure, the containment isolation valves can be closed and opened again in case of a new containment pressure increase. Therefore the system is suitable also for multiple venting. Water refill might be required, after the autarky time, if the water level drops below the critical limit. This operation can be easily carried out by opening manually dedicated valves from the shielded local control room.

A.3.3.1 Filtration process

Aerosol removal

The overall aerosol removal process depends on thermal-hydraulic conditions, bubble hydrodynamics and geometry of the internals. Most of the total aerosol retention takes place in the nozzles region of the Stage 1.

The following phenomena contribute to the aerosol removal in the lower part of the Stage 1 zone:

- In the expansion nozzle's zone, the gas containing the aerosols reaches high velocity because of the orifice, which causes also high pressure drops. The gas, at the exit of the orifice, comes into contact with the surrounding water and a two phase flow is established. The mass and energy exchange between gas and water is maximized because of the velocity difference between the two fluids and a high collection is achieved.
- In the impact plates' zone, the two phase flow bump into the plates and part of the flow, which is deflected from the plates, is sheared off from the main steam, thus being scrubbed. In addition, the bubbles become smaller because of this impact and, increasing their interfacial area, enhance the aerosol retention. The remaining part of the two phase mixture goes on flowing through the holes. Thanks to the circulation established in the whole Stage 1, the process is repeated many times, thus scrubbing the largest amount of aerosol contained in the gas.
- Aerosol decontamination is also initially enhanced by diffusiophoretic forces due to condensation. At the beginning of the ventilation process, the temperature difference between the water pool and the entering mixture of non-condensable gases and steam is large enough to cause condensation. However, the water temperature increases rapidly and reaches levels which make diffusiophoresis negligible [75].

Experiments on aerosol removal have been carried out at PSI (see [77,76,77]) under several different conditions (e.g. flow rate, submergence, particle size). They have shown retention efficiency larger than 99 %, in case of gas impingement on small submerged surfaces with solid particles size ranging from 1 to 3 μm . Therefore, a larger impingement surface area, like in the filter design, would definitely produce a considerable aerosol removal already within this zone.

The second region for the aerosol removal is the pool zone between the impact plates and the mixing elements entry. In this region, particle's inertia and condensation-driven retention (already explained previously) affect the scrubbing process.

The water level plays a crucial role in the retention processes because the higher is the water height the longer is the residence time of the particle and the higher is the retention efficiency. The drag force due to the water velocity and the buoyancy force due to the bubble size are the key parameters to enhance the bubbles' residence time in the water.

The increase of the bubbles' hold up time, because of the circulation in the region between the riser and the annulus, is equivalent to increase in height of the water column by several meters. Therefore, a large enhancement in the aerosol removal was proven due to the extended bubble residence time.

The mixing elements region represents the last zone of the Stage 1. Here the bubbles enter the structured mixing elements and are forced to follow a so called "zigzag motion". This bubbles motion through the narrow space of these elements contributes to remove further the remaining particulates and gaseous species. In fact, the special design of the mixing elements, enhancing turbulence, allow the bigger bubbles to be broken up into smaller ones. This results in a large surface area per volume, which is needed for an efficient mass transfer for the aerosol and gaseous species removal.

Relatively large droplets, containing active dissolved fission products, are produced when the bubbles burst at the water pool surface. However, they fall back to the pool since the gas velocity above the pool is low. The smaller droplets move further to the final separation unit (moisture separator) where they are removed from the gas flow and drained back to the water pool.

It must be pointed out that the hydrodynamic conditions established in the filter are not sensitive to the pressure at the initiation of the venting.

Iodine removal mechanism

During a SA, a large amount of radioactive iodine in gaseous and aerosol form is released in the containment atmosphere. The aerosol forms of radioactive iodine are represented by metal iodides, such as CsI and AgI. Their removal can be obtained with the same methods used for the other aerosol types, like other fission products or other structural materials appearing in a particulate form.

In addition, most of them, except AgI, are soluble in water and may form iodide ions and radicals, which are oxidized, thus forming volatile iodine.

The fraction of gaseous iodine in the release, which may be quite significant, is dependent on numerous parameters and complex chemical reactions, i.e., composition of the released materials and gas composition, thermodynamic parameters, and kinetics of the reactions involving iodine in the primary circuit components.

