FILTRA-MVSS (Multi Venturi Scrubber System)

Presentation to U.S. NRC, Washington DC

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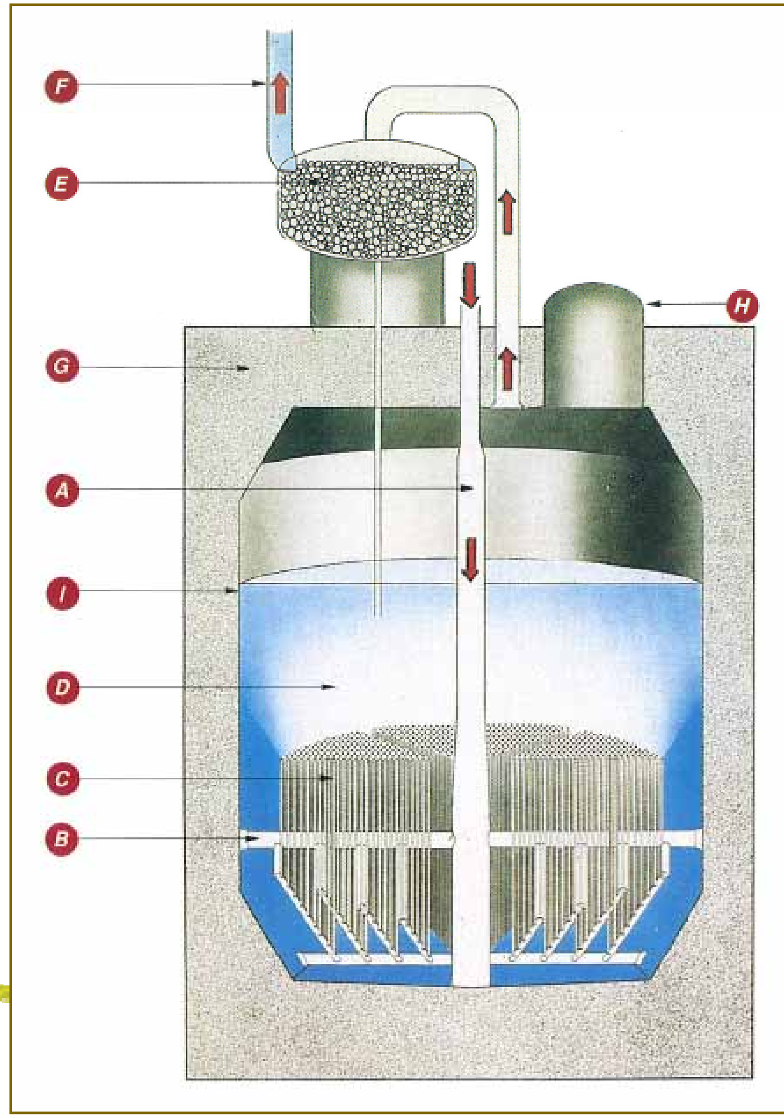
POWER | ALSTOM

Agenda

- Historical background
- New System Design
- Filtering Technology
- Qualification of FILTRA-MVSS
- Sizing assessment regarding severe scenarios
- Stress Test Conclusions
- Conclusions

Multi Venturi Scrubber (Liner Version) 1988 design

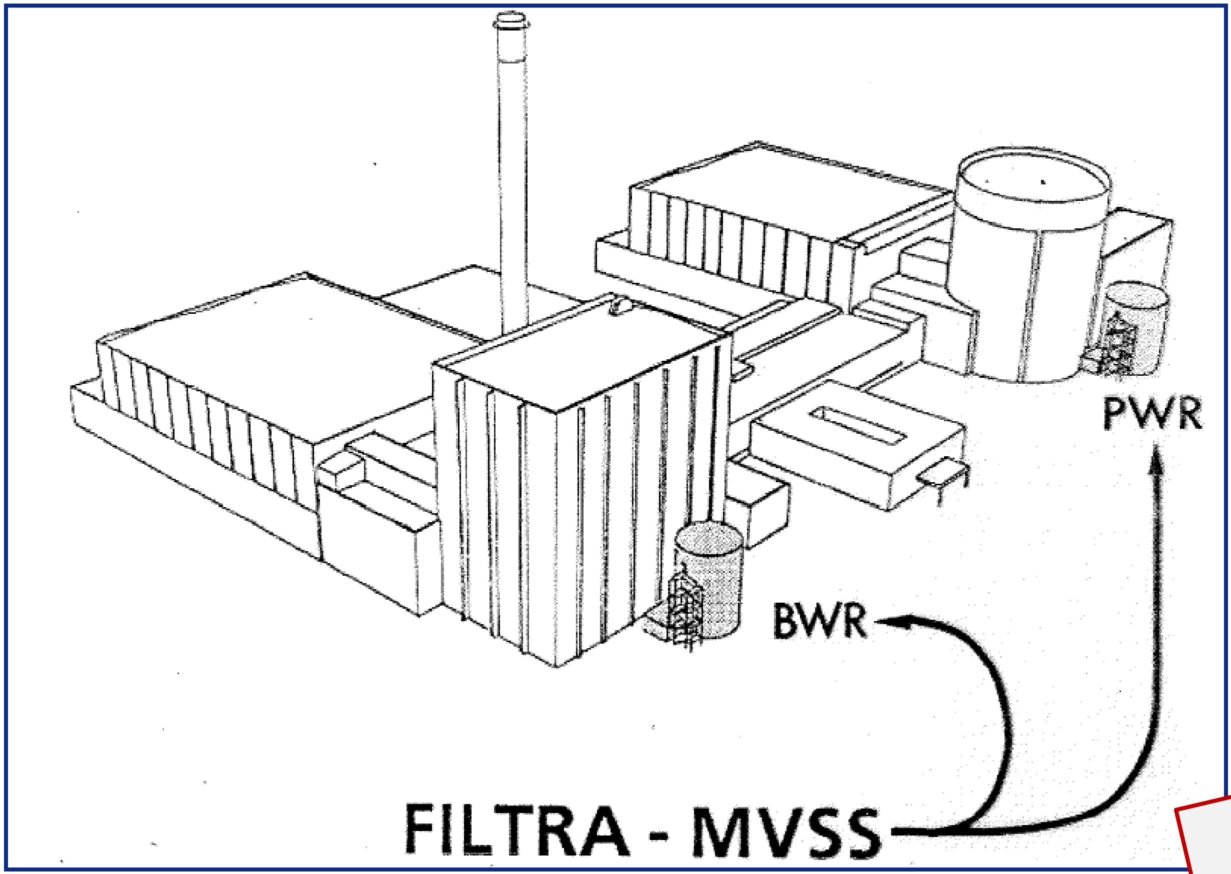
A: Pressure relief line from reactor containment
B: Venturi distribution system
C: Venturis including riser pipe
D: Pool
E: Moisture separator
F: Release to atmosphere
G: Pressure Vessel
H: Manhole
I: Liner



The Swedish FILTRA – MVSS is located outside the reactor building in a concrete pressure vessel equipped with a liner.

The concrete serves as both a pressure retaining structure and shielding. A gravel bed is used as moisture separator due to the sturdy design requirement.

Installed in both PWRs and BWRs



- Equally suitable for both PWR and BWR
- Excellent design features for both types

Installation example:
Ringhals PWR and BWR

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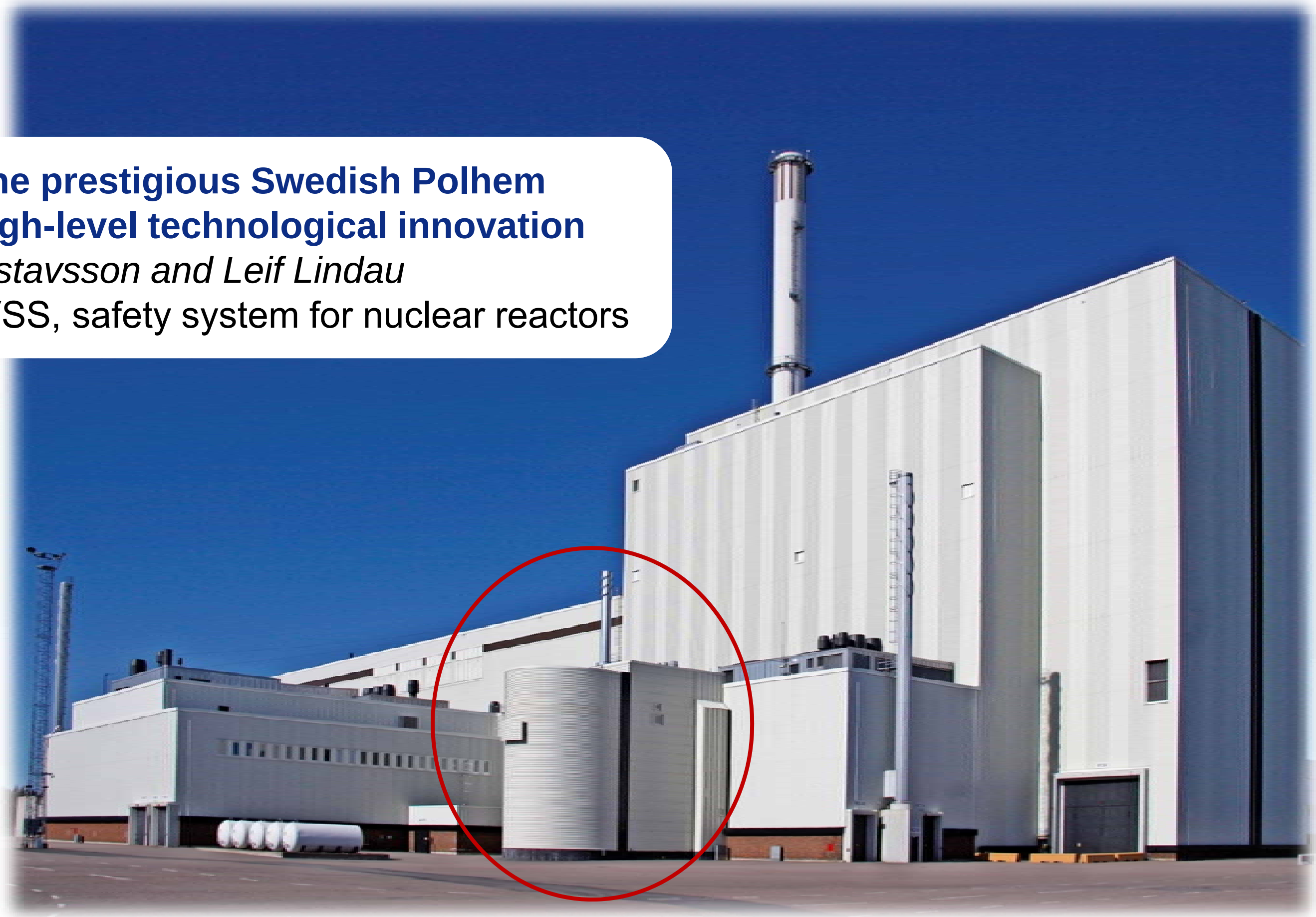
FILTRA-MVSS - Proven, awarded design

