AREVA's Filtered Containment Venting System (FCVS)

Basic Design, Performance and Verification Test of FCVS for BWRs

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After the great earthquake and a tsunami as consequence March 11, 2011, a severe accident happened at nuclear power plant Fukushima Daiichi. The severe accident lead to core damage and containment failure and finally to large release of radioactive substances to the environment. As part of the severe accident management and to reinforce the mitigation concepts against a containment failure, the Filtered Containment Venting System (FCVS) will be introduced at Japanese nuclear power plants, to have a possibility to depressurize safely and reliable the containment via a filtered process. This paper describes AREVA FCVS technology and its application for Japanese BWRs and also the background of the qualification and the licensing approach.

Key Words: Severe Accident Management, Containment integrity, Filtered Containment Venting, FCVS, Qualification, ACE test, JAVA test

1. Introduction

After the great earthquake and a tsunami as consequence March 11, 2011, a severe accident happened at nuclear power plant Fukushima Daiichi. The severe accident lead to core damage and containment failure and finally to large release of radioactive substances to the environment. As part of the severe accident management and to reinforce the mitigation concepts against a containment failure, the FCVS will be introduced at Japanese nuclear power plants, to have a possibility to depressurize safely and reliable the containment via a filtered process.

2. AREVA FCVS Technology

The AREVA FCVS is based on a three stage filtering:

・Stage 1: wet scrubber with high speed venturi
・Stage 2: dry filter with metal fiber filter (MFF)
・stage 3: sorbent section with molecular sieve

The patented key technology for the AREVA FCVS is the sliding pressure principle in combination with the high speed operated venturi nozzles and the passive superheating of the sorbent section mainly by isenthalpic throttling. By the introduced throttle orifice downstream the MFF it is ensured that independent of the containment pressure the volume flow through the venturi/MFF is widely constant. Downstream of the throttle orifice a passive superheating effect for the molecular sieve is generated to ensure high retention efficiency of the sorbent section for organic iodine.

The three stage FCVS process design of AREVA has the following advantages:

・highest retention for all types of aerosols
・safe transfer of majority of fission products and decay heat in wet scrubber by high aerosol and elemental iodine retention
・elimination of filter gap for aerosols by combining high speed operated venturi in the wet scrubber and MFF
・no clogging risk for MFF and minimum decay heat on MFF by upstream venturi section
・molecular sieve only affected by pre-cleaned gas
・passive superheating is ensured by isenthalpic expansion of gas downstream of the second retention stage
・compact size and split vessel design gives high flexibility

A principle flow diagram of the Sliding Pressure Venting is given in figure 1.

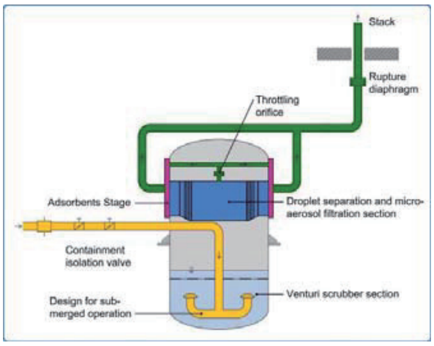

Fig.1: AREVA FCVS – Principle flow diagram

The Venturi scrubber unit is operated at pressures close to the prevailing containment pressure. The venting flow entering the scrubber is injected into a pool of water via a small number of submerged, short Venturi nozzles. The ratio of the diameter of the aerosols and the Venturi throat precludes any clogging.

As the vent gas passes through the throat of the venturi nozzle, the incoming gas flow develops a suction which causes scrubbing water to be entrained with it and, on account of the large difference between the velocity of the scrubbing water particles and that of the incoming vent flow, a large proportion of the aerosols are retained

Due to the high velocities a huge speed difference between the

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scrubbing water and the incoming vent flow, more than 99 % of the aerosols are retained in the venturi pool section and even small aerosols (0.5 μm and lower) are quantitatively retained. At the same time, the particles of the entrained scrubbing water provide large mass transfer surfaces inside the throat of the nozzle, which permit effective sorption of iodine.