Further chemical reactions occurring in the containment atmosphere and in the sump as well as those with the surfaces in the containment might change the initial iodine species and their time-dependent concentrations in the atmosphere and in the sump.

Elemental Iodine (I_2) and organic iodides (RI) are the most important volatile species. RI are classified as light or heavy molecular weight or a mixture of both, depending on the molecular structure of the organics, and the low molecular weight organics are dominant with respect to higher molecular weight organic iodides. In particular, methyl iodide (CH_3I) is the most volatile organic species and constitutes the largest fraction of organic iodides in containment during a SA, as emerged also from the past AECL Radionuclide Test Facility (RTF) tests conducted within the International Advanced Containment Experiment (ACE) Project in the early 90s.

In the CCI filter system, different processes are aimed at scrubbing iodine in gaseous form.

- The mass transfer plays a crucial role not only in the aerosol removal but also in I_2 and CH_3I scrubbing and is mainly due to concentration gradients in the boundary layers in both sides of the bubble – water interface;
- steam condensation rate;
- diffusion rate of the gaseous species both in the bubble and the water;
- partition coefficients of these species.

The total amount of mass species, transferred from the gas bubbles into the water is directly related to the bubble residence time in the water pool. As explained above, the mixing elements, as well as the circulation zone, ensure a long residence time in the water of the CCI FCVS.

Similar to the aerosol removal, the first zone in the system, where the removal of the major fraction of the gaseous elemental iodine and methyl iodide occurs, is the zone between the exit of the orifice and several centimetres above the gas-jet deflector assembly. In this zone the removal is driven by:

- gas iodine wash carried out by droplets;
- steam condensation, which is enhanced by mass transfer;
- high turbulence due to the continuous impingement of gas-jet/bubbles on the gas-jet deflector.

In the second zone, extending from the impact plates to the mixing elements entry gaseous species in the bubbles diffuse towards the water during the bubbles' rise. In this phase, the governing parameters are:

- individual partition coefficients;
- bubbles' surface area their concentrations in the water;
- bubble size and bubble rise time in this zone.

In the third zone, the removal is carried out by the mixing elements, which are designed specifically for efficient absorption of the dissolvable gas constituents of the bubbles. As already explained, the bubble-water circulation through the annulus provides a long residence time in the water pool, enabling a very efficient removal of the gaseous species as long as concentration of elemental iodine and methyl iodide in the water is lower than in the bubbles.

As introduced above, low concentrations of the gaseous species in water must be ensured in order to attain high mass transfer rate, thus maximizing the concentration gradient between the bubbles and the water at any time.

This goal can be reached by reducing elemental iodine and decomposing methyl iodine to non-volatile iodide ions in the water in the fastest way, in order to ensure the removal of the methyl iodine within the bubbles' residence time in the water. Dissolved I_2 and CH_3I may be rapidly decomposed in non-volatile iodide ions by using sodium thiosulphate (THS). This reagent, which is added to the water for obtaining high pH, is very effective in terms of high reaction rates with CH_3I and I_2 .

Summarizing, an effective decontamination of the volatile iodine species depends on the competing time scales defined by the gas hold up time, mass transfer rate and the decomposition reaction in the aqueous phase.

In order to increase the CH₃I decomposition, also under irradiated conditions, a phase transfer catalyst, that is Aliquat®336, has been chosen [78] for being added to the water- THS solution. This mixture removes very fast CH₃I and I₂ from the gas bubbles under all anticipated conditions (low to high water temperature, low to high pH, under irradiation, low to high methyl iodide concentration, low to high iodide concentrations, etc.). In addition to the removal, the simultaneous use suppresses effectively the thermal and radiolytic formation of volatile species in the water pool under all anticipated conditions. The use of this solution has no adverse effect on the removal of aerosols as well as on other dissolved fission products.

A.3.3.2 Anticipated decontaminations factors based on existing data bases

An extensive experimental activity has been carried out during the 20 years in order to improve the retention of aerosol, elemental and organic iodine.

Experimental campaigns on facilities properly scaled [80,79,80,81] ensure the achievement of decontamination factors shown in Table A2.