Awarded the prestigious Swedish Polhem prize for high-level technological innovation
Lennart Gustavsson and Leif Lindau
FILTRA-MVSS, safety system for nuclear reactors



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Swedish Requirements for Installed Systems

Design Basis
Station black-out
Design requirements
Passive system for at least 24 h
High decontamination factor for aerosol and elementary iodine
Cover a wide range of hypothetical severe accidents for BWR's and PWR's
Operation
Automatic or Manual activation (allows early venting)

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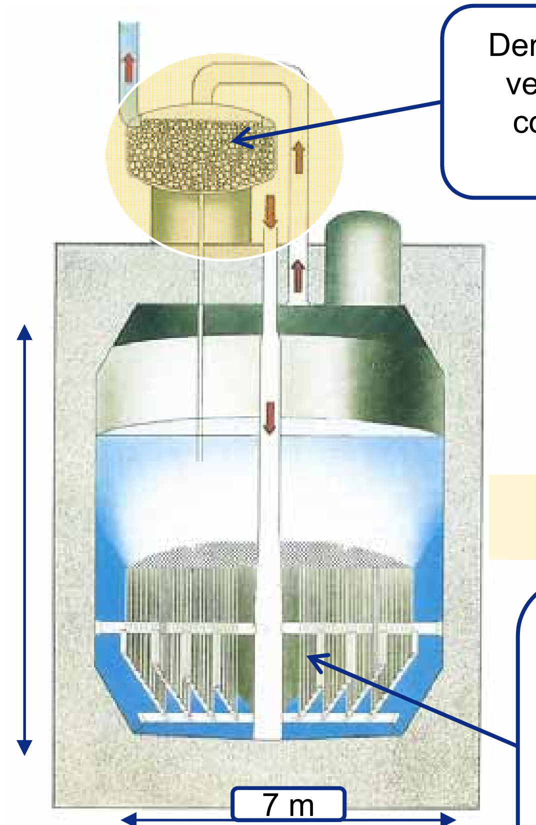
FILTRA-MVSS, New system design

1st generation and 2nd generation design

New version of the FILTRA-MVSS system:

Liner version



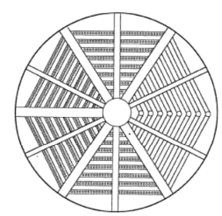
8,5 m - 10,5m

7 m

Demister moved inside vessel with standard components of less weight and size

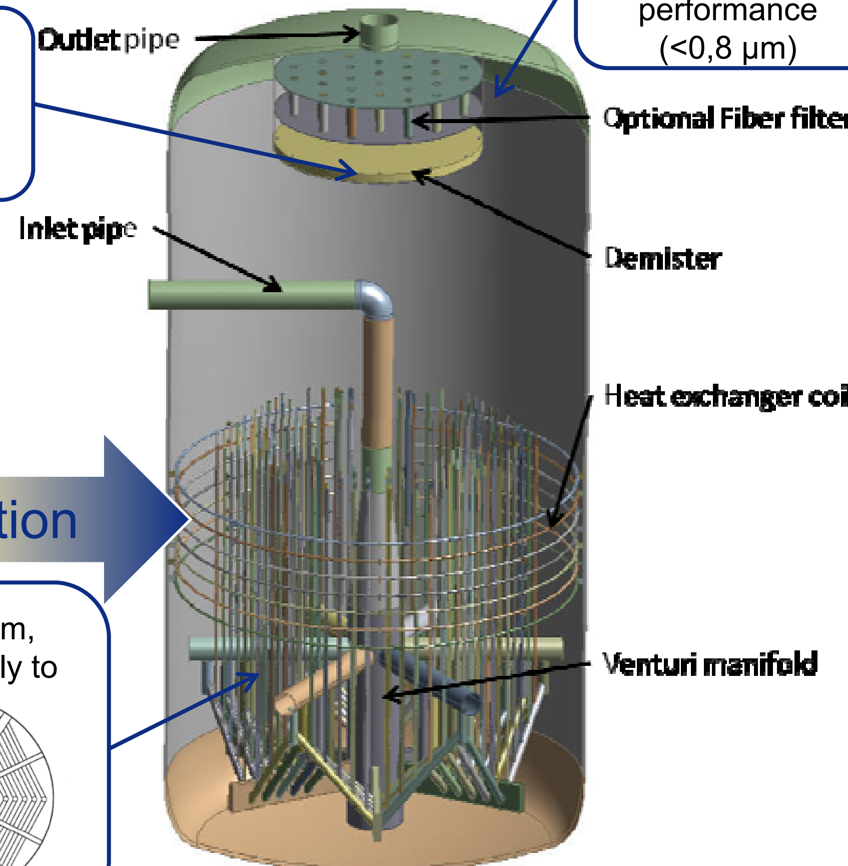
2nd Generation

Same venturi system, changes related only to vessel



Steel tank version

Metal fiber filter (sintered) added for improved performance (<0,8 µm)



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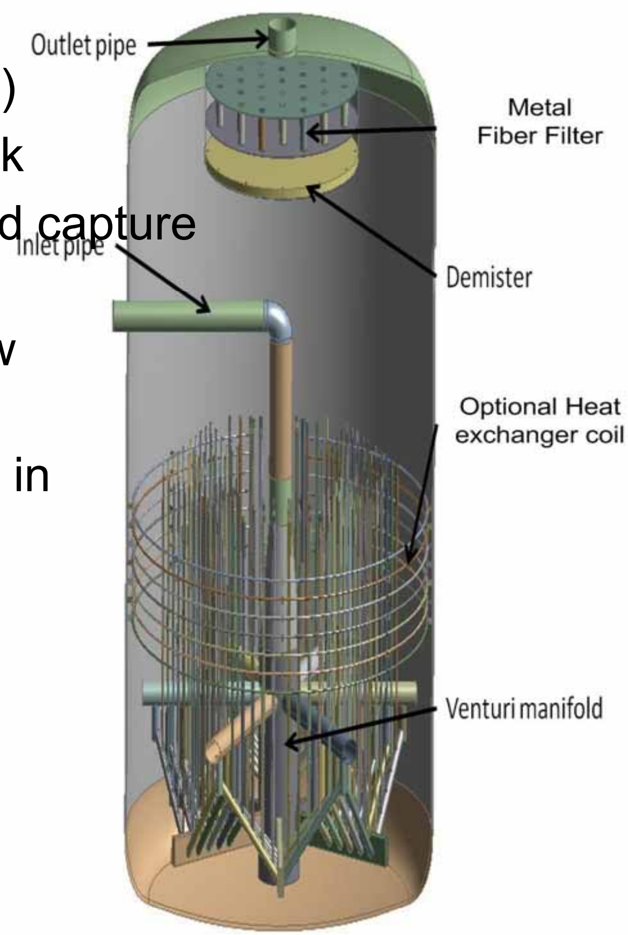
FILTRA-MVSS, New System Design

Overall improvements

- Steel tank allowing pressurization to reduce size
- Easily adjustable to NPP unit needs (size, weight, DF)
- Standard demister with less weight, moved inside tank
- Metal fiber filter (sintered) in series to increase DF and capture even smaller particles
- Shortened installation time since tank and venturi now is manufactured independent from building.
- Tank and internals verified for seismic loads provided in the Design Specification
- No change in venturi design, it is verified for the new conditions and requirements and has solid base for licensing