Optimum retention of iodine, especially elemental iodine, in the pool of water inside the scrubber is attained by conditioning the water with caustic soda and other additives. The gas exiting from the pool of water still contains small amounts of hard-to-retain aerosols as well as scrubbing water droplets. In order to ensure high retention efficiencies specifically also over a long period of time - for example operation of more than one week - a high-efficient droplet separator and micro-aerosol filter is provided as a second retention stage.

The combined advantages of high speed wet scrubbing technology with the most efficient dry fiber filter feature enables reliable mid and long term operation. Even under extremely low flow conditions the reduced venturi retention efficiency is fully compensated by the filter demister. The combination of both filter sections provides retention efficiency for aerosols of 99.99 % and more.

This retention capability also applies to micro-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 elemental iodine under various conditions is verified to be above the required retention efficiency of 99.5 % in the scrubber section and is further increased by the third stage.

The third filter stage, the sorbent section with molecular sieve, receives only pre-cleaned gas and functions solely with high retention efficiency for organic iodine and re-volatilized or remaining elemental iodine, if present.

3. AREVA FCVS Qualification

3.1 Principle

The AREVA FCVS qualification is fully based on large scale tests and additional international testing series by third party.

Large scale verification of performance is the state-of-the-art approach for reliable function of severe accident (SA) mitigation equipment, due to:

・process verification under realistic conditions

・scale up models and scaling factors are vulnerable for errors for complex processes as FCVS is one

・large scale test minimizes scaling effects and increase reliability of results

The AREVA FCVS qualification is based on the large scale tests with JAVA facility and JAVA PLUS facility, where PLUS stands for the organic iodine retention tests. The functional tests were performed under representative conditions using a complete process segment with a scaling factor up to 1:5 and full scale components.

In the frame of the so called international ACE (Advanced Containment Experiments) program the community discussed under participation of authorities, various research institutes and filter experts the relevant requirements. Finally they formulated the enveloping standardized test conditions for the participating FCVS suppliers.

3.2 JAVA - Iodine and Aerosol Testing Facility

The tests in the full-scale JAVA facility covered aerosol removal efficiency tests as well as tests for iodine retention on a full-scale test facility (stages 1 and 2), especially at pressures above the atmospheric level.

Aerosol retention tests were performed using soluble Uranine and non-soluble $BaSO_4/SnO_2$ aerosols having a mass mean diameters in the region of 0.5 - 1 μm.

As a result of the combination of venturis with MFF, at system pressures of 1 to 10 bar aerosol retention efficiencies of > 99.99 % were verified under full-flow conditions and even at reduced gas flows - due to the higher efficiency of the second section (see Table 1).

Table 1: Exemplary JAVA Test results for fine aerosols with Uranine

Pressure (bar)	Temp. (°C)	Gas Flow (m^3/h)	Medium	Contaminated Gas Concentration (mg / m^3)	Total Removal Efficiency (%)
2.4	99	1000	Air	0.795	99.999
2	98	600	Air	0.875	99.999
6	119	600	Air	1.265	99.999
6	107	1350	Air	0.086	99.999
6	116	1000	Air	0.254	99.999
2	99	1000	Air	0.451	99.999
3	105	1220	Air	0.332	99.997

The total iodine removal efficiency of the entire venturi unit was determined in short-term and long-term tests. The elemental iodine removal efficiencies provided by this two stage filtration equipment were consistently above the required retention efficiency of 99.5%. These results have been obtained even under operating conditions that have an unfavorable effect on gas sorption such as the following:

・elevated system operating pressure

・reduced venturi velocities and

・every higher pH value than neutral condition.

Iodine re-vitalization tests yielded re-vitalization rates of < 0.1 % over an operating period of 24 hours and using air content in the vent flow of 10 % by volume. [1]

3.3 ACE Test Program Phase A – Filter Test Program

Extensive tests were performed according to the recommendations of international experts on the testing and qualifying of containment venting devices for severe accident conditions, e.g. with accident typical aerosols Cs, I, etc. and in addition a standard dioctyl phthalate (DOP) test in the submicron size range and furthermore tests to study of re-entrainment effects. The results of the US ACE Phase A Filter Test Program showed filter specific findings in retention ability, loading capacities and re-suspension effects of the different dry and wet filter devices

The atmospheric tests on aerosol retention carried out at Battelle Northwest as part of the international filter comparative tests with supervision of international independent Third parties (authorities) were performed under standardized test conditions using the following aerosols and included resuspension measurements.