Table A2: Anticipated DF for GenII FCVS

	CCI Filter System (Gen II)
Aerosols	> 10,000
Elemental iodine	> 2,000
Organic iodine	>1,000

A.3.4 CCI FCVS references

CCI FCVSs have been reviewed and licensed by the Swiss authorities under strict regulations and have been installed in three Swiss nuclear power plant units.

APPENDIX 4

Technical description of AREVA's Combined Venturi Scrubber FCVS

AREVA offers 2 different types of combined Venturi scrubber systems:

- The FCVS STANDARD consisting of two main retention stages, and
- The FCVS PLUS consisting of three main retention stages providing enhanced gaseous iodine retention.

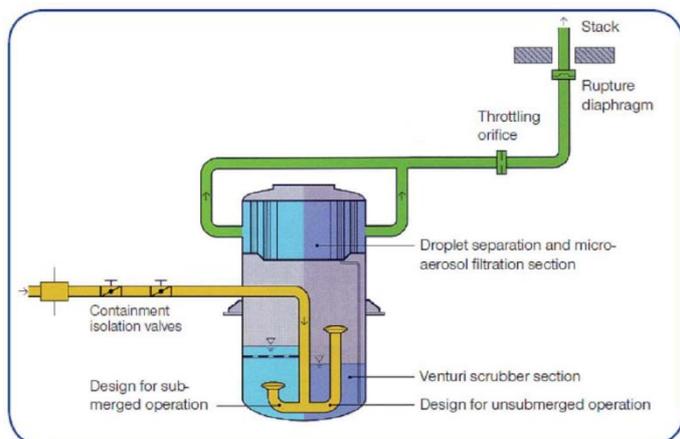
A.4.1 Description of the AREVA FCVS STANDARD

The AREVA FCVS STANDARD comprises a Venturi Scrubber Unit (see Figure A.4.1 and A.4.2) consisting of a Venturi section and a combined droplet separator and metal fibre filter section (wet/dry deep bed filtration) and a throttling orifice for a sliding pressure process (Figure A.4.3).

The Combined Venturi Scrubber Unit is connected at one end to the containment via vent piping and isolation valves and at the other end to the exhaust stack via a line equipped with the throttling orifice. The FCVS is activated when the containment vent pressure has been reached by opening of the containment isolation valves. Closing of one of the containment isolation valves when the predetermined pressure has been reached shuts off the venting process.

The Venturi scrubber unit is operated at pressures close to the prevailing confinement pressure. The vent gas flow entering the Venturi scrubber is injected into a pool of water via a number of submerged Venturi nozzles. As the vent gas, containing aerosols and iodine, passes through the throat of the Venturi nozzle, it is accelerated to high velocities and provides effective suction of scrubbing liquid into the Venturi throat which is entrained.

FCVS STANDARD



1. Venturi Scrubber (wet section)

- ▶ Most aerosols retained
- ▶ Most elemental iodine retained (mid term)

2. Metal fiber Filter (dry section)

- ▶ Large pre and fine filter surfaces
- ▶ Penetrated Fine Aerosols retained
- ▶ Re-suspension Aerosols captured

Figure A.4.1: Scheme of AREVA Combined Venturi Scrubber FCVS Standard



Figure A.4.2: Installation examples of FCVS STANDARD

By the entrainment and dispersion of the scrubbing liquid large reaction surfaces are created in the Venturi nozzles which result in an additional effective sorption of iodine. For optimum iodine retention, the scrubbing liquid is conditioned with caustic soda and other additives.

According to the very high velocities of the vent gas and the large velocity difference between the scrubbing liquid and the incoming vent gas more than 99.5 % of the aerosols are already retained in the

liquid pool, including fine aerosols sized $< 0.5 \mu\text{m}$ (see A.4.3). The vent gas leaving the liquid pool still contains a small amount of hard to retain so called micro aerosols and water droplets from the liquid pool.

To ensure high retention efficiencies – even in a long operating time – a high efficient filter demister-droplet separator and a dry operated metal fibre filter is installed as a second filtration stage. The metal fibre filter combination is arranged in the upper region of the vessel vertically to enable large filter surfaces and optimized filter velocities.