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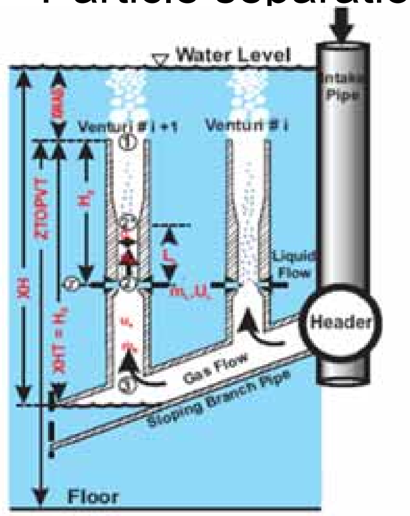
FILTRA-MVSS, Filtering technology

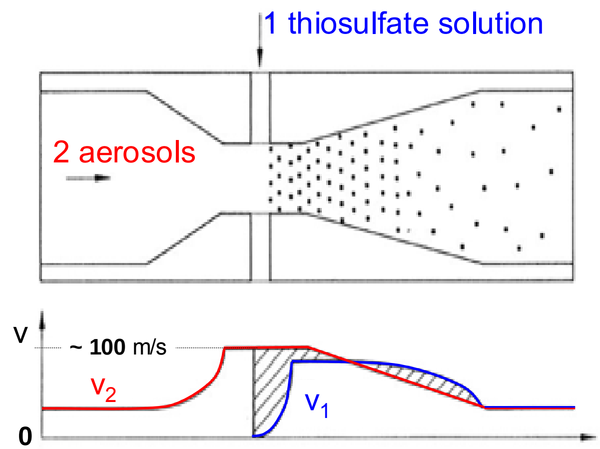
Principles of decontamination in a MVSS venturi

Key physical and chemical separation processes

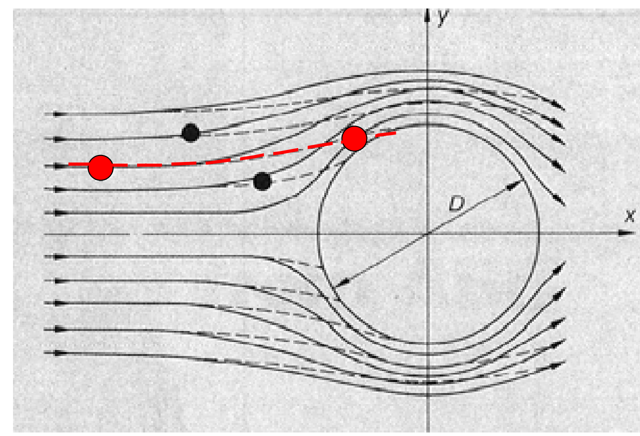
- Particle separation in multi-venturi nozzles:



i) adapting mass flow



ii) velocity difference at throat



iii) inertial particulate separation

- Pool scrubbing of aerosols and elemental iodine
  - Reinforced aerosol separation in the pool
  - $S_2O_3^{2-}$ (thiosulphate) chemical absorption of Elemental Iodine (I_2):

$$2\,S_2O_3^{2-} + I_2 \rightleftharpoons S_4O_6^{2-} + 2\,I^-$$

$$2\,S_2O_3^{2-} + I_3^- \rightleftharpoons S_4O_6^{2-} + 3\,I^-$$

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FILTRA-MVSS, Filtering technology

Comparison to conventional venturi system

CONVENTIONAL VENTURI :

- Fan to pump gas for pressure drop
- Pump to supply liquid
- Active control device (variable throttle) for gas capacity control

MVSS is PASSIVE:

- Uses vertical pipe length water column as pressure drop
- Uses inlet gas acceleration under pressure suction to pump liquid into gas for uniform coverage
- Uses sloping pipe water lock as optimal gas capacity control
- Uses pool bubbling as additional *gas* absorption step and as scrubbing drop collector
- Results confirm DF is independent of operating conditions and given by total pressure drop:at all conditions, the same DF was obtained

MVSS venturi design was developed based on classic venturi theory - verified by testing

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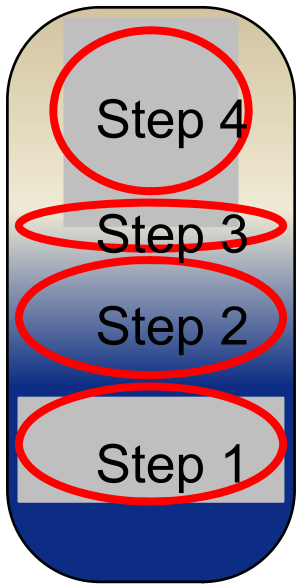
FILTRA-MVSS, Filtering technology

Key critical elements of filtration

- **Step 1 High DF for aerosols**
  - Keep aerosol mass (=decay heat) from accumulating in later steps
  - Must not clog
- **Step 2 Efficiently retain and cool captured aerosols**
  - Must have coolant enough to not dry out during passive period
  - Captured aerosols must not accumulate to create hot spots that may lead to damages
  - Efficiently retain and cool captured aerosol and iodine by chemical bonding to sodium thiosulphate in water
- **Step 3 Prevent contaminated droplets from leaving the scrubber**
  - Must not be clogged by water or two phase foam
- **Step 4 High DF for small aerosols**
  - Fiber filters should only receive small amounts of aerosols to prevent melt between repeated venting.
  - Must not clog



FILTRA-MVSS, Filtering technology

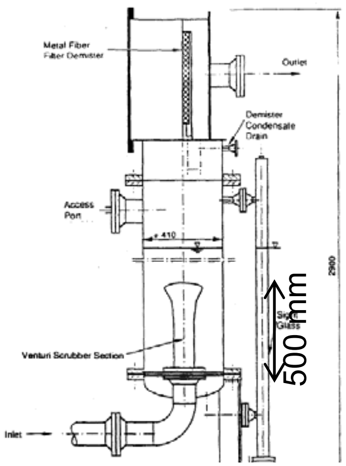
Filter step 1 - Venturi

- High efficient venturi scrubbing
  - DF > 1000 for aerosols so that all fission products are kept in water
  - Prevents fiber filter step from large decay heat
  - Superior nozzle design, most efficient water scrubber function
  - Efficient scrubbing of elemental iodine
- Independent of ventilated flow
  - Same excellent DF within design flow range
  - Genius flow distribution activates necessary number of venturi
  - Allows venting from low containment pressure, start from 7 psi (g)
- No risk for clogging or hotspots
  - No narrow passages that collects particles
  - Venturi pipes in robust design made of 316L stainless steel

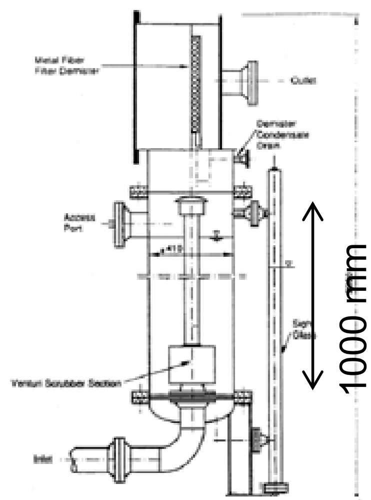
FILTRA-MVSS, Filtering technology

Filter step 1 - Venturi design a key parameter for DF

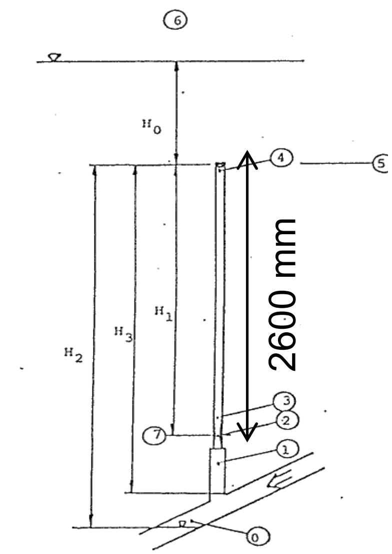
From ACE - test report



Other supplier
short tube



Other supplier
long tube



MVSS

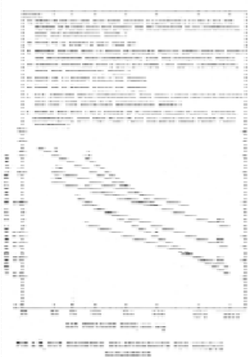
- DF particles is given by total pressure drop between the venturi throat and the riser pipe outlet
- Highest pressure drop for MVSS (height of 2600 mm) other suppliers (500 mm and 1000 mm)

A tall venturi pipe is important for a high DF for particles

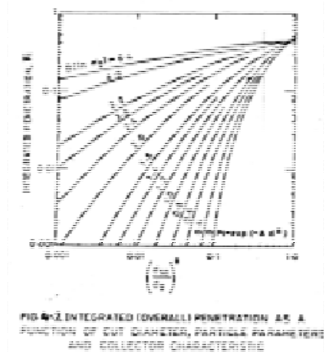
FILTRA-MVSS, Filtering technology

Filter step 1 - Venturi design a key parameter for DF

Estimated DF particles from established design rules and ML/MG 1 - 3



Emperical relation between the cut size (the aerodynamic particle diameter having 50% collection efficiency)and the venturi pressure drop



Integrated total DF as a function of cut diameter

The FILTRA-MVSS **venturis** are performing ~10 times better than nozzles used in other wet filtered scrubber systems

Design	Height (m)	Total dp (kPa)	Venturi dp (kPa)	D50% Aerod (µm)	DF MMD*=1.5 (µm)	DF MMD*=1 (µm)	DF MMD*=0.5 (µm)
MVSS	2.6	26	25	0.2	1100	400	150
Other supplier Long tube	1	10	9	0.35	110	60	9
Other supplier Short tube	0.5	5	4	0.5	60	30	2