A plasma-torch-generated mixed aerosols (Cs, Mn, I – injection via mixing vessel to enable formation of different chemical forms and aerosol growth and agglomeration) and a

micro-aerosol (DOP – injected directly to avoid aerosol growth and agglomeration) served as the principal test aerosols.
The decontamination factor (DF) of the AREVA Combined Venturi Scrubber, which were determined by the mixed aerosol test are shown in table 2.

Table 2: ACE Test results for AREVA FCVS

Aerosol	DF
CS	1,400,000
Mn	> 1,000,000
I	300,000

Re-suspension has a significant effect on the entire iodine and aerosol removal efficiencies during continuous long term operation and imposed by the authorities in this respect. This subject was investigated using very sensitive methods in the ACE tests (to quantify even smallest re-suspension effects).
In the official ACE report the evaluation of the combined Venturi scrubber, based on the obtained experimental results for retention and re-suspension, were summarized as follows:
・no rise of pressure drop detected during the test (loading with aerosols) and therefore no clogging risk
・high loading capacity for aerosols
・high retention for large and fine aerosols
・high process robustness
・high compactness
"All DFs were very high, on the order of 10^6, indicating excellent aerosol removal…"[2]

3.4 Improved Organic Iodine Retention

3.4.1 Selection and Development of Technology

In order to increase the organic iodine retention zeolites seem to be best suited. Due to their non-flammable nature and their insolubility in water they can be employed under the FCVS specific process conditions. Especially sorbents with a silver based coating proved to have a high affinity for organic iodine, even at temperatures close to the dew point. The iodine retention reaction is based on a chemisorption which is of a non-reversible nature since the affinity of silver to iodide is much higher than its affinity to other halogens or volatile compounds that can be released during core melt accidents. Due to the high loading capacity of the selected zeolite the fixed bed provides sufficient "storage capacity" for iodine during a core melt accident without need of replacement or regeneration.

3.4.2 Sorbents qualification for harsh environmental conditions

AREVA has assigned for independent third party testing the TUEV (independent German institute for technical supervision) to conduct retention experiments on the sorbents media. During numerous performance tests on laboratory scale basis the organic iodine retention efficiency of the molecular sieve was examined under defined conditions. At different superheating conditions CH_3I was injected in an air/steam mixture and continuously supplied into the molecular sieve. In addition stress tests were performed in order to verify that temporary condensing conditions, long term tests (more than 100 h of continuous operation) and exposure to thermal stress and irradiation, etc. do not challenge the organic iodine retention.

The performance testing of different sorbent materials had been performed to find the best sorbents for the required application. Further, the test data had been used for sizing the molecular sieve stage of large scale test facility JAVA PLUS.
In general, the chemical industry follows often the approach from laboratory to process component via the intermediate step of a prototype in the scale of about 1:10.
It is obviously known that scaling of chemical processes has to be well understood, mathematically correctly expressed and dissolved to enable correct scaling up.
Due to the difficulties of complex microscopic and macroscopic processes it is often more reliable and cost effective to choose the approach via this intermediate step of a prototype performance testing than a theoretical scaling immediately to the process component. [4]

3.4.3 JAVA PLUS – Large Scale Performance Testing of Organic Iodine Retention

The organic Iodine retention large scale tests were performed after modification of the JAVA test facility to JAVA PLUS (see Figure 2),