By retaining the majority of the aerosols in the scrubbing pool the thermal loads (decay heat) as well as the aerosol loads (mass) to the metal fibre filter are reduced to a minimum, thus avoiding any clogging. Decay heat removal during system operation as well as in the following phase will be ensured by evaporation of scrubbing liquid.

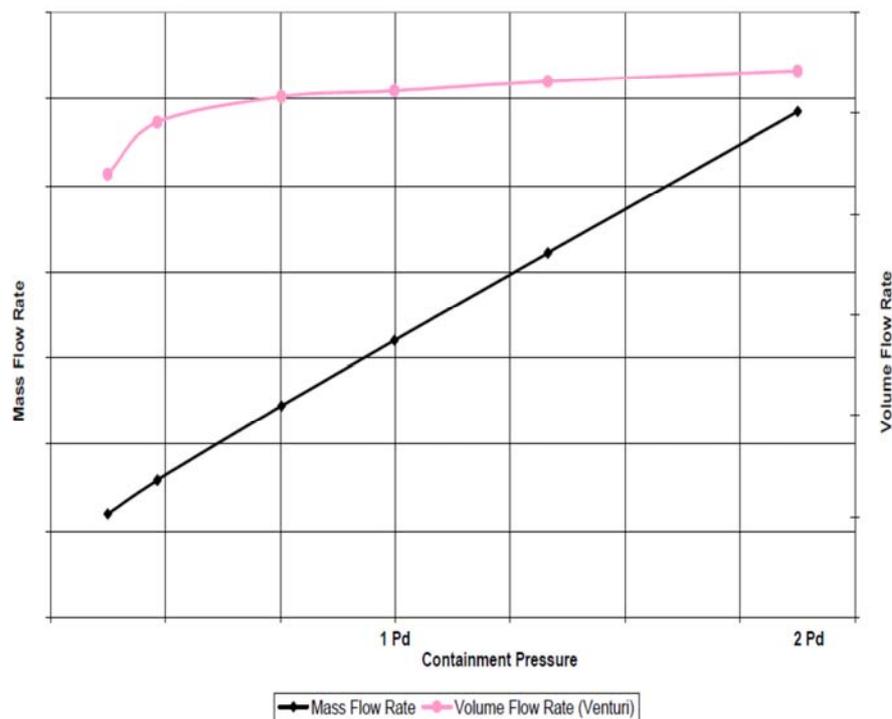


Figure A.4.3. High Speed Sliding Pressure Process – Principle comparison of mass flow rate and volume flow rate during the venting phase

The Venturi Scrubber Unit is operated in a passive manner at pressures close to the prevailing containment pressure levels due to the provision of the throttling orifice in the filter discharge line. This sliding pressure mode and the specific process design ensures that the system operates in a wide range of high speed velocities in the Venturi stage and limited velocities at the metal fibre filter stage for optimum system function.

Thus in case of system activation beyond the designed start-up pressure, e.g. very late system activation at a higher containment pressure (2x design pressure), the mass flow rate will be further increased. However, due to the sliding pressure process (Figure A.4.3) the operating velocities of the

retentions stages (Venturi nozzles and metal fibre filter) remain in optimum operation conditions and hence achieve the required retention rates. The optimum retention stage operation will also be reached in early venting system activation cases (e.g. at half of design pressure or lower).

Thus the AREVA FCVS provides internationally qualified retention efficiencies for aerosols > 99.99 %, which is also applicable for micro aerosols smaller than 0.5 μm , over a wide operating range and total retention efficiencies for gaseous molecular iodine > 99 %. As a consequence combining the unique features of very high speed Venturi scrubber operation and a high efficient metal fibre filtering provides reliable operation of the system even during long term system operation.

A.4.2 Description of the AREVA FCVS PLUS

Based upon the observation of the Phebus tests [59,60] organic iodine is produced in a greater extent during core melt accidents as assumed before. Although the expected total amount of CH_3I remains small, the radiological impact of unfiltered organic iodine is significant when high decontamination factors (DF) are reached for aerosols and elemental iodine. Recent studies show a significant generation of organic iodine in the containment atmosphere during a SA [59,60]. Hence, a significant increase of organic iodine retention of FCVS System would be a meaningful optimization that is currently discussed in the nuclear community.

