Unclassified **NEA/CSNI/R(2013)12/ADD1**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **19-Dec-2013**

English text only

NEA/CSNI/R(2013)12/ADD1
Unclassified

Updated Knowledge Base for Long Term Core Cooling Reliability

JT03350626

Complete document available on OLIS in its original format

English text only

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

"The Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for the activities of the Agency that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2011-2016 and the Joint CSNI/CNRA Strategic Plan and Mandates for 2011-2016 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings, and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are produced and available to members in a timely manner.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and the construction of new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor designs.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiation Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and the Nuclear Science Committee on matters of common interest."

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APPENDIX A - TERMINOLOGY IN CONJUNCTION WITH THE ECCS BLOCKAGE ISSUE

Asbestos Containing (no longer on the market):

Insulation with any measurable quantity of asbestos is considered asbestos-containing and is a hazardous material. The asbestos content can vary from near zero percent to near 100 percent. One common form is calcium silicate reinforced with asbestos fibers. Another common form is a corrugated asbestos paper. Note that while asbestos-containing insulation has not been produced in North America since about 1972, considerable quantities were installed in nuclear containments constructed prior to that time.

As-Fabricated Fibrous Material:

Fibrous materials in their original configuration and form. For insulation blankets, this term indicates the insulation material only (without the cloth covering). For preparation of test samples, representative larger pieces are uniformly cut by mechanical means (i.e., knife, scissors).

Binder: A chemical, typically organic, added to insulation during manufacture to hold the material in a desired shape and impart specific properties such as resilience, compressive strength, and parting strength.

Calcium Silicate:

Insulation composed principally of hydrous calcium silicate and which usually contains reinforcing fibers (See Appendix C for additional details). These reinforcing fibers can be fiberglass, nylon, rayon, pulp, or asbestos.

Ceramic Fiber Felt:

Insulation composed principally of ceramic fiber yarn sewn into insulation felts without the use of binders

Chemical Effects: A group of phenomena that results in the formation of precipitates by chemical reactions between chemical species (precipitants) in the post-LOCA sump water and which can interact with a debris bed in a different manner than that of the materials from which the chemical reactants originated.

Chemical Kinetics:

Study of the rates of chemical processes. Chemical kinetics includes investigations of how experimental conditions influence the speed of a chemical reaction and yield information about the reaction's mechanism and transition states, as well as the construction of mathematical models that can describe the characteristics of a chemical reaction. Chemical kinetics deals with the experimental determination of reaction rates from which rate laws and rate constants are derived. Relatively simple rate laws exist for zero-order reactions, first-order reactions, and second-order reactions, and can be derived for others. The main factors that influence the reaction rate include: the physical state of the reactants, the concentrations of the reactants, the temperature at which the reaction occurs, and the presence of catalysts.

Chemical Species:

Atoms, molecules, molecular fragments, ions, etc., being subjected to a chemical process or to a measurement. Generally, a chemical species can be defined as an ensemble of chemically identical

molecular entities that can explore the same set of molecular energy levels on a characteristic or delineated time scale.

Coatings (paint):

A coating is a covering that is applied to the surface of an object, usually referred to as the substrate. In many cases coatings are applied to improve surface properties of the substrate, such as appearance, adhesion, wetability, corrosion resistance, wear resistance, decontamination, and scratch resistance.

Conventional Insulation:

A term generally applied to a homogeneous insulation material (such as fiberglass, mineral wool, calcium silicate, cellular glass, etc.). This insulation material is often covered with sheet metal jacketing attached with wires, bands, screws or heavy fabric.

Debris Traps:

Methods that capture debris upstream or downstream of the strainers. The captured debris caused by the break (primary or secondary) can be of all type (particulates, fibers, coatings, etc.). Their shape and mean density are key parameters for determining their potential for capture. In the US, the term for upstream traps is debris interceptor. One strainer design (Enercon) uses debris by-pass eliminators

Downstream Debris Source Term:

Downstream debris source term is the potential total amount of debris postulated to pass through the screens of the sumps.

Downstream Effects: A term used to denote all phenomena that apply to components after the water/debris mixture has passed through the sump strainer.

Ex-vessel Effects: The aspect of downstream effects that deals with the effects of debris that has passed through the strainer on components like pumps, valves, heat exchangers and nozzles.

Fiberglass Fabric (also Fiberglass Cloth):

A woven fabric made of glass fibers.

Fiberglass Insulation:

A homogeneous thermally-insulating material manufactured specifically from spun glass fibers.

Fibrous Debris:

Fibrous materials which have become displaced from their intended service application. Debris may be generated through a number of mechanisms including high-energy jet impingement, damage during outage activities or deterioration of materials with time. For Fibrous Insulation Blankets, generated debris may include the insulation and/or the covering fabric cloth.

Fibrous Insulation:

Thermal insulation composed principally of fibers manufactured from rock, slag, glass or ceramic materials, with or without binders. Includes such materials as fiberglass, mineral wool, ceramic fiber and ceramic wool.

Fibrous Insulation Pillow, Fibrous Insulation Mattress, Fibrous Insulation Blanket:

A non-homogeneous thermal insulation assembly consisting of, at a minimum, a homogenous fibrous insulation material, a fabric enclosure or case, and having some attachment mechanism. These blankets are typically flexible in nature and are designed for repeated removal and reinstallation.

Fines of Fibrous Insulation:

Fibrous materials broken into very small random shapes by tearing such as would result from a high-pressure steam or water pipe break. For preparation of test samples, the tearing is accomplished by special mechanical means (such as fluid/steam jets, mechanical shredders, etc.). The general definition of size is the fiber diameter in one direction and up to 100 times that diameter in the length direction. These could be single fiber, or a piece of a single fiber.

Flowrate through Strainers:

The flowrate through the strainers gives key information on the ability of the strainers to behave as decanters or filters. This parameter given as a unit is used to evaluate the debris transport.

Glass Fiber Felt

Insulation composed principally of glass fiber yarns needled into insulation felts without the use of binders.

Glass Wool (UK) or **Fiberglass Insulation** (US) is an insulating material made from fibres of glass (fiberglass), arranged into a texture similar to wool. Glass wool is produced in rolls or in slabs, with different thermal and mechanical properties. After the fusion of a mixture of natural sand and recycled glass at 1,450 °C, the glass that is produced is converted into fibers. It is typically produced by being forced through a fine mesh by centripetal force, cooling on contact with the air. The cohesion and mechanical strength of the product is obtained by the presence of a binder that "cements" the fibers together. Ideally, a drop of bonder is placed at each fiber intersection. This fiber mat is then heated to around 200 °C to polymerize the resin and is calendered to give it strength and stability. The final stage involves cutting the wool and packing it in rolls or panels under very high pressure before palletizing the finished product in order to facilitate transport and storage.

In-vessel Effects: The aspect of downstream effects that focuses mainly on the blockage of fuel assemblies by debris that has passed through the strainers.

Isover: Glass Mineral Wool and Stone Mineral Wool - inert vitreous silicate mineral wool bonded with a thermosetting resin, which has been urea extended. Contains up to 0.7% mineral oil. Melting point is above 600 °C and the material is insoluble (<0.1mg/L). Finished product is chemically inert in dry conditions at 20 °C. Used primarily in Europe.

Latent Debris

Latent debris is defined as unintended dirt, dust, paint chips, fibers, and pieces of paper (shredded or intact), plastic, tape, or adhesive labels, and fines or shards of thermal insulation, fireproof barrier, or other materials that are already present in the containment prior to a postulated break in a high-energy line inside containment. Potential origins for this material include activities performed during outages and foreign particulates brought into containment during outages.

Metal Reflective Insulation (MRI) (also Reflective Metal Insulation (RMI)):

A non-homogeneous thermal insulation assembly consisting of, at a minimum, spaced metal foils, either flat or shaped into various profiles, contained within a sheet metal panel or cassette, and having some attachment mechanism. The foils and sheet metal are typically stainless steel, although aluminum has been used in some applications. These panels or cassettes are typically rigid in nature and can be designed for repeated removal and reinstallation.

Microporous Insulation: Material in the form of compacted powder or fibers with an average interconnecting pore size comparable to or below the mean free path of air molecules at standard atmospheric pressure, and which may contain opacifiers to reduce transmission of radiant heat.

Mineral Wool or Rock Wool Insulation:

A homogeneous thermal insulation manufactured specifically from rock or metal slag products, with or without binders, and which usually has a shot, or non-fibrous content, of up to 30% by weight.