MMD= GMMD=Geometrical Mass Median Diameter based on the particle size distribution with respect to particle geometrical diameter

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Filter step 2 - Water mixing

- Contributes to total aerosol filter efficiency with DF>2
- Large free water volume
  - Sized to allow long passive period of collect and retain active fission products
  - Efficiently decay heat removal from retained aerosols with internal heat exchanger sized for venting during extended SBO
- Elemental Iodine removal
  - Sodium thiosulphate Increases total DF of Iodine with fast chemical reactions
  - Large water volume can dissolve and retain large quantities of Iodine

Large amount of water gives best overall system functionality

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Filter step 3 - Demister

- Verified functionality
  - Tested in laboratory for all related conditions
  - Reduces more than 97% of droplets
  - No collection of contaminated aerosols, rinsed and cooled by steam
- Dependable design in 316L stainless steel
  - Mounting inside tank and verified seismic together with stress analyses for tank and all other internals
- Accessible for service and inspection
  - Contributes to total DF

FILTRA-MVSS, Filtering technology

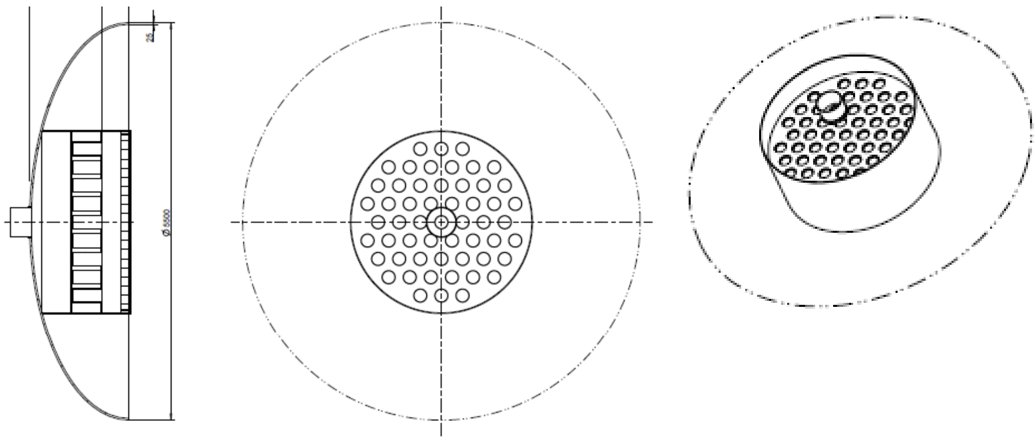
Filter step 4 - Metal Fiber Filter (Sintered)

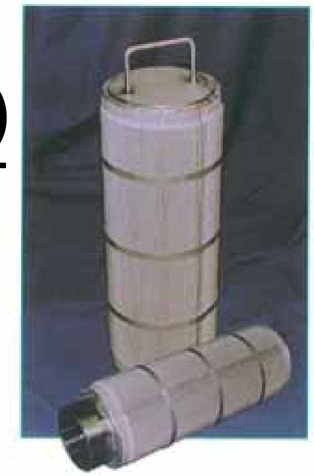
- Used for small particles with size less than 0,8 µm
- Modular design, particle holding capacity and differential pressure is decided by the number of filter elements
- Extensive laboratory testing for HEPA quality
- Dependable design in 316L stainless steel
- Mounted inside tank and verified seismic together with stress analyses for tank and all other internals
- No loose parts, by-pass after seismic chock not possible
- Accessible for service and inspection
- Contributes to total DF > 10000

Protected from large decay heat collection by efficient venturi filter step 1

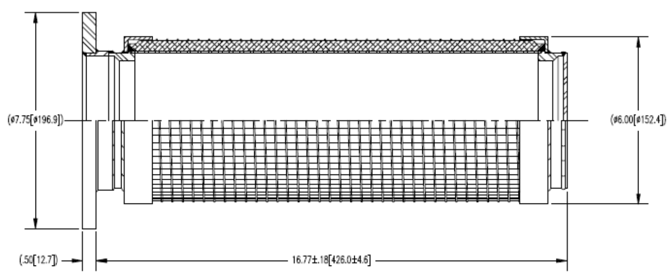
FILTRA-MVSS, Filtering technology

Filter step 4 - Optional metal fiber filter (Sintered)





Tank top with filter elements installed



Media pack construction of the proposed filter – end fittings and dimensions according to plant specific demand

Experience

- Fifty-eight installations in Europe
- Four installations in China (two under manufacture)
  - Two units - delivered in 2002
    Two units - scheduled for delivery the end of January 2013

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FILTRA-MVSS, Qualification Process

Venturi Verification Process - Model building

Experiments under near prototypical conditions with controlled scaling using proven chemical engineering scaling laws and detailed modelling

The venturi model has been modularized and each step has been validated by experiments

- **Step 1**
  - Two-phase modelling of flow in each venturi →lab testing
  - Drop size modelling →lab testing
  - Particle collection (DF) modelling →lab testing
  - Transient behaviour evaluation →lab testing
- **Step 2,** Full scale dynamic test. Pool behaviour
- **Step 3,** Advanced Containment Experiments

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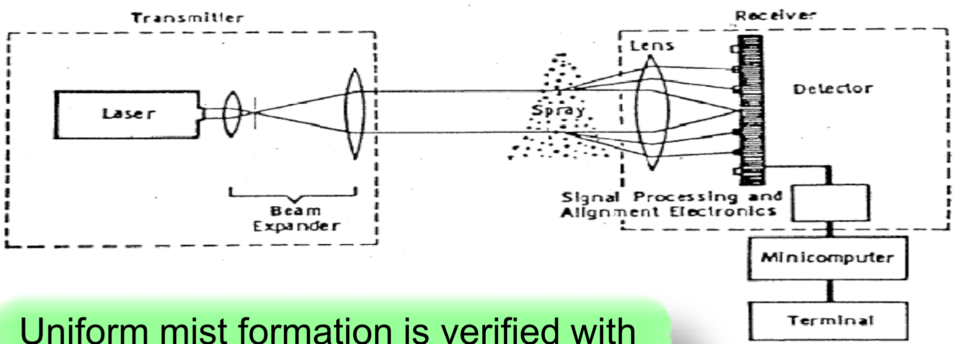
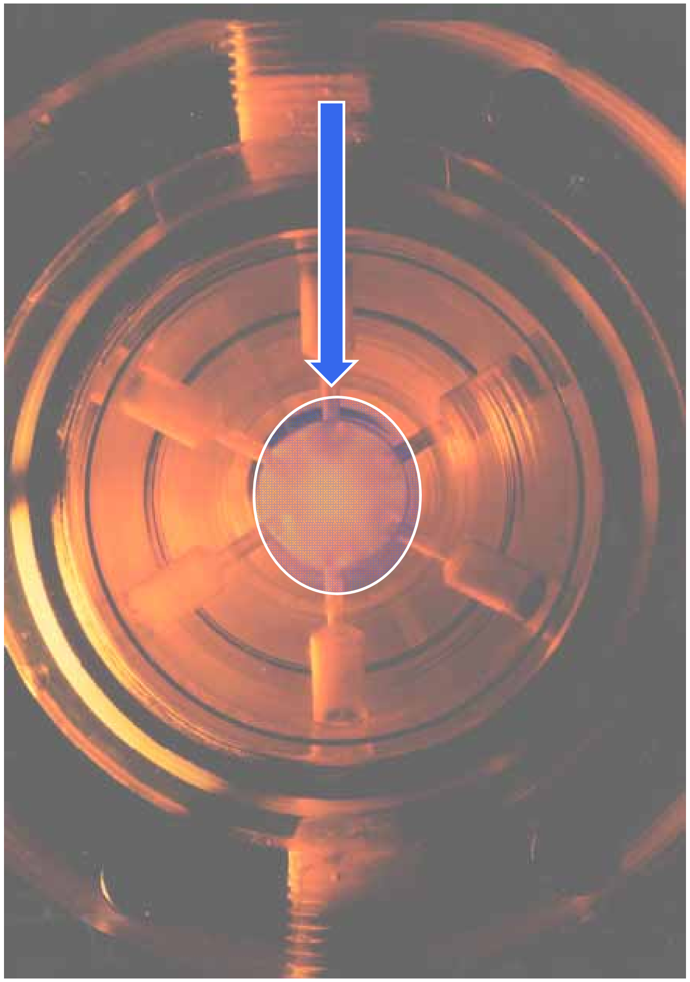
FILTRA-MVSS, Verification process - Step 1

Two-phase modelling of flow in each venturi

- Flow visualization using Perspex models
- Example to the right is study of various design alternatives to find maximum coverage of gas flow by injected water
- Laser diffrator rig for droplet size determination, below





Uniform mist formation is verified with labrig for visual overview and size determination (laser diffraction)

FILTRA-MVSS, Verification process - Step 1

Particle collection modelling

- DF model is based on classic venturi theory*
- Single drop collection mechansim is mainly *Impaction of* particles in high velocity flow around droplets
- Impaction controlled by dimensionless Stokes number, K
- This gives expression