Consequently, the AREVA FCVS Plus was developed by supplementing the existing FCVS Standard Combined Venturi Scrubber with an integrated Sorbents as a third retention stage (Figure A.4.4).

After the gas is cleaned and dried in the Venturi and metal fibre filter section, the gas is throttled, which is generally described as an extensively isenthalpic and adiabatic process. Thus although the temperature downstream the orifice decreases, the gas entering these molecular sieve section – avoiding any heat losses – reliably superheated. This passive process ensures high, superheated temperatures in the molecular sieve under operating conditions which guarantee high retention efficiencies of organic iodine.

The adsorptive retention stage is characterized by its high robustness. As a commonly used industrial technology molecular sieves can be designed to target specific adsorptive, e.g. organic iodine. Additionally, they are highly insensitive to poisoning effects. Molecular sieve based filters are today in operation at the dissolving process of used fuel elements, e.g. in la Hague, for the retention of organic iodine.

FCVS PLUS

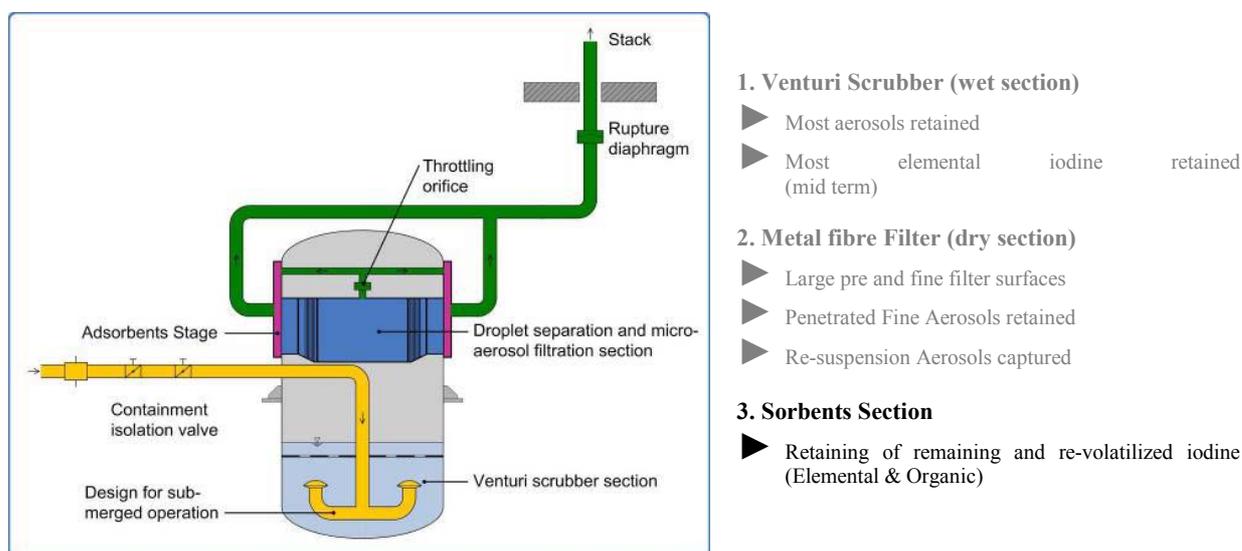


Figure A.4.4: Scheme of AREVA Combined Venturi Scrubber FCVS^{PLUS}

In addition clogging of the molecular sieve is ruled out due to the combined process. Aerosols as well as water droplets are removed by the Venturi stage and the metal fibre filter section. The molecular sieve is made completely from non-burnable material and is resistant to high temperature ($> 300^{\circ}\text{C}$). Due to its high loading capacity, it is able to retain the specified amount of iodine without regeneration or replacement.

A.4.3 Qualification

The AREVA High Speed Sliding Pressure Process for containment filtered venting is internationally qualified by independent third parties. In addition all relevant qualification tests were generally performed on a large scale basis. A process section in original height - fully representative regarding relevant parameters, e.g. as velocities in the Venturi nozzles, metal fibre filters, droplet separator, sorbents section, etc. – was extensively tested.