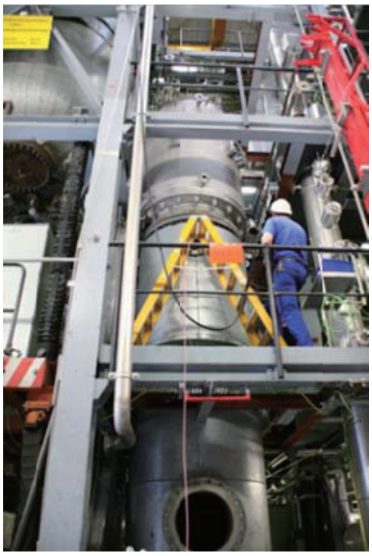

Fig. 2: AREVA JAVA PLUS Test Facility

These large scale tests were performed simulating different venting scenarios as containment pressure, gas composition. Special focus was given on superheating effect and residential time as key factors for the retention efficiency of the molecular sieve
As representative organic iodine species it had been decided to use methyl iodide (CH_3I) for the performance tests. Methyl iodide is very volatile and (in terms of quantity) supposedly the most dominant organic iodine species. In addition methyl iodide is very hard to retain due to its volatility and small size. Hence it is generally considered as a conservative, representative molecule for the group of organic iodine.
The approach for the molecular sieve qualification as third stage of the AREVA FCVS is shown in Figure 3.
The organic iodine removal efficiencies provided by this third stage filtration of the FCVS were consistently > 98 %. These results have been obtained even under operating conditions that

have an unfavorable effect such as the following:
・start up with cold molecular sieve
・low superheating effect
・short retention time

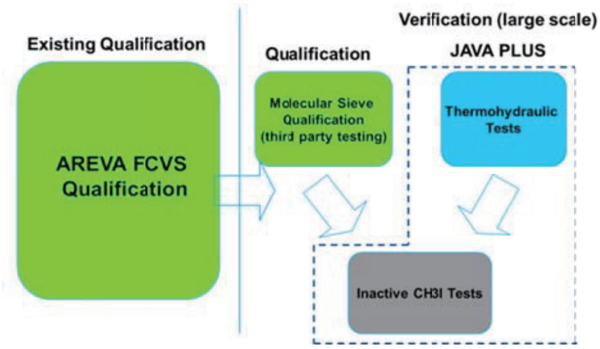

Fig. 3: AREVA FCVS PLUS Qualification

The retention efficiency with >98% is the minimum value, under various process conditions retention efficiencies > 99 % were measured. [3]
The sorbents stage is usually subject of customization to target DF defined by customer/country specific requirements.

4 AREVA FCVS for Japanese BWRs

BWR utilities as e.g. Chubu and Chugoku decided on AREVA FCVS implementation. For this implementation AREVA is cooperating with Hitachi-GE and Toshiba. The AREVA technology provides the highest process efficiency and robustness, the most extensive process qualification and the highest expertise enhanced by continuously project execution. The product is always benchmarked by competition and by discussions in the international expert community leading to continued R&D and product enhancements.
The basic requirements as discussed for the BWR application are as follows:

- 1 % of the reactor rated thermal output from PCV
- FCVS capacity designed for a venting via drywell with preferred venting path via wet well
- Fulfill seismic requirements
- High retention efficiency for aerosols and Iodine (elemental and organic)
- fail-safe overload capability in case of delayed venting operation up to two times of PCV design pressure without any cliff edge effect regarding filtering efficiency

5. Summary

AREVA FCVS is a proven design and worldwide installed. AREVAs experience covers all designs as PWRs, BWRs, VVERs and PHWRs and includes one vessel solutions and split vessel solutions (see Figure 4). AREVA demonstrated also that installation inside existing building is feasible. Even FCVS with molecular sieve section was already installed in Bulgarian VVER Kozloduy 3 and 4. In Japan currently several AREVA FCVS systems for BWR and PWR are under construction.

Fig. 4: AREVA FCVS – worldwide references installed and under construction (status April 2014)

The FCVS process design of AREVA with three stages filtering overcomes:
・disadvantages of single filtration as for wet scrubber and dry filters as stand-alone filtration
・filter gap for aerosols is widely eliminated
・patented technologies ensure highest retention also for fine aerosols in wet scrubber section and also ensures passive superheating for effective organic iodine retention in the molecular sieve.

The qualification and performance tests of AREVA FCVS are fully based on large scale testing and international tests with third, independent party involvement resulting in
・minimization of scaling effects
・high reliability of FCVS process

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