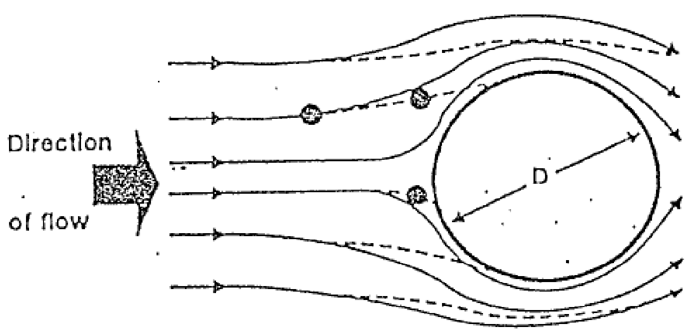
$$\text{Fractional DF} = \text{DF(particle size)} = f\,(K, M_L/M_G)$$

$$(K = C \cdot \rho \cdot d^2 \cdot v / 9 \cdot \mu \cdot D)$$

- Result integrated over all venturis and over all particle sizes for total DF

C =Cunningham slip correction
ρ= particle density
v= gas velocity
μ = gas dynamic viscosity
D = drop size
d= particle size

*"Venturi Scrubber Performance Model", USEPA 1977 Rep. No. 600/2-77-172



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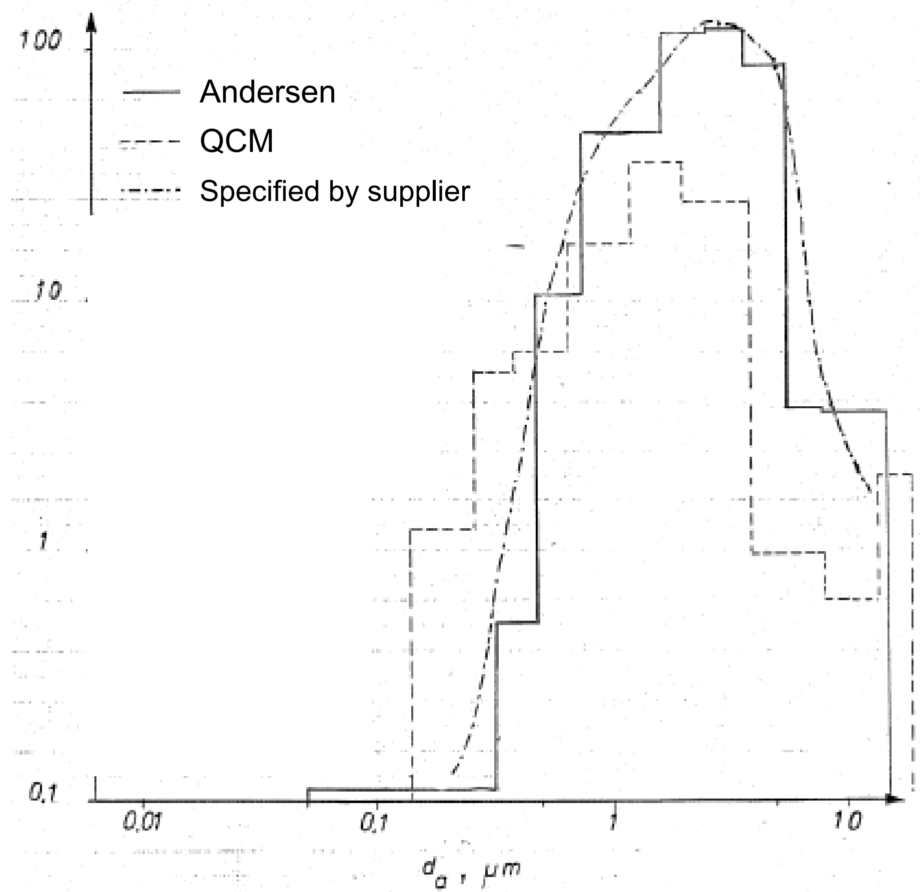
FILTRA-MVSS, Verification process - Step 1

Particle collection modelling

Concluded test aerosol

- Redispersed "Minusil" (silica) arerosol
  - MMD = 1.5µm
  - P = 4000 kg/m3
  - Distribution = σ2
- Impactor measurements confirm that aerodynamic size distribution is prototypical
- Measured with impactors
  - Andersen method (chosen method)
  - QCM method



*MMD= GMMD=Geometrical Mass Median Diameter based on the particle size distribution with respect to particle geometrical diameter

FILTRA-MVSS, Verification process - Step 1

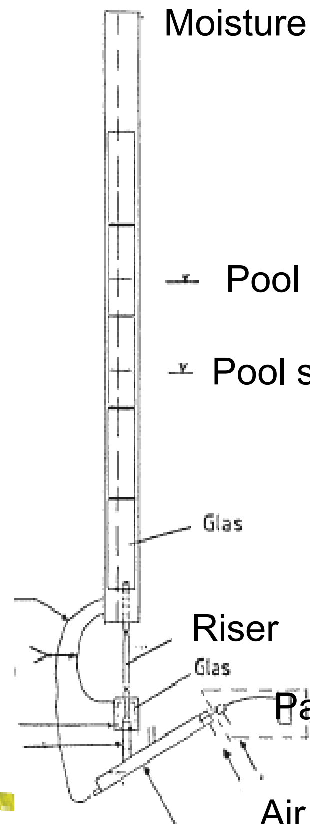
Particle collection modelling

High pressure single nozzle test rig

Lower Part

Massive laboratory work to determine model parameters by empirical methods

Single nozzle test rig 1



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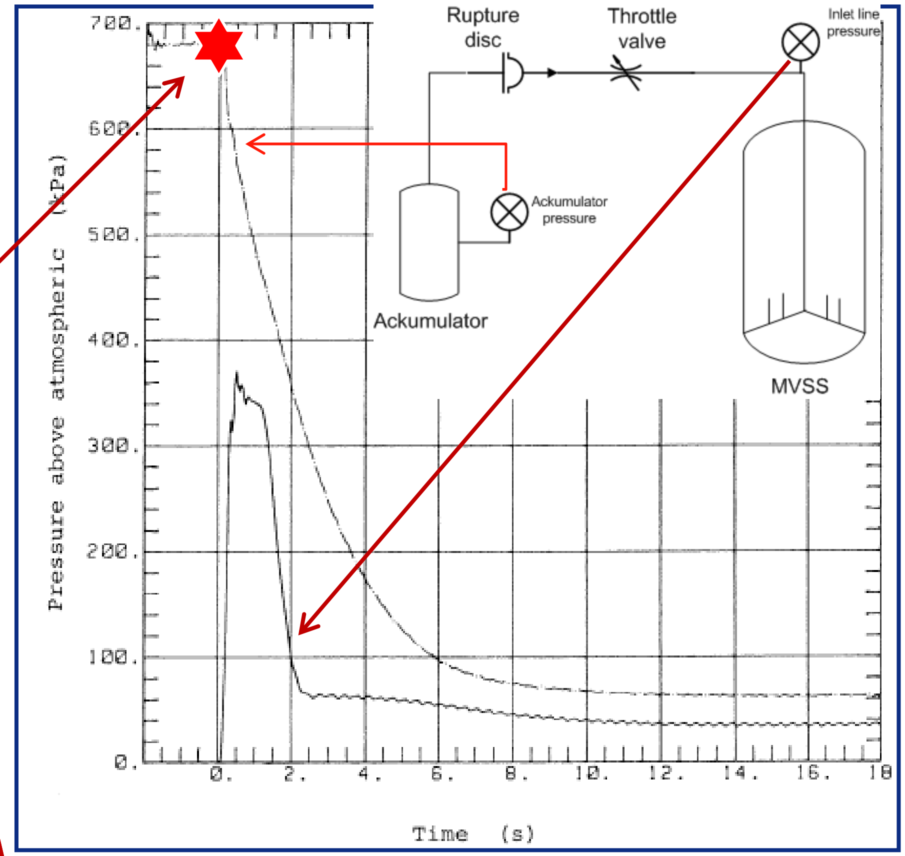
FILTRA-MVSS, Verification process - Step 2

Full scale dynamic test

- Performed at Forsmark 2, 1988
  - Full size FILTRA test after installed in Forsmark
- Verify transient pressure and water levels for different gas mass flows
  - Transient behavior of water after rupture disc break
- Rupture disc break at 780 kPa (abs)
  - Ackumulator tank filled with compressed air
- Max inlet pressure 460 kPa (abs)
  - Pressure rise to remove water from tubes
  - After less then 10 seconds only pressure difference in filter was due to water level in tank
  - According to calculations
- Max. water level +0,6-0,7m
  - Water density lower (volume increase) during "bubble phase"
  - According to calculations



APPROVED by Swedish regulatory body

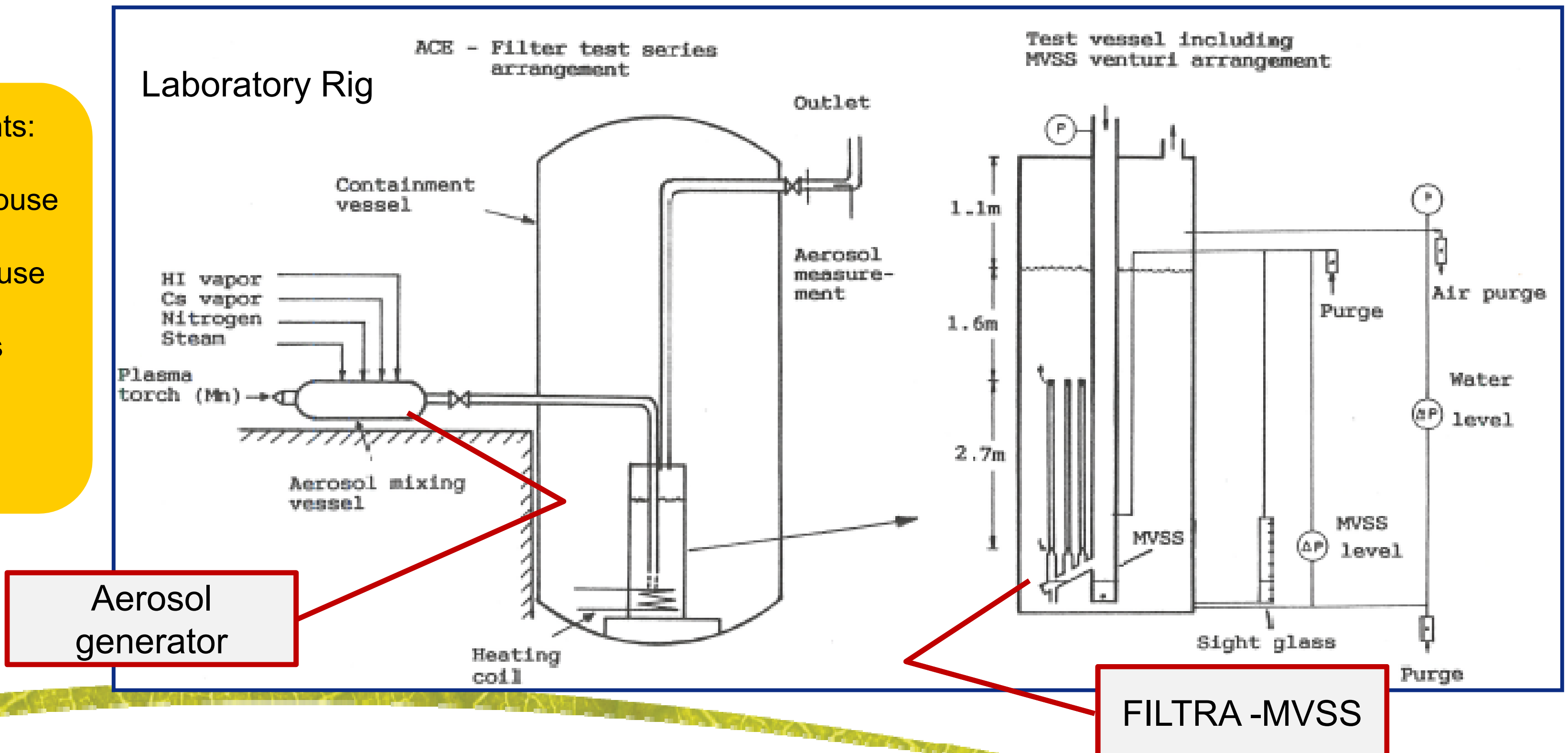
FILTRA-MVSS, Verification process - Step 3

ACE verification

- Advanced Containment Experiments
- Performed in the Containment Systems Facility (CTF), Hanford Engineering Development Laboratory, U.S.

ACE Participants:

ABB/Westinghouse (Wet)
YIT/Westinghouse (Dry)
Areva/Siemens (Wet)
Edf (Dry)
Russia (Wet)



FILTRA-MVSS, Verification process - Step 3
ACE-verification, summary of results

- Aerosol with AMMD*= 2µm, sigma=2
- Measured DFs:

Aerosol	1% steam	40% steam
DF Cs	25000	31000
DF I	19000	54000
DF Mn	1500	1500

	AA11	AA12
INLET:		
Gas flow rate, m^3/s	0.090	0.093
Gas temperature	113	129
Pressure, kPa	153	150
Volume steam fraction	0.012	0.407
Saturation temperature, °C	17	87
OUTLET:		
Gas flow rate, m^3/s	0.096	0.061
Pool temperature, °C	23	32
Submergence of top of MVSS, m	1.67	1.77
Pressure, kPa	106	105
Volume steam fraction	0.024	0.044

- Overall DF Mn same as calculated
- Cs and I components interaction with steam improves DF with a factor of the order of 15

Terminology explanation:
*AMMD = Aerodynamic Mass Median Diameter = SQRT(particle density) x diameter

FILTRA-MVSS, Stress test
Result from Sweden 2011

2 Nov 2011

Beneficial Filter system

"One strength of the Swedish NPP are that all reactors are equipped with filtering systems, preventing release of radioactive particles in the event of a severe accident.

The filters was installed as a lesson learned from the Three Miles Island accident.

The system considerably reduces the consequences to the environment in case of a severe accident.
If a release occurs the filters contribute to only releasing very small amounts of radioactive materials."

Jan Hanberg, head of section at the Swedish Radiation Safety Authority

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FILTRA-MVSS, Stress test

Result from Switzerland 2012

Available at :http://www.ensi.ch/en/2012/01/10/eu-stress-test-swiss-national-report-online/.

Published January 2012

The containment venting system at KKG, as part of the containment, displays low seismic robustness but this is determined by the waste gas cleaning tank that is positioned outside of the containment. A failure of this tank would therefore have no effects on the integrity of the containment itself. The safety margins for the containment integrity at the Swiss nuclear plants are assessed by ENSI as high.

In ENSI's opinion, the system for containment venting must in general be at least as seismically robust as the containment integrity, in order to guarantee ongoing effective protection of the containment in case of accidents due to severe earthquakes with failure of the core cooling (an exception may be allowed if the safety margins of the venting system are already quite high). This requirement is not met at KKG and KKL. Moreover, KKG (unlike KKL) does not report a safety margin for the containment venting, although the system was originally designed against hazard level H2. From ENSI's viewpoint, therefore, measures to improve the earthquake resistance of the containment venting systems in case of beyond-design basis accidents should be reviewed at KKG and KKL (open point 2-3).

ENSI identified the following open points: existing deployment strategies for the containment venting systems in case of severe accidents, and restoration of containment integrity during shutdown conditions in case of a total SBO.

- *KernKraftWerk Leibstadt, KKL, GE BWR with 2 CCI scrubber tanks installed*
- *KernKraftWerk Goesgen, KKG, KWU PWR with a AREVA scrubber installed.*
- *KernKraftWerk Muhleberg KKM, GE BWR with FILTRA-MVSS installed.* ***NO REMARKS***

Summary Advantages of FILTRA-MVSS

- Designed for SBO filtered venting
- High and same DF over entire flow range – independent of vent flow
- Completely passive (no manual actions, no power, no additional water) for at least 24 h
- High decay heat capacity of captured filtered material, no need for extra water storage tanks
- Verified for very tough seismic loads
- Modular delivery for ease of installation
- May be used for long term cooling of molten core decay heat (feed & bleed)
- Independent Venturi system /metal filter for Safety
  - With postulated failure of the metal filter, 99% mass fraction of contaminant are still removed
- DF after each filtration stage is known

Thank you for your attention

Backup Slides

FILTRA-MVSS, Filtering technology

Scrubbing technology, general

The Non-Nuclear Global Industrial Experience:

- For industrial gas cleaning processes, since 100 years, *one* scrubber principle is used for high performance *particle* material removal: **Venturi scrubber**.
- Cleaning filters are used for particulate removal from dry gases and scrubber systems are used for wet gases.
- Nuclear accident venting gas is hot with varying flow, contains steam, has both large and small particles, has hygroscopic material, and noxious gas components. Conditions are similar to gas cleaning from electric arc furnaces or other thermal processes.
- Venturi scrubbers have moderate *gas* absorption capacity (must be chemical reinforced)
- For *gas* component removal: packed tower, spray tower and bubbling bed.
- Packed towers are not used on gases with high particle content due to risk of clogging.

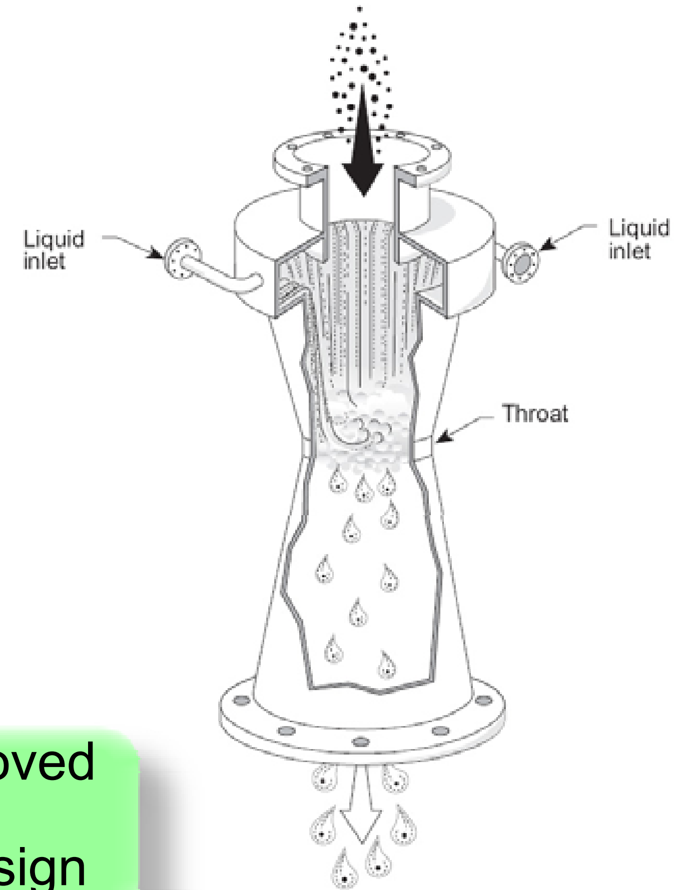
FILTRA-MVSS manage to solve the different filtering problems in a single solution

FILTRA-MVSS, Filtering technology

Venturi scrubbing principal, general

Venturi nozzle step-by-step

1. Gas carrying aerosols enters from top
2. Liquid is added to gas wall
3. Gas is accelerated in throat
4. Water is atomized to a droplet mist in the throat
5. Water droplets have slower velocity compared to gas and particles and will ”glue” particles that come close
6. To ensure high velocity in venturi a variable throttle is normally used, MVSS have a more intelligent system
7. Scrubbing drops are collected in water tank and separated from gas



Systems without above features cannot be proved as venturi collector.
FILTRA-MVSS has a clearly proven venturi design

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FILTRA-MVSS, New System Design

Actions to ensure a safe operation of the venturi system

- Regular sampling, to ensure good water quality and therefore equipment durability:
  - Values measured :
    - PH & Concentration of Thio-sulphate & Sulfide
    - Concentration, type & size of mechanical dirts
    - Obscurity of the liquid phase
    - Concentration of some additives such as biocide
  - Only one chemical adjustment made during 24 years of operation on Swedish MVSS.
- Sampled boroscopic (fiber optics) inspection of tubes made from a platform inside the tank
    - Periodical
    - When water quality measurements reveals unusual values.
- Every filter step is fully accessable for service and inspection, total filter efficency is possible to maintain within filter system lifetime

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Historical Background

- ***1979 Three Mile Island***
- 1981 Filtered Containment Ventilation (FCV) decision in Sweden
- 1985 10.000 cubic meter gravel filter installed at:
  - Barsebäck 1 and 2
- (1986 Chernobyl)
- ***1988 New requirements on pressure relief stipulated by the Swedish Government***
  - Cs release limited to 0.1% of core inventory
- 1988 FILTRA - MVSS (Multi Venturi Scrubber System) installed at:
  - Oskarshamn 1, 2 and 3
  - Forsmark 1, 2 and 3
  - Ringhals 1, 2, 3 and 4

Design parameters for BWR and PWR, 1988 conditions

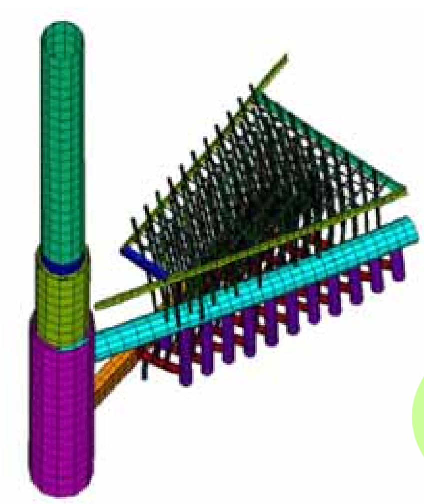
	BWR	PWR
Gas mass flow	*0,1 – 13 kg/s*	
Gas composition	*Steam* *N_2, H_2* *O_2 (PWR)*	
Gas temperature	*70 – 150 °C*	
Rupture disc opening pressure	*0,5 – 0,6 MPa*	
Earthquake, ground acceleration	*0,15 g*	
Operation	*0 – 8 h totally passive* *8 – 24 h manual action* > 24 h improvisation	
DF (aerosols)*	*100/500*	*500/1500*
DF (iodine)*	*100/500*	*500/1500*
Hydrogen combustion	*Sturdy design*	
Physical separation	*Preferred*	

** guarantee/design*

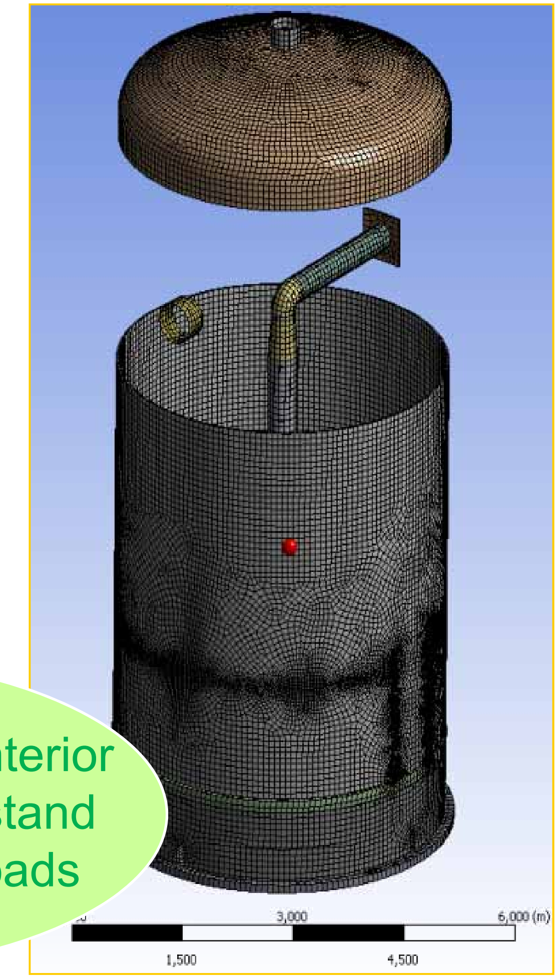
FILTRA-MVSS, New System Design

Seismic capability, tank and internals

- Steel tank and interior equipment (including demister and MFF) is exposed to
  - Seismic loads
  - Sloshing loads
- FEM based evaluation relative to ASME III



Steel tank as well as interior equipment will withstand very high Seismic loads



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FILTRA-MVSS, Filtering technology

Iodine filtering - Chemical absorption of elemental iodine

Experimentally determined:

Solubility of I_2 gas into water is low (0.2 g/l) .

Thiosulfate ions speeds up reaction :

$I_2 + 2S_2O_3^{--} \rightarrow S_4O_6^{--} + 2I^-$ (fast reaction kinetic)

Dissolution rate is also increased by the reaction :

$I_2 + I^- \rightarrow I_3^-$

Followed by:

$I_3^- + 2S_2O_3^{--} \rightarrow S_4O_6^{--} + 3I^-$

Thiosulfate concentration about 0.01 mol/l

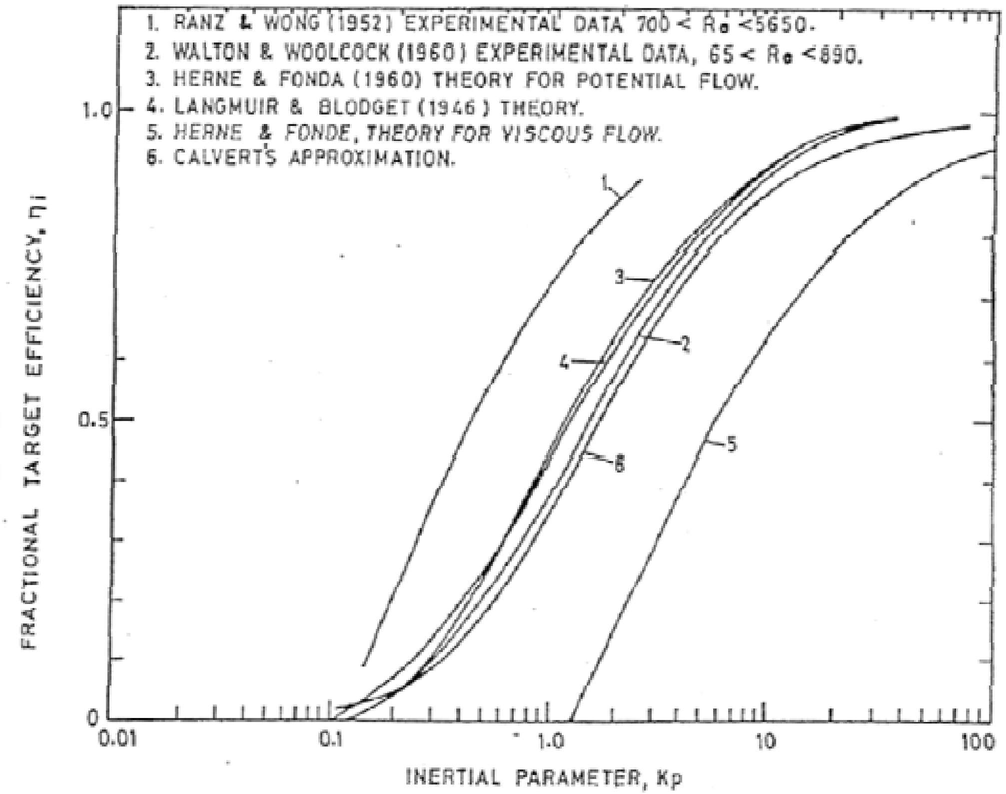
PH adjusted to > 10.5 to minimize thiosulfate oxidation

Reaction rate will increase very much with increasing temperature and pressure

FILTRA-MVSS, Verification process - Step 1

Particle collection modelling

- Single drop target effeciency for particle collection vs. Stoke´s number .
- In the present work, the Calvert (curve 6 in the graph) expression is used.



The venturi model has a strong base from classic venturi theori

Literature: SPS Gas Cleaning Manual Volume 3, Wet Dedusting, 1987

FILTRA-MVSS, Verification process

Verification process Outline of MVSS

Experiments under near prototypical conditions with controlled scaling using proven chemical engineering scaling laws and own modelling

Modelling and model validation:

Parameter	Tested range	Unit	Remarks
Venturi gas throat velocity	40 -115	m/s	
Liquid mass flow/ gas mass flow (ML/MG)	1-4	-	
Gas density (air)	1.5-7	kg/m3	Saturated steam :14 bara = 7.1 kg/m3
Gas pressure (air)	~1.3-6	bara	
System temperature	10-80	°C	Water temperatuer in the tank during the test.
Particle size range for the total and fractional DF	0.1 -4	µm	DF (particle size)= DF fractional
Varying pool height (above riser pipe)	0.1-3		

APPROVED by Swedish regulatory body

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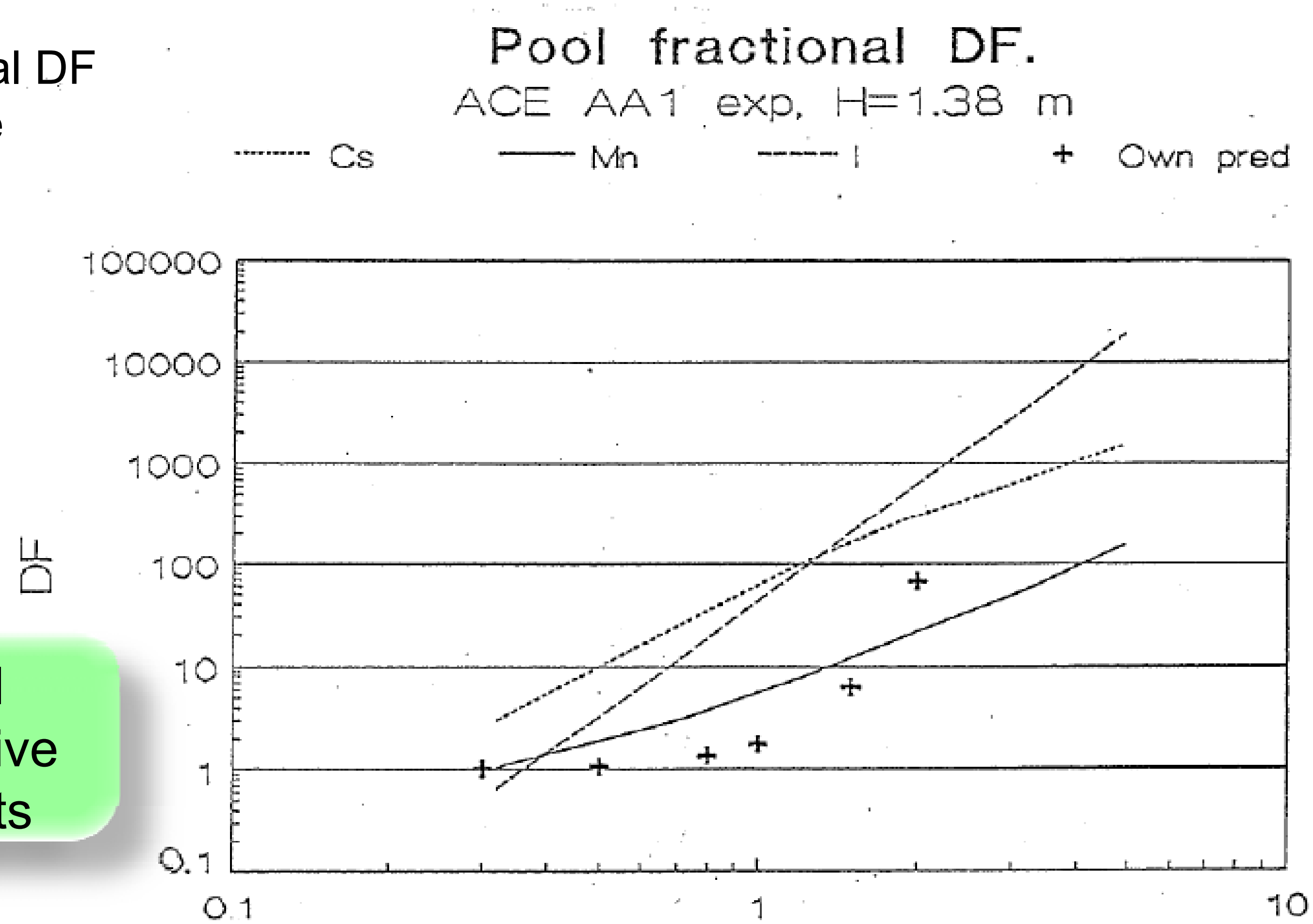
FILTRA-MVSS, Verification process - Step 3
ACE-verification, pool scrubbing

Contribution to total DF from bubble phase



Particle size (µm)

Analytical model predicts conservative DF for all elements

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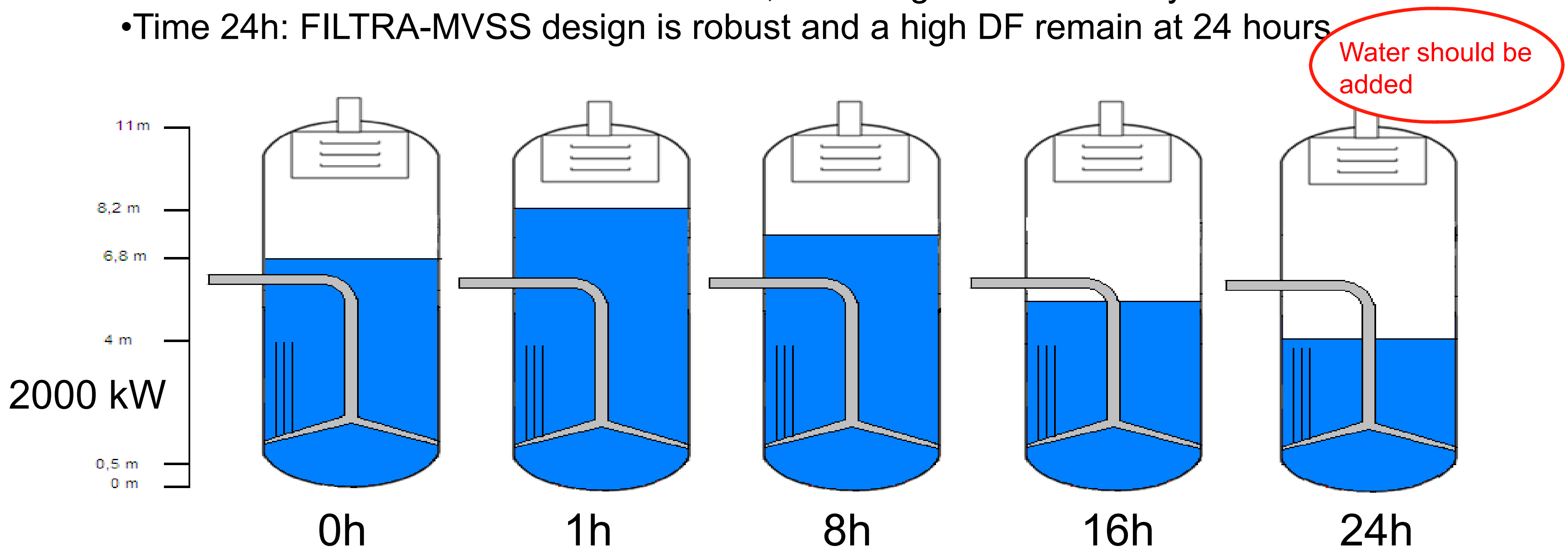
FILTRA-MVSS, sizing assessment

Mark II, 2000 kW; 26 kg/s @ 2pd; Tank dia. 5,5m

Mass balance and tank water level during an accident for a Mark II, 2000 kW heat load

- Time 0h: Start point of venting.
- Time 1h: The water level increases due to condensed steam and pool swelling
- Time 1h-24h: The water level decreases, same high filter efficiency remain
- Time 24h: FILTRA-MVSS design is robust and a high DF remain at 24 hours



DF in scrubber after 24 h will be ≈1000 but total system DF will be >10000 due to metal fiber filter. Minimal amount of aerosols expected after 24 h

FILTRA-MVSS, Licensing

Sweden experience

- In Sweden the implementation of Severe Accident Mitigation features, including Filtered Containment Venting System, were proceeded by a governmental requirement.
- Technical requirements were developed via interaction between Regulatory body, utilities and vendor
  - Suitable severe accident analysis tools
  - Selection of design basis events
  - Developments of emergency operating procedures
  - Acceptable releases after a severe accident
- Licensing of FILTRA-MVSS was a part of the licensing of all Severe Accident Mitigation features

FILTRA-MVSS, Licensing

Sweden experience

- For FILTRA-MVSS licensing purposes a verification package was submitted to the Swedish Regulatory body.
- The verification package was reviewed by an expert team.
- The verification package consisted of three parts
  1. Theoretical and practical verification
     - aerosol collection, absorption of elemental iodine, moisture separation and industrial experiences
     - Laboratory tests to verify the aerosol collection capability
     - Two test rigs; single venturi and multi venturi test rig
  2. Full scale dynamic test of one unit to simulate a rupture disc opening
  3. Participation in ACE test (3^{rd} part independent test)

MVSS is licensed in 2 countries

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