A.4.3.1 Qualification of FCVS STANDARD

A.4.3.1.1 JAVA Test Programme (Large-Scale Tests)

In order to determine the overall retention efficiency of AREVA FCVS, the retention efficiencies for aerosols and iodine as well as the aerosol load capacity were verified by a process verification test programme at the large scale iodine and aerosol retention rate test facility JAVA in Karlstein / Germany.

The retention rates for aerosols of different sizes including hard highly penetrating fine aerosols and iodine were tested at the JAVA test facility using a full scale section of the Venturi scrubber. The tests were performed for steam, air and mixtures of both, for steady state and start-up conditions, for pressures from 1 to 10 bar and for flow rates varying over a wide range.

Further, CO₂ was added to the test gas to cover situations with molten-core-concrete-interaction to investigate the influence on the scrubbing liquid regarding iodine retention.

Also the scrubbing liquid was investigated and tested regarding its stability and robustness considering the chemical additives for iodine retention. Special attention was given to ensure that the scrubbing liquid does not have any negative effect on aerosol retention.

The pool is operated under saturated water conditions and only an insignificant amount of water is lost from the pool, obviating the need for scrubbing water makeup.

The main mass fraction of aerosols (>> 99 %), including smaller aerosol sizes, will be retained in the scrubbing liquid. That means that a decay heat value of only a few kW will be deposited into the metal fibre filters.

Considering the large metal fibre filter area the related thermal rating can be handled by heat conduction to the outside vessel. Additionally, the convective heat transport by the gas flow through filters (mainly steam after operation) would allow an even higher decay heat load. However, no credit was taken for this fact.

Results for aerosols

The results of these test series showed for the combination of a Venturi scrubber with a metal fibre filter, retention efficiencies of > 99.999 % for aerosols over the entire operating range (even at low gas velocities). The retention efficiency for these aerosols was verified by tests using a relevant aerosol composition covering the entire spectrum.

Results for fine aerosols

The qualification tests carried out at a full scale test facility showed retention efficiencies for the fine aerosols greater than 99.99 %.

This retention capability applies to micro-aerosols (fine aerosols) of less than 0.5 µm so that, for example, variations in the particle size distribution of the aerosols cannot diminish the removal efficiency. The retention efficiency for those fine aerosols was verified by dedicated tests using a fine aerosol fraction.

Results for iodine / organic iodine

The water in the scrubber pool is alkaline conditioned to retain elemental iodine, in addition to the aerosols. The average retention efficiency for elemental iodine was measured to be > 99.8 %.

The tests were performed using elemental iodine, but organic iodine was generated inside the test facility as a by-product.

Therefore, some retention potential for organic iodine inside the scrubbing pool could be observed.

Results for re-suspension / re-volatilization

Furthermore, owing to the high efficiency of the second filter stage, re-volatilization – even of soluble aerosols – has been found negligible. Re-volatilization of iodine was found to be less than 0.1 % over an operating period of even 24 h.

A.4.3.1.2 ACE – Phase A (International programme)

In the frame of the international ACE programme, the international community discussed, under participation of authorities, various research institutes and filter experts the relevant requirements. They finally formulated the enveloping standardized test conditions for all participating FCVS systems. These independent international tests are to be considered as the agreed international venting qualification standard requirements and complement the venting process qualification conducted at the JAVA facility.

The ACE tests were also performed for aerosols of different sizes (Cs / Mn) including high penetrating fine aerosols (DOP) as well as for iodine. At the ACE test facility an adapted section of the AREVA Venturi scrubber (Venturi nozzle and a filter/demister) has been used and the standardized tests were performed for steam / air mixtures (expected vent gas composition).

The results showed significant features in retention ability, loading capacities und re-suspension effects of the different tested dry and wet filter devices (a few filter designs failed in the tests – others did not participate).

Results for aerosols

Within these test series wet scrubber systems (Venturi scrubber with a metal fibre filter) showed an excellent performance for the used test aerosols (Cs / Mn) and reached very high decontamination factors. For the AREVA FCVS a DF greater than 1,000,000 was reached for the tested conditions.

For the high penetrating fine aerosol fraction test with DOP (AMMD of 0.7 µm) - representing a late venting situation with predominant fine aerosol releases - a DF of 20,000 was reached.