Particulates:

Insoluble individual materials (non-fibrous) that have the potential to adhere to, or be collected by, fibrous debris, thereby causing a change to the known properties of the fibrous debris bed (i.e., density, sink rate, etc.). As individual particles, particulates are generally very small, especially if they originate from fibrous insulation material or from corrosion products; however, they can be much larger if they originate from paint or concrete. Typical examples of particulates encountered in BWR drywells and suppression pools include corrosion products from piping or metal structures (i.e., rust), welding by-products (i.e., weld slag), grinding by-products (i.e., metal chips and composite grinding wheel debris), general dust and dirt, concrete chips or dust, paint chips and non-fibrous insulations (i.e., calcium silicate which produces a chalk-like power debris). "Particulates" refers to the individual insoluble materials. (See the definition of "sludge," which refers to a composite of materials).

Precipitant: A chemical agent that causes the formation of a precipitate. In the context of ECCS strainer blockage, precipitant refers to a chemical species released into solution by corrosion or dissolution of containment materials that has the potential to form a precipitate.

Precipitate: A solid formed in solution as the result of a chemical reaction between dissolved species in the solution. Precipitates can form when two soluble species react in solution to form one or more insoluble products, or when the solution conditions change (e.g, pH or temperature) and reduce the solubility of a salt.

Settlement Phenomena:

Settlement phenomena can be observed when the flowrate in the pool is much lower than the debris sinking capacity flowrate. The settlement phenomenon increases with the temperature of the medium. Local turbulence and eddy curents may reduce the tendency for settlement

Shreds of Fibrous Debris:

Fibrous materials, broken into small random shapes by tearing, such as would result from a high-pressure steam or water pipe break. A shred would have random irregularly shaped surfaces, none of which will be in their original manufactured condition. A shred will be larger than a fine and is usually smaller than a fragment, although that is not necessarily always the case. For preparation of test samples, the tearing is accomplished either by hand or by mechanical means.

Sludge:

Suppression pool sludge consists predominately of corrosion products from carbon steel piping systems which connect to the suppression pool and from unpainted carbon steel surfaces within the pool.

Strainer Mesh:

Strainer mesh is related to the size and spacing of the holes in the strainer surface. It is a key parameter determining the strainers ability to retain debris. As a corollary, the strainer mesh plays an important role in determining the extent of downstream effects.

Temperature-Conditioned Fibrous Insulation:

A term used in testing of fibrous insulation materials to indicate that the insulation has been pre-exposed to its intended service temperature conditions on a hot plate, hot pipe, or oven. Note that the term "preconditioning" is a broader term which may involve a combination of temperature pre-exposure as well as other methods of simulating aging conditions (i.e., radiation exposure, mechanical compression, etc.).

Temperature Effects:

The rates of most chemical reactions increase with a rise in temperature. Raising the temperature increases the fraction of molecules having very high kinetic energies. These are the ones most likely to react when they collide. The higher the temperature, the larger the fraction of molecules that can provide the activation energy needed for reaction. Note that the frequency of two-particle collisions in gases is proportional to the square root of the kelvin temperature. Precipitation of the dissolved chemicals typically occurs when the temperature drops.

Totally Encapsulated Insulation (Also Cassette-Type Insulation):

A non-homogenous thermal insulation assembly consisting of, at a minimum, one or more homogeneous insulation materials, contained within a sheet metal panel or cassette, and having some attachment mechanism. The sheet metal is typically stainless steel, although aluminum and galvanized metals have been used in some applications. These panels or cassettes are typically rigid in nature and can be designed for repeated removal and reinstallation. The seams can be either welded, or riveted.

Upstream Debris Source Term:

The upstream debris source term is the potential total amount of debris postulated to reach the screens of the sumps

Whole Blanket (also Whole Pillow, Whole Mattress):

Synonymous with "Fibrous Insulation Blanket," but used to describe the material in debris form. Indicates that the entire assembly is dislodged (or tested) without cutting or tearing of the fabric covering or insulation.

Zone of Influence (ZOI)

The zone of influence represents the zone where a given high-energy line break will generate debris that may be transported to the sump. The size of the ZOI can be defined in terms of pipe diameters and is determined based on the pressure contained by the piping and the destruction pressure of the insulation surrounding the break site.

APPENDIX B - HISTORICAL BACKGROUND

B.l Incidents Concerning Debris Generation

The containment pool collects reactor coolant and containment spray solutions (where applicable) after a LOCA. The sump serves as the water source to support long-term recirculation for residual heat removal, emergency core cooling, and containment atmosphere cleanup. This water source, the related pump inlets, and the piping between the source and inlets are important safety components. The performance of ECCS and CSS strainers in currently operating BWRs and PWRs was recognized many years ago as a regulatory and safety issue and has received a significant amount of regulatory oversight as a result. The primary concern is the potential for debris generated by a jet of high-pressure coolant during a LOCA to clog the strainer and obstruct core cooling.

A primary system leak challenges the integrity of the reactor coolant system (RCS) pressure boundary which is essential to supporting the defense-in-depth concept. The safety significance of a leak depends on its location, rate and duration. The location of a leak may be such that the leak disables or degrades a safety system and contributes to an increased likelihood of core damage. In most, if not all member countries the Limiting Conditions of Operation do not permit continued operation with an identified RCS pressure boundary leak

This appendix reviews the historical background and some of the more significant RCS leaks and reported incidents concerning debris generation that have occurred.

B.1.1 Barsebäck Incident

One of the more significant operating events in the nuclear power industry in regards to LOCA debris generation happened at Barsebäck Unit 2 in Sweden on July 28, 1992. Barsebäck Unit 2 is a BWR/Mark 2. The reactor was in a startup procedure after the annual refueling outage and the reactor power was below 2% of nominal when a rupture disc at the outlet of a safety relief valve (SRV) inadvertently opened. The cause of the erroneous opening was a leaking pilot valve. The pilot valve had been examined and tested during the outage, and it had been incorrectly assembled. The leaking pilot valve caused the main SRV to open and the reactor pressure acted directly on the rupture disc when the reactor pressure reached the setpoint of the rupture disc, which was about 3.0 MPa (435 psi). The disc failed and steam blew directly into the drywell. The containment was isolated and the drywell was pressurized so that the blowdown pipes cleared.

Both the CVSS and the ECCS were automatically started. Initially, the pressure in the reactor vessel was higher than the head of the ECCS pumps, and actual injection of ECCS water started when the reactor pressure reached about 2.2 MPa. The operators quickly turned off the ECCS injection. Both trains of the

CVSS were allowed to continue in order to control the pressure in the drywell. After a while, the operators tried to reduce the flow in order to avoid ground faults in electrical equipment and to reduce debris transportation to the wetwell pool.

The steam jet caused mineral wool insulation to be dislodged from the piping located close to the SRV. The operators observed, via video cameras in containment, that insulation material was flying in the containment atmosphere.

During cleanup after the incident, the amount of dislodged insulation material was estimated to be 200 kg (440 lbm), of which approximately 100 kg (220 lbm) had been flushed down to the condensation pool by the steam flow and by the water flow from the CVSS. The amount was estimated on the basis of the amount of material that had to be replaced and the number of bags carried out during cleanup.

Differential pressure measurements had been installed to monitor the pressure drop over the strainers of the CVSS and the NPSH. The operators noticed a high pressure drop alarm after 1 hour. The operators gave priority to other problems and let the pumps continue to run. After about 2 hours, one of the pumps cavitated. Earlier analyses had shown that clogging of strainers and loss of NPSH, if occurring at all, would take place after more than 10 hours; however this occurred 1 hour into the incident.

A preliminary analysis (Ref. B.l) showed that the strainers could clog in less than half an hour in case of a large-break LOCA. The criterion for operator intervention in an accident is that no critical manual functions should be needed within 30 minutes and the Swedish Nuclear Power Inspectorate (SKI) decided to revoke operating permission for the five oldest BWRs, which had strainers of small area, until the strainer issue was resolved.

B.1.1.1 Timeline of Events

The incident began at 05.39 on 28 July, 1992.

Incident	Time	Minutes
+0	0539	A containment isolation signal was received at a reactor pressure of 3.0 MPa. CVSS immediately starts.
+1	0540	Valve 314V12 indicates open. Steam blowdown from the valve is verified by a video camera.
+5	0544	Valves V48-51 in the pressure relief system are opened to relieve the pressure on valve V12. The pressure history indicates that these valves never opened.
+6	0545	The ECCS injection starts 2.2 MPa in the reactor vessel.
+7	0546	The ECCS pumps were stopped due to an alarm of high level in the reactor vessel. The ECCS flow is terminated by the operators to avoid topfilling of the reactor vessel and water in the steam lines.
+12	0551	The pressure in the containment decreases and the valves to the CVSS are closed. The intention is to minimize ground faults and the transport of insulation material to the suppression pool.
+14	0553	The isolation valves to the CVSS open due to increasing pressure in the drywell. The pressure in the reactor vessel is 1.5 MPa.
+25	0604	The water spray through CVSS circuit 1 is interrupted and the isolation valves are closed. Instead, circuit 1 is used to cool down the suppression pool. The steam blowdown through valve VI2 has stopped.
+67	0646	The water spray through CVSS circuit 2 is interrupted and the isolation valves are

closed. Instead, circuit 2 is used to cool down the suppression pool.

+69 0648 Decay heat cooling circuit is started for cooling the reactor.

+69.5 0648.3 High differential pressure (20 kPa[1]) is indicated over CVSS intake strainer for pump P3. Nothing unusual is noticed for the flow of the pumps PI and P3. Instead of backflushing, the connection of the decay heat removal system is prioritized.

Incident Time Minutes

+73 0652 High differential pressure (20 kPa) is indicated over CVSS intake strainer for pump PI. Nothing unusual is noticed for the flow of the pumps PI and P3. Instead of backflushing, the connection of the decay heat removal system is prioritized.

+ 81 0700 Change of shift

+111 0730 Preparation is made for the backflushing operation of the intake strainers for pumps PI and P3 in the CVSS.

+117 0736 Pumps PI and P3 for the CVSS are stopped because of oscillations in the pump engine currents and the water flow caused by clogging of the intake strainers.

+148 0807 Backflushing operation of the strainers accomplished.

+158 0817 Pump P3 in the CVSS circuit is restarted after the backflushing operation. A minor leak in the shaft packing is detected.

+249 0948 Cold shutdown is reached.

B.1.2 Details of the Incident

Data reported in this appendix are based on reports that were presented after the incident. The experiments discussed are basically experiments done after the incident.

B.1.2.1 Debris Generation

B.1.2.1.1 Amount of Debris

An exact amount of material that was dislodged during the incident is not available due to inaccurate measurements. About 200 kg (440 lbm) dry insulation was installed to replace the insulation blown away from the adjacent piping. The judgment is that 180-200 kg (397-440 lbm) was dislodged from the leaking valve (Ref. B.2).

Two references describe the extent of the area with dislodgement of material. According to Reference B.3, the insulation was completely removed at a distance of approximately 1.5 m (5 ft) on each side of the valve. Insulation was partly removed up to 2.5 m (8 ft) on each side of the valve. It was judged that about 25% of the dislodged material had been blown upward and was fixed to structures above the valve location.

B 1.2.1.2 Analysis of Amount of Dislodged Material

Attempts were made to compare the incident data with the conceptual cone model (Ref. B.4). The cone model is applicable to pressures between 15 MPa and 8 MPa and the incident occurred at 3 MPa. The geometry near the valve was not typical since the geometry assumed for the cone model is basically a pipe rupture. The different regions used by the cone model are difficult to identify after a break.

[1] The control room personnel had instructions to backflush the strainers in order to clean them if the differential pressure exceeded 20 kPa

The analysis estimated that total disintegration should occur up to 3 L/D at 3.0 MPa pressure. The affected zone in Barsebäck was larger than that, which indicates that the cone model in its current form is less applicable for a steam blowdown. Dislodgement experiments using steam also indicate that the current cone model is less applicable in such situations.

B 1.2.1.3 Other Information about the Debris Generation

The steam temperature in the reactor vessel was approximately 200 °C (392 °F) at 3 MPa pressure, the pressure in the reactor tank decreased at a rate of 0.12 MPa/min until 10 minutes into the incident. Recordings from the incident show that the steam flow was about 38 kg/s (84 lbm/s) at the beginning of the incident. The flow decreased to 33 kg/s (73 lbm/s) after 10 minutes. Data were only sampled during the first 10 minutes in the incident.

Valves V48-51 in system 314 (steam relief system) should have opened after about 4 minutes in order to relieve the V12 leaking. This did not seem to work and all steam passed through the valve V12 as long as the sampling of data continued (Ref. B.5).

A control room technician using a video camera observed flying debris which was fixed against a point 10-15 m (33-50 ft) from the leaking valve V12. It was impossible to see where the debris landed and how it was transported down to the suppression pool since steam made the view foggy. The size of the debris was difficult to see, but some parts were large enough to be observed by the video camera.

B.1.2.2 Drywell Transport

B.1.2.2.1 Amount of Insulation Material Transported to the Suppression Pool

The amount of insulation material that was transported to the suppression pool is uncertain. The first judgment from the incident was that 200 kg (440 lbm) of wet insulation was transported to the suppression pool. This assumption was calculated from the collected debris which amounted to 10 bags of approximately 20 kg (44 lbm). Analyses after the incident indicate that approximately 100 kg (22 lbm) of dry insulation was transported to the condensation pool. According to Reference B.7, the density of wet insulation could vary between 100 kg/m^3 and 1000 kg/m^3 (6.24-62.4 lbm/ft^3) depending on the water content of the insulation.

The insulation material was transported to the wetwell in two phases. An engineering judgment was made that 30% was transported in the steam and 70% was transported with water from the CVSS.

The distribution of the insulation which was left in the drywell was approximately:

- 50% on the beamwork. This amount was largely concentrated within three areas: at the drywell floor, near the outer containment wall, and on and near the gratings over the blowdown pipes
- 20% on the wall next to the stripped pipe and on the components around the safety valve
- 10% on the wall opposite to the stripped pipe
- 12% on the walls above the grating located over the safety valve
- 8% on the grating located over the safety valve

The insulation which was left in the drywell appeared "spread on." The judgment was that it was hard to transport the remaining insulation by the CVSS water.

B.1.2.2.2 Analyses and Experiments

Experiments were performed in order to enhance understanding of the transport phenomena so that technical solutions could be identified which could prevent insulation from reaching the suppression pool. The experiments were conducted on steam transport and spray transportation.

Steam blow experiments were carried out in a scaled facility (Ref. B.7) at Karlshamn in order to study the transportation by steam. The experiments indicated that a very small fraction of the insulation (about 3%) in a steamline break would reach the wetwell pool. For a large-break LOCA in the main circulation line, the amount was estimated to be about 8%. The recommendation was that 10% could be used for safety calculations. These experiments were carried out in a small-scale facility and failed to explain the observation at Barsebäck.

A full-scale test which addressed transport by spray was performed in the Oskarshamn-2 containment, which is similar to the Barsebäck containment. 200 kg (440 lbm) of new and old mineral wool insulation was placed in a sector of the drywell and the spray system was started. Only 11 kg flushed down to the wetwell. In the experiments, frames were installed around the gratings over the blowdown pipe inlets to collect debris. Such frames were not installed in Barsebäck at the time of the incident. The experiments indicate that much less material would be transported down to the wetwell pool than was observed in Barsebäck.

Differential pressures over the strainer were measured during the experiment; the pressure increased about 2 kPa before the backflushing of the strainers. The backflushing operation worked well. The mixer was not operated during the test. The insulation material was initially located in the same quadrant of the drywell as the strainers.

According to Reference B.8, large amounts of the insulation remained at the same location where it was initially placed in drywell. The old insulation mixed with water appeared like mud. The mud had compacted against the frames. The frames did stop insulation from reaching the suppression pool, but the effect could not be quantified. There were no experiments without frames.

B.1.2.2.3 Discussion

The uncertain judgment that 100 kg (220 lbm) of insulation was transported to the suppression pool was based on the number of bags of wet insulation collected and the amount of insulation that was replaced. Experiments carried out to support the observations in Barsebäck showed that much less material would be transported. These experiments thus failed to support Barsebäck observations.

B.1.2.3 Suppression Pool Transport

There is not much information about the suppression pool transport from the Barsebäck incident. The cleanup in the drywell after the incident showed that much of the insulation debris stayed in the 0°-90° quadrant, in which the leaking valve V12 was also located. The insulation transported to the suppression pool had probably gone through the blowdown pipes in this quadrant. The strainers that were clogged were located in the 180°-270° quadrant, the diametrically opposite quadrant (Ref. B.6). With this assumption, the insulation debris must have been transported between 11 and 22 m (36 and 72 ft) in the suppression pool.

The observation made during cleanup was that the insulation was evenly spread over the suppression pool floor. This was observed a significant time after the incident.

A mixer had been installed to mix the water to avoid temperature stratification in the suppression pool. The mixer was in operation during the incident (mixer systems such as this are not installed in BWRs in all countries). The mixer had a mass flow of 1-1.4 m^3/s (35-49 ft^3/s). Measurements close to the mixer outlet showed that the water velocity was about 3 m/s (9.8 ft/s) (Ref. B.9). The mixer was located such that the water stream was directed from the strainers against the opposite wall (Ref. B6). Table B.l lists the results of measurements of water speed at different elevations in the suction area of the mixer close to the strainers. The measurements were taken about 4 m (13 ft) from the mixer (Ref. B.10).

Table B.l: Water Velocities in the Suction Area of the Mixer

Height from bottom m(ft)	Velocity cm/s	Velocity in./s
1(3)	6-7	2.4-2.8
3(9)	8-10	3.2-3.9
4(13)	4-5	1.6-2.0

The mixer was located 4.5 m (14.8 ft) from the suppression pool wall (Ref. B.9) and approximately 2.5 m (8.2 ft) over the bottom.

The judgment is that the mixer was effective in maintaining the condensation pool homogeneous, and probably also helped to keep insulation debris suspended and thereby accessible for strainer clogging. It is also probable that the mixer significantly contributed to the relocation of insulation debris to the strainers at the opposite side of the containment.

An experiment was performed to investigate possible effects of the water flow from the blowdown pipes on the flow in the suppression pool. The blowdown pipes have a diameter of 600 mm and the distance between the pipe outlet and the suppression pool bottom is 3.3 m (10.8 ft). Flows of 60, 50, and 40 kg/s (132, 110, and 88 lbm/s) were injected in a blowdown pipe and the water velocities at different elevations in the suppression pool were measured. It was determined that the influence of the flow in the blowdown pipes on suppression pool velocities was very small. The flow range tested was 10 times larger than the expected flow during the washdown.

Insulation debris was probably transported to the wetwell through the blowdown pipes near the failed valve. The valve location was diametrically opposite to the strainer location. It is probable that the mixer helped distribute the debris evenly over the suppression pool. The blowdown pipes were barely cleared in the incident and the flow in these pipes was probably insufficient to provide mixing. In the case of a large-break LOCA, it is believed that the violent flow through the blowdown pipes, and possibly other phenomena like "chugging," would significantly contribute to the mixing. The fact that both strainers were clogged at approximately the same time is also an indication that the debris probably was evenly distributed in the pool.

The data from the incident indicates that insulation debris stays suspended in the water for a significant time. Considering the measured velocities set up by the mixer and the distance to the most probable injection location, the settling velocities of the debris must be much lower than 1 cm/s in order to reach the strainers. Tests showed that larger clumps of debris would sink faster than this, a fact which indicates that finer fractions of the debris actually caused the strainer blockages. This is in accordance with other tests performed. The debris on the strainers was not characterized after the Barsebäck incident.

The CVSS spray continued for about 25 minutes into the transient. The pressure drop over the strainers continued to increase after this incident. This is qualitatively in accordance with tests performed on strainer clogging and supports the hypothesis that the pressure drop is influenced by the small particles and compaction of the bed.

B. 1.2.4 Strainer Pressure Drop

B. 1.2.4.1 Information from Incident

Data are not available on the actual form of the debris on the strainers. The recorded data are summarized in Table B.2. Registered data are the times when the 2 mvp alarm[2] sounded and when the pump P3 presumably cavitated. The strainer has a pressure drop of 0.4 mvp (Ref. B.l 1), which should be subtracted from the values in the table in order to get the correct bed pressure drop over the debris bed.

Table B.2 Observations at Barsebäck

Pumps	Wetwell Temp (°C)	2 mvp (20 °C, 68 °F) Alarm	3.4 mvp (20 °C, 68 °F) Cavitation	Difference in Time Between Both Alarms	Pressure Drop Increase After Alarm
CVSS P3	35	69.5 min	117 min	47.5 min	1.4 mvp
CVSS PI	35	73 min	Not applicable	Not applicable	Not applicable

The pressure drop increase was 1.6 mvp after 69.5 minutes.

B.1.2.4.2 Analyses and Experiments after the Incident

A full-scale test was performed in the suppression pool after the Barsebäck incident (Ref B.6). An amount of 2 m^3 (71 ft^3) of mostly old mineral wool was injected into the suppression pool. The insulation had been disintegrated before the experiment and wetted for 18 hours. In the first experiment, the insulation was injected from a vent pipe between 1 and 1.5 m (3.3 and 4.9 ft) from the strainer C2. At every injection, 3-5 bags of insulation debris were introduced. The debris started to sink and moved against the strainer. The differential pressure reached 2 mvp after 80 minutes, which is close to the Barsebäck observations. The mixer was not in operation during the experiment.

B.1.2.4.3 Discussion

In Sweden the sump clogging incident in Barsebäck was a surprise and five NPPs were closed while remedies were considered. Analyses done in the mid-seventies in Sweden showed that the earliest clogging of the strainers was expected after 10 hours. At that time, safety assessment analyses indicated that the probability of core damage was influenced by operator failure to recognize clogging. Therefore, differential pressure measurements were introduced to alert the operators so that they could backflush the strainers (Ref. B.12). The high-pressure drop alarm came after 1 hour into the incident, which is a factor 10 times faster than earlier assumptions.

Although the full impact of the mixer was not fully determined, the experiments at Barsebäck confirmed the observation made during the incident that earlier clogging is possible. It was confirmed that erroneous conclusions were drawn from the experiments in the seventies and that the clogging was not just a human factor problem.

No general regulatory requirements or technical guides concerning strainer clogging were issued after the incident, and regulatory decisions were made for each individual reactor. These decisions implied that the backflush capabilities with associated instrumentation should be tested and controlled for appropriate function, installation of very large strainers to fulfill the original requirement of 10 hours, supply of clean water from external sources for at least one hour after a LOCA, and exchange of mineral wool with glass fiber insulation of more defined properties. The solutions chosen should be “robust” which implied that they should not easily be challenged, for instance, by new experience or assumptions; a requirement which

[2] 1 mvp = 10 kPa

implied very large conservatisms. The closed power plants could be taken into operation about 6 months after the closure.

B.1.2.5 Related Issues of Potential Safety Concern

Samples were taken near the pumps downstream of the strainers. These samples were collected on the same day as the incident. The first inspection showed no traces of insulation debris. Additional samples were taken the day after the incident when the circuits were emptied. The results of the analysis are summarized in Table B.3.

Table B.3: Results of Analyses of Samples Taken near the Pumps

Pump	Debris in pump
ECCS P2	No fibrous debris visible
ECCS P2 Suction side	No fibrous debris visible
ECCS PI	Traces of fibrous debris
CVSS PI	Distinct traces of fibrous insulation

Both ECCS circuits were examined in order to investigate if fibrous insulation had reached the core after the incident.

During the incident, a shaft packing in CVSS P3 was damaged and the pump started to leak. The pump is a double-suction axial pump that has the shaft packing mounted on the suction side. The pump failure was caused by low suction pressure in Barsebäck (Ref. B.13). The pump probably cavitated. Other hypotheses, such as debris in the pump or breakdown of the water film between the axis and the packing, could not be supported.

B.1.3 Description of Plant Layout

This section describes the role played by plant geometries in the Barsebäck incident.

B.1.3.1 Barsebeck Plant Layout

Barsebäck is a BWR with external pumps of ABB-Atom design. The reactor has a nominal power of 1800 MWth. The containment is of Mark-II design, and 95 blowdown pipes with a diameter of 600 mm lead from the drywell floor vertically into the condensation pool. The submergence depth is 3 m and the nominal pool depth is 6.3 m. The pool contains 1924 m^3 of water.

The reactor has an ECCS for spray cooling of the core and a CVSS for control of drywell pressure in the case of a LOCA, and washdown of radioactive materials. The systems take water from the condensation pool through the strainers. The CVSS can also be connected to cool the condensation pool.

B.1.3.2 System 314, Pressure Relief, and Function

B.1.3.2.1 General

The V1-V13 valves are the safety relief valves (system 314). The design of the V1-V13 valves is shown in Figure B.l. These valves are controlled by the combined V62-V74 release and pilot valves, also called the servo valves. The interaction between the servo valves and the main valves can be tested at reactor pressures of less than 15 bar. The test is carried out using the V136-V148 test unit. The hydrogen gas and moisture that can leak out of the main and servo valves are flushed down to the system 316 wetwell with the help of nitrogen gas. To prevent these gases from being discharged into the drywell, the main valve is equipped with a rupture disc.

B.1.3.2.2 Function at High Reactor Pressure

The main valve (1) (Figure B.l) has a free-moving stem with a seat, a valve guide, and a control guide. The valve guide has a larger diameter than the seat. The control guide is smaller. The valve guide moves along with the control guide in separate cylinders. For pressure equalization, there is a throttled connection (3) between the area above the valve guide and the body of the valve housing. When the valve (1) is closed, the reactor pressure forces the upper parts of the seat and the guides to close, and forces the valve guide's lower part to open.

If the pressure in the main steam line (4) rises above 85 bar, this pressure will affect the stem of the release valve (6) over the impulse line (5). The stem (6) lifts and the pressure rises in the chamber (12). The control valve opens due to the rapid pressure increase in (12) and when this occurs, the guides (7) and (8) are raised. The guide (8) opens the outlet below, releasing the steam in the chamber (9) of the main valve.

The pressure on the upper part of the valve and the control guides decreases and the force on the bottom part of the valve guide exceeds the force on the upper part, pressing the stem upward and opening the main valve. When the pressure of the steam line reaches the failure pressure of the rupture disc of the main valve (designed to burst at 30 bar), the disc ruptures and steam is released into the containment drywell. When the steam pressure drops, the valve closes.

B1.3.2.3 Function Testing of the Main Valve

Function of the V1-V13 main valves is tested at a reactor pressure of 11-15 bar. The test involves checking the opening and closing of the valve. In order to open the main valve, the V136-V148 test unit is activated, causing the guide in this unit to raise the stems (7) and (8) of the control valve. The process is now the same as at high reactor pressure.

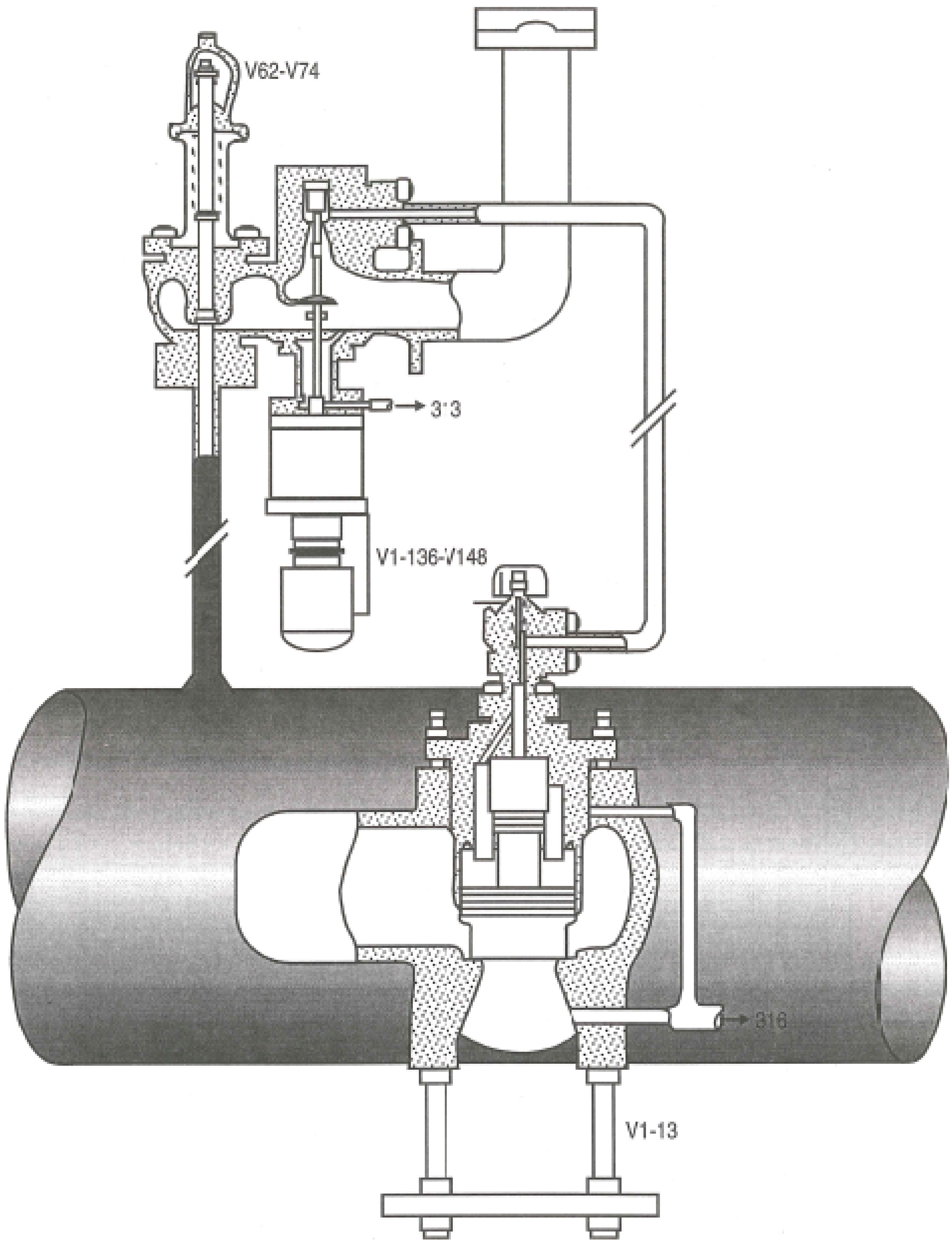

Figure B1: System 314 Pressure Relief Valve

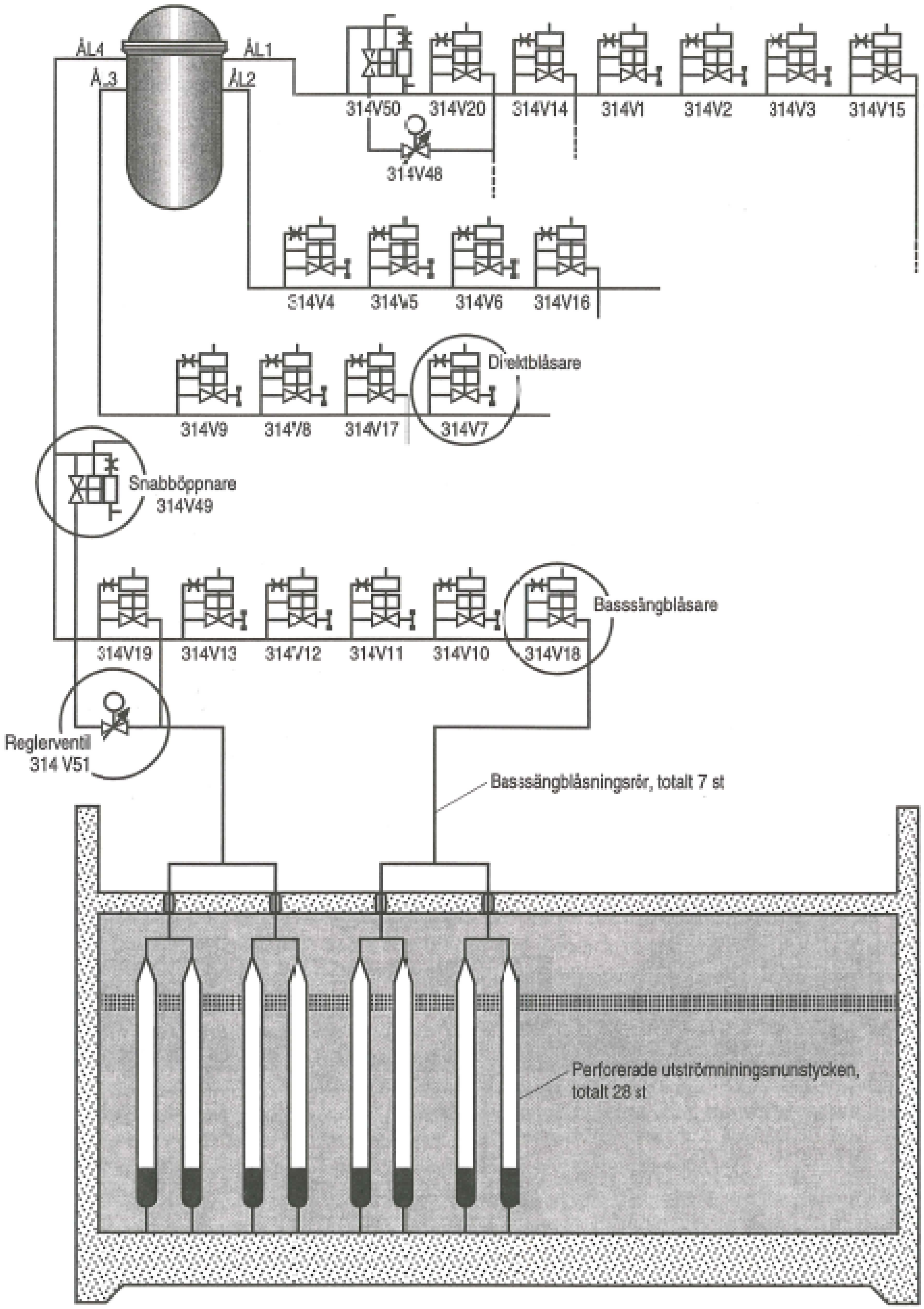

Figure B2: System 314 Pressure Relief System

VI2, which is the valve that failed, is placed (level 117.67 m) approximately 6 m (26 feet) over the drywell floor (level 111.5 m) and there is one grating between the valve and the drywell floor.

B.1.3.3 System 322, Containment Vessel Spraying System (CVSS)

B.1.3.3.1 Functions of the System

The system cools the condensation pool during relief blowdowns, and sprays the drywell in the event of a pipe break. The system should also supply the ECCS (system 323) with water if there is a malfunction in the ECCS. The system also has a number of additional functions which are of minor importance (Figure B.3).

B.1.3.3.2 Technical Description

The CVSS consists of two parallel and separate circuits and has three pumps. One pump started half an hour into an accident and was not started during the Barsebäck incident. The pumps are of centrifugal type with a flow of 100 kg/s and a pump pressure head of 0.8 MPa. The containment spray consists of two spargers; each sparger consists of 120 nozzles with an estimated maximal flow of 1.7 kg/s. The spargers are placed 5.5 m (level 116.4 m) and 11.5 m (level 122.9 m) above the drywell floor (Figure B.4).

The water for backflushing three strainers in the CVSS was taken from the ECCS flow when the incident occurred. This could be done because of the assumption that it would take at least 10 hours before the strainers clog. A 10-hour delay in clogging would allow the operators to remove the debris from the strainers with the ECCS water. Such an activity takes 5-10 minutes and is not allowed during the first hour in case of a LOCA from full reactor power.

B.1.3.4 System 323, Emergency Core Cooling System

B.1.3.4.1 Function of the System

The ECCS cools the reactor core with water from the condensation pool if the core is uncovered. This system was only operated for 1 minute during the Barsebäck incident. The ECCS was manually stopped to keep the reactor vessel from overflowing (Figure B.5).

B.1.3.4.2 Technical Description

The ECCS consists of two parallel and separate circuits and has two pumps of centrifugal type with an estimated flow of 170 kg/s and a pump pressure head of 1.8 MPa. It starts to spray the core when the reactor pressure is lower than 1.8 MPa and reaches the maximum flow at 1.0 MPa.

B.1.3.S System 316 Suppression Pool

The suppression pool is of a cylindrical type with a radius of 22 m. It contains approximately 1924 m^3 of water during normal operation.

There are 95 vent pipes with a radius of 600 mm each which connect the drywell with the wetwell. The vent pipes submerge 3 m down in the water in the suppression pool. The vent pipes are mounted flush with the drywell floor and are covered with gratings.

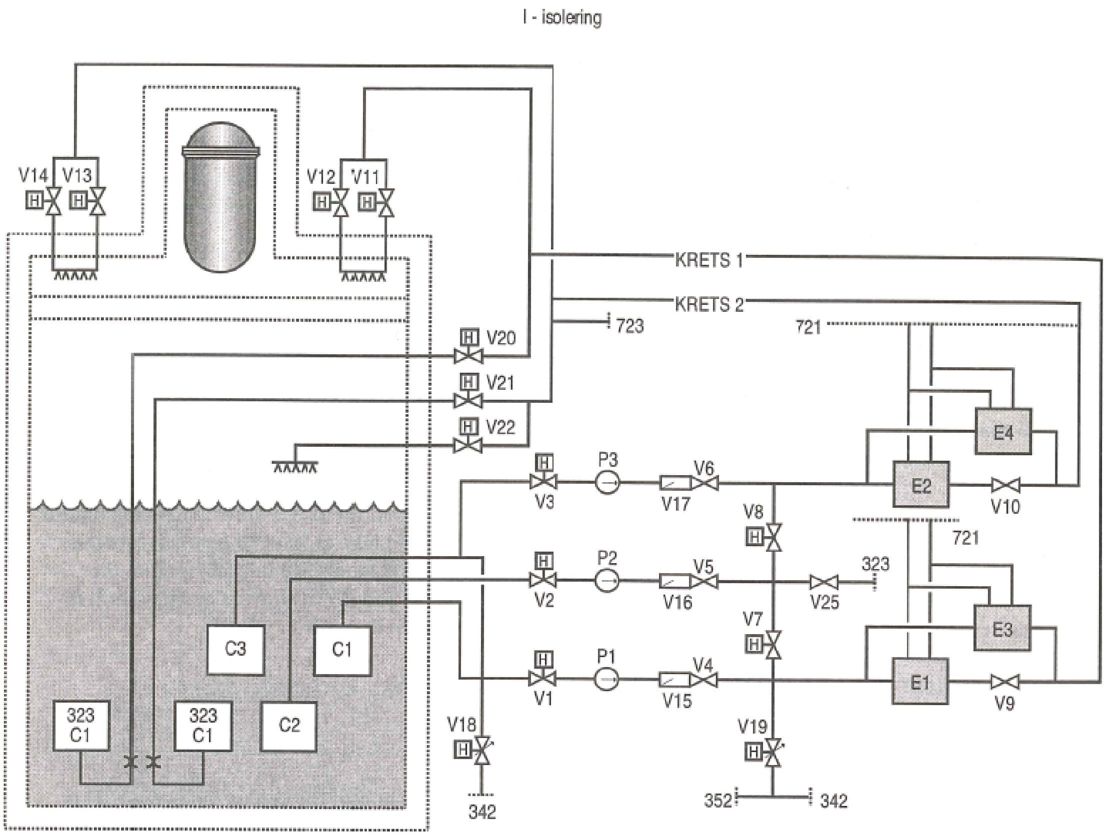

Figure B3: System 322, Containment Vessel Spraying System (CVSS).

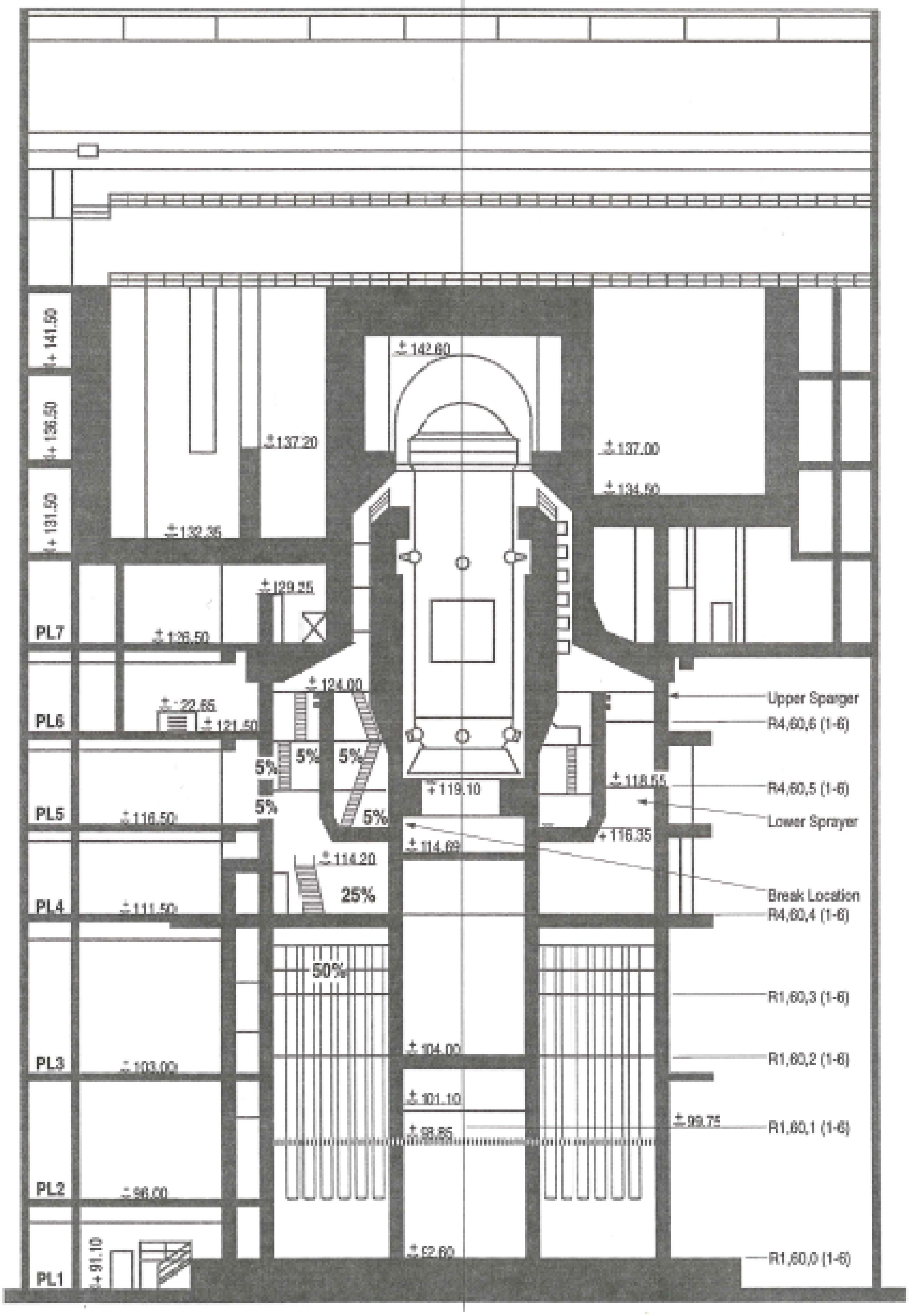

Figure B4: The Containment with Break Location.

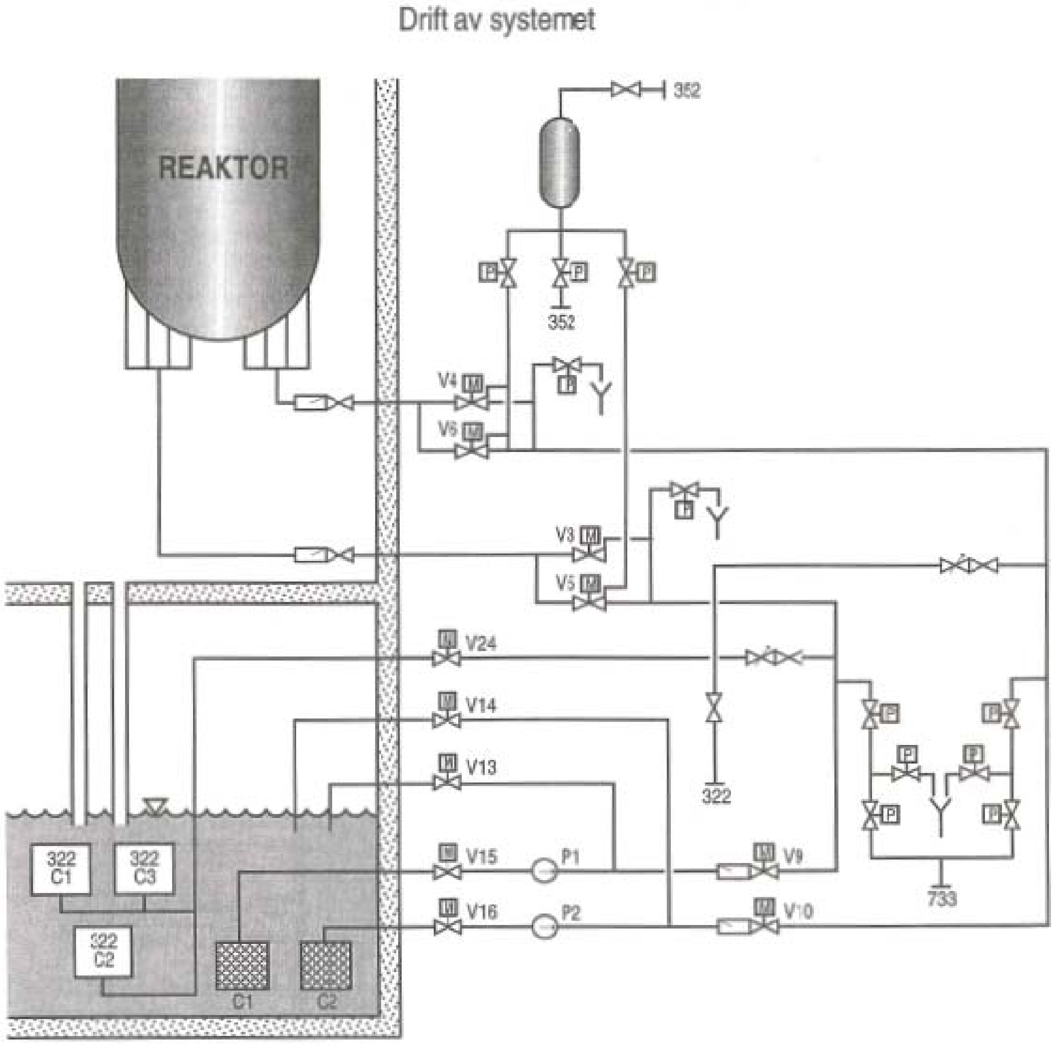

Figure B5: System 323, Emergency Core Cooling System.

B.1.3.6 Strainers

The suction for the ECCS and CVSS in the suppression pool is equipped with a strainer. The strainer was of a cylindrical type with an effective strainer area of approximately 1 m^2 at the time of the Barsebäck incident. The holes had a diameter of 4 mm with an 8-mm distance between the center of the holes, which gives a 0.79 hole area fraction of the total strainer area.

The pipe which is connected to all three strainers in Figure B6 provided the strainers in the CVSS with backflushing water from ECCS. The CI and C3 strainers were clogged during the Barsebäck incident; they are installed approximately 3.5 m above the suppression pool bottom.

B.1.3.7 Other Information

The maximal pressure in drywell was 1.3 bar and the temperature was 90 °C (194 °F) in the incident (Ref.B.14). The actual steam blast damaged cables and the protective housings of two of the containment

video cameras. Ground faults occurred in electrical equipment and instrumentation in the containment. The most probable cause of this was the spraying of the containment.

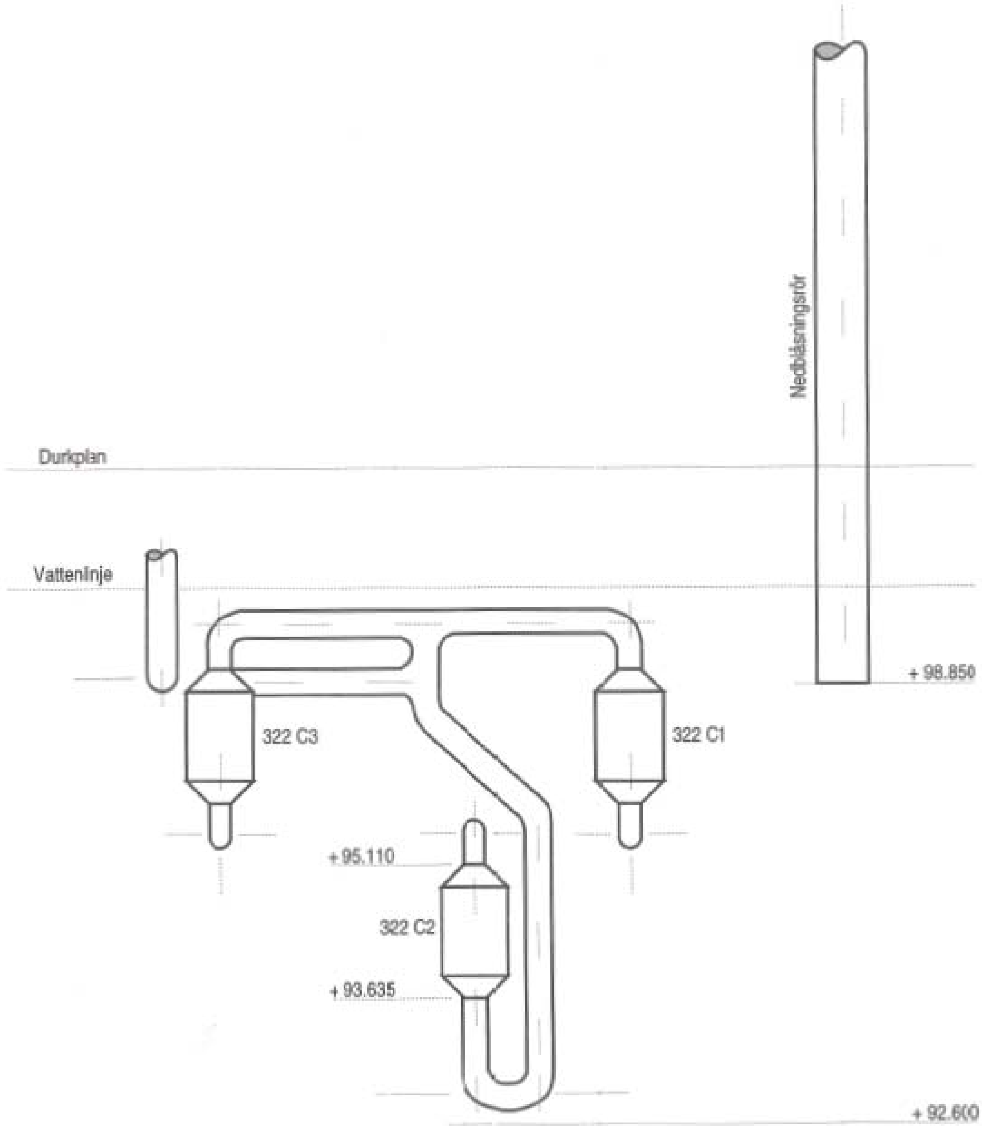

Figure B6: System 322, the CVSS Strainers in the Barsebäck Plant.

B.2 Event at Grundremmingen I (KRB-1), 1977 (Germany)

Another LOCA event with a large quantity of debris generation occurred at the Grundremmingen I plant in Germany in 1977. This nuclear power plant was a dual-cycle BWR with a primary and a secondary circuit. The high-pressure part of the turbine was driven by steam from the primary circuit, that is, steam generated directly in the reactor pressure vessel (RPV). The low-pressure part of the turbine was driven by secondary steam, generated in steam generators heated by the recirculation water of the primary circuit. The event in January 1977 started with disturbances in the grid. A transient was initiated, during which all 14 SRVs of the primary circuit opened at pressures between 8.5 MPa and 8.9 MPa. Due to a problem with feedwater control, the RPV was overfilled and the SRVs vented water. They had not been designed for

this, and one valve was torn off.

The SRVs were located inside the containment at the pipe attached to the main steam line from the RPV to the high-pressure turbine. The valves relieved directly into the containment atmosphere where the ensuing fluid jet impacted nearby insulated pipe. The insulation of pipes in the compartment of the pressure relief valves consisted of glass fiber reinforced with wire mesh and jacketed with sheet-zinc. According to reports written after the incident, the insulation in the affected compartment was torn off the pipes to the "greatest possible extent" [Ref. B.16].

After the incident, approximately 450 m^3 (16,000 ft^3) of water was found in the sump, of which slightly more than half originated from the primary circuit, with the remainder delivered by the containment spray system. This water transported a substantial quantity of insulation debris into the control drive mechanism compartment directly below the SRVs. The floor was covered with flocks of insulation material. No large pieces of the insulation were transported there. A thick layer of fiberglass insulation debris was found at strainers installed in front of ducts leading from this compartment into the sump. Because recirculation from the sump was not required for this event, the layer of insulation debris had no further consequences. Therefore, it is not known whether ECCS recirculation flow from the sump would have been possible. No details regarding the insulation debris quantities generated or transported were made available.

B.3 Operational Experience with Fibrous and Particulate Debris

1. Grand Gulf Nuclear Station (U.S. BWR-6/Mark III) experienced problems with RHR suction strainer blockage. On March 18, 1988 and again on July 2, 1989, the RHR "A" pump before-start suction pressure fell below the in-service inspection (ISI) acceptance criteria of 17.2 kPa gauge (2.5 psig). The licensee determined that the low suction pressure was caused by a clogged strainer that takes suction from the suppression pool. The licensee developed more stringent suppression pool cleanliness requirements and more restrictive pump suction pressure limits to ensure that the strainers are cleaned when pump after-start pressures reach the new limits. After an initial cleaning including hydrolazing the walls and floor, the licensee also established a requirement for vacuum cleaning the suppression pool at the end of every refueling outage (Ref B.17).

2. In March 1988, Susquehanna Unit 2 (US BWR-4/Mark 2) reported that drywell insulation had deteriorated and that the aluminum foil coating of the insulation could fail and block strainers in the ECCS during a LOCA. During a refueling outage, the drywell was inspected. Extensive delamination of the aluminum foil coating on the surface of the fiberglass insulation used on valve bodies and pipe hangers as well as in other areas that are awkward or difficult to insulate, was observed. The aluminum foil covering was 0.025 mm (1-mil) thick, bonded to the outer covering of a fiberglass cloth. An upper-bound estimate was that 464 square meters (5000 square feet) of this insulation is used in more than 300 different locations within the drywell. The estimate was that 50 percent of the insulation has undergone some degradation. Although the exact cause of the degradation of the foil covering on the insulation at Susquehanna was not known, the causes may include temperature, humidity, and the effects of radiation on the neoprene-type adhesive used in the bonding process (Ref B.18).

3. Two events at Perry (U.S. BWR-6/Mark III) demonstrated that strainer plugging can occur during normal operations with particulate as well as fibrous material. A description of this experience follows: In May 1992, during a refueling outage, Perry performed an inspection of the suppression pool using an underwater video camera mounted on a robotic submarine. Debris was found on the suppression pool floor and on residual heat removal (RHR) A and B suction strainers. The debris consisted of general maintenance-type material and a coating of what appeared to be fine dirt that covered most of the surface of the strainers and the pool floor. As a corrective action, the suppression pool was vacuumed and the strainers were cleaned during a mid-cycle outage in January 1993. After cleaning the suppression pool and strainers, it became evident that the strainers were deformed. The strainers were replaced with identical spares in February 1993, prior to startup from

the mid-cycle outage. A review of the historical data on RHR A and B pump suction pressure and strainer differential pressure revealed no significant trend in pump suction pressure or the rate of strainer fouling.

The second event occurred at Perry in March 1993, during which several SRVs were manually lifted and RHR was then used for suppression pool cooling. The licensee inspected the strainers to assess their condition after use and found that the RHR "B" strainer was again coated with debris. A test was run on the RHR "B" pump with the strainer in the as-found condition to determine pump operability. The test was terminated after 10 hours when pump suction pressure dropped from an initial reading of 44.1 kPa gauge [6.4 psig] to 0 kPa gauge [0.0 psig]. A second test that used improved suction pressure instrumentation was run on the same loop with similar results (pump suction pressure dropped to 0 kPa gauge [0.0 psig] after 18 hours). The licensee continued to run that pump for an additional 8 hours during the second test, and observed no further decrease in pump suction pressure. Also, in both tests, no change in system flow rates or pump motor amperage was observed. The debris found on the strainer was analyzed and found to consist mostly of fibers from air filter material hat had been inadvertently introduced into the suppression pool, and corrosion products that had been filtered from the pool by the fibers adhering to the surface of the strainer. (Ref B.17)

4. On September 11, 1995, Limerick Unit 1 (US BWR/4 Mark 2) plant was being operated at 100 percent power when control room personnel observed alarms and other indications that one SRV ("M") was open. Emergency procedures were implemented. Attempts to close the valve were unsuccessful and within 2 minutes a manual reactor scram was initiated. The main steam isolation valves were closed to reduce the cooldown rate of the reactor vessel. The maximum cooldown rate during the event was 69 °C/hr [156 °F/hr]. Before the SRV opened, the licensee was running the "A" loop of suppression pool cooling to remove heat being released into the pool by leaking SRVs. Shortly after the manual scram, and with the SRV still open, the "B" loop of suppression pool cooling was started. Operators continued working to close the SRV and slow the cooldown of the reactor vessel. Approximately 30 minutes later, fluctuating motor current and flow were observed on the Unit 1 "A" suppression pool cooling loop. Cavitation was believed to be the cause and the loop was secured. After checking out the pump, the "A" pump was restarted, but at a reduced flowrate of 8 kL/m [2000 gpm]. No problems were observed so the flow rate was gradually increased to 32 kL/m [8500 gpm]. No problems were observed so the licensee continued to operate the pump at a constant flow. A pressure gauge located on the pump suction was observed to have a gradually lower reading, which was believed to be indicative of an increased pressure drop across the pump suction strainer located in the suppression pool. After about 30 minutes of additional operation, the suction pressure remained constant. The rest of the reactor shutdown was routine and there were no further complications. After a plant cooldown following the blowdown event, a diver was sent into the Unit 1 suppression pool to observe the condition of the strainers and general pool cleanliness. Each strainer was a "T" arrangement with two truncated cones fabricated from perforated plate; the entire cone surface is covered by a 304.8 mm (12 inch) x 304 mm (12inch) 316 L stainless steel wire mesh. The suction strainer in the "A" loop of suppression pool cooling was found to be covered with a thin "mat" of material consisting of fibers and sludge. The "B" strainer had a similar covering, but to a lesser extent. These were the two loops that had been used for suppression pool cooling necessitated by the leaking SRVs. The other strainers in the pool were covered with a dusting of sludge. Debris was subsequently brushed off the surface of the strainers, and the suppression pool floor and water were cleaned by use of a temporary filtration system. It is believed that, during operation of the suppression pool cooling system, the strainer filtered out fibers that were in the pool water. The resulting "mat" of fibers improved the filtering action of the strainers thereby collecting sludge and other material on the surface of the strainer. About 635 kg [1400 lb] of debris was removed from the pool of Unit 1. A similar amount of material had previously been removed from the Unit 2 pool. Analysis showed that the sludge was primarily iron oxides and the fibers were of a polymeric nature.

The source of the fibers has not been positively identified, but it was determined that the fibers were not inherent with the suppression pool. There was no trace of either fiberglass or asbestos fibers. (Ref B.19)

5. On August 23, 1992, while the H. B. Robinson Nuclear Plant (US PWR 3-loop) was in mode 4, hot shutdown, plant personnel were performing an operations surveillance test of the ‘B’ train safety injection (SI) pump. This test found that the recirculation flow was 20 percent lower than it had been when it was last measured 6 weeks earlier. The next day a re-test found zero recirculation flow. The licensee also