Loading capacity

Only combined scrubber systems showed high loading capacities (deep bed filter systems were found to be sensitive to clogging due to high aerosol loads – which is important in the case of low flow rates / low containment pressures during long term operation).

Results for iodine

Like in the JAVA test series, the scrubber liquid in the pool is alkaline conditioned for optimum iodine retention. The following DFs were reached: A DF greater 3,000,000 for particulate iodine (aerosol bounded iodine) and 300,000 for total iodine (including gaseous) were reached for the tested conditions.

Results for re-suspension

Furthermore, due to the high efficiency of the second filter stage (metal fibre filter) a very low re-volatilization rate – even of the critical, but representative soluble Cs aerosols – less than 0.0034 % of the retained aerosols was measured even over a period of 24 h. For insoluble aerosols - e.g. Mn - significantly lower re-volatilization was measured compared to Cs.

Scrubber systems without efficient second stage (metal fibre filter) showed significant re-suspension rates for aerosols (especially unfavourable during long term operation as already retained aerosols in the scrubber are re-entrained by the gas and finally released).

A.4.3.2 Qualification of AREVA FCVS PLUS

For organic iodine retention in the third retention stage a high performance adsorptive is included in the AREVA FCVS^{PLUS}.

Due to the separation into a third retention stage the verified DFs for the first two stages (Venturi and metal fibre filter section) are not affected. Hence the Qualification of the FCVS STANDARD is fully applicable to the FCVS PLUS.

According to state-of-the-art qualification practice also independent third party testing was incorporated from the beginning of the test programme for the molecular sieve (TÜV – German Inspection Agency).

Sorbents qualification (laboratory scale)

The TÜV had been assigned to conduct retention experiments on the sorbent media for optimization and qualification support. Organic iodine is continuously injected into a steam / air mixture and channelled through the molecular sieve which is used for the FCVS^{PLUS}. The performance of the molecular sieve under extreme conditions e.g. very low superheating, condensing steam conditions, long term operation, radiological aging etc. could be verified. Further the influence of the parameter residence time had been investigated.

Large scale verification (JAVA PLUS)

The former JAVA test facility had been modified into the JAVA PLUS test facility (see Figure A.4.5). The test facility is especially constructed for the testing of FCVS and hence includes specific instrumentation and process control.

In order to demonstrate the retention efficiency under the relevant operating cases – especially to optimize the process design and avoid unpredictable laboratory scale-up effects - , e.g. tests as,

- frequent start-up;
- continuous operation with containment pressure variation;
- variation of gas contents;
- etc.

have been performed.

The combined scrubber vessel (original height) as well as the mass flow rate injected represents a scaling factor in the range of approximately 1/10 of a real venting system (depending on the application). Since the single process sections are integrated in the original scale full representative results can be produced.

The large scale organic iodine retention tests have been conducted at the JAVA^{PLUS} test facility in order to improve the real technical design and to verify the retention efficiency of the supplemental organic

iodine retention section within the FCVS PLUS. Under various process conditions for the representative technical process section, decontamination factors (DF) for organic iodine > 50 ($> 98\%$ retention) have been verified.



Figure A.4.5: Computer model and Picture of the JAVA PLUS test facility, Karlstein Germany

Comparison of organic iodine retention efficiency results of TÜV laboratory tests with integral large test verification tests (JAVA plus)

Comparing the JAVA PLUS large scale tests of the measuring campaign and the TÜV laboratory scale tests it was observed, that the organic iodine decontamination factors at lab scale were significantly (unrealistic) higher (**factor $> 10 -100$**), compared to the obtained large scale tests retention factors of >50 ($< 98\%$).

These observed scaling effect/factor are generally caused by the locally different operating condition (e.g. velocities, temperature, turbulences, reaction surfaces, chemical concentrations, etc.) inside such heavy, large scale retention unit. It may be caused by the following parameters:

- The partly different (not uniform) operating condition and flow dynamics inside the larger scale retention unit;
- Wall effects, caused e.g. by the heavy mechanical design (weights, wall thickness of retention devices, arrangement restrictions of mixing, filtering and adsorption elements, etc.);
- Mass transfer surface effects of mixing and retention elements; (e.g. influence on bubble size and quantity, accessibility of reaction surfaces);
- Complex heat transfer effects (e.g. cold surfaces and edges combined with locally low flow velocities may result in an unexpected slow heating process);
- Dirt effect (no clean laboratory conditions);
- Transient operation conditions (e.g. heat up and cooling down operating cases, including frequent operation);

- Sum of all these integral effects measured at the entire process verification, combining
 - process internal passive generation of the super heating enthalpy by throttling / expansion drying;
 - and
 - the retention of the real mechanical equipment (including realistic heat transfer effects and heat losses in transient operating cases as heat up and cooling down, including frequent operation, etc., as mentioned above.

Conclusions:

As reported laboratory test results may hence lead to unrealistic high retention factors and operating features, if laboratory tests results are simply copied to full size retention devices. The principle and method of common industrial praxis, to perform integral large scaled prototype tests - generally at a scale factor in the range of 1/10 - is agreed to deliver very reliable results. The method of integral large scale retention testing provides therefore reliable results which are an excellent basis in the licensing procedure.

A.4.3.3 Summary of Qualification

The AREVA FCVS solutions are extensively qualified. A wide variety of aerosol types in different gas flow and gas content conditions have been tested in order to cover the different aerosol properties (e.g. solubility, hygroscopic, density, gas conditions, etc.) and the diameter range to a maximum extent including the filter gap region (including 0.1 µm particles).

Used Aerosol Remark

- BaSO₄ solid
- Uranine soluble; fine aerosol
- SnO₂ solid; fine aerosol; high/low concentrations possible
- CsI hygroscopic, soluble
- MnO solid
- DOP solid; fine aerosol

In addition, also the retention of gaseous iodine (elemental and organic iodine) was tested.

The qualification is strongly based on most representatives large scale tests. In addition the independent third party testing was included to a significant extend (ACE & TÜV). A summary of the tests results is displayed in Table A.4.1.

Table A.4.1: Summary of test results of AREVA's Combined Venturi Scrubber FCVS based on large scale tests

PROJECT	YEARS	Materials tested	Conditions Tested			Measured retention Efficiency %
			Pressure [bar abs]	Temperature [°C]	Gas composition % steam	
JAVA	1989-1990	BaSO ₄	1.6-10	75-192	0-100	99.992 - 99.999
		SnO ₂	1.8-6.1	90-200	0-100	99.997 - 99.999
		Uranine	2-6	98-119	0	99.997 - 99.999
		gaseous I	1.6-10	140-160	30-100	99.0 ^a -99.9
ACE	1989-1990	Cs	1.4	145	42	99.9999
		Mn	1.4	145	42	99.9997
		Total iodine (particles and gaseous)	1.4	145	42	99.9997
		DOP	1.2-1.7	ambient	0	99.978 - 99.992
JAVA PLUS <i>[applicable for FCVS PLUS only]</i>	2012-2013	Gaseous organic iodine	1.5-8	80-170	50-95	> 98

^a Measured at severe conditions: non-alkaline pH value, non-submerged Venturi nozzle. Not representative for normal operation.

A.4.4 Licensing / Standard Compliance

In different types of nuclear power plants for a wide range of requirements and different standards.

A.4.5 References

More than 50 applications in PWR, BWR and VVER nuclear power plants worldwide (Germany, Switzerland, Netherlands, Finland, Bulgaria, Canada; China, Korea; Japan,...).

A.4.6 Key Features

The resulting key features could be summarized as follows:

- Control of captured fission product decay heat, even up to values of > 100 to > 1000 KW;
- Reliable retention of activity in short and long term vent operation;
- Hydrogen safety considered (system may be designed to withstand hydrogen combustion loads).

Highly efficient regarding:

- Reliable mid- and long-term operation thanks to the combined benefits of the high speed wet scrubbing technology and the most efficient dry metal fibre filter features;
- Maximum retention rate of aerosols > 99.99 % (DF > 10,000) and molecular iodine > 99.5 – 99,9 % (DF > 200 – 1,000) and organic iodides > 98 % for FCVS plus (DF > 50);
- Large excess storage capacity for aerosols and iodine, e.g., > 200 to 500 kg;
- Complete process verification, even under elevated sliding pressure and temperature conditions with different types and sizes of aerosols and iodine;
- Recirculation of the activity back to the containment;
- etc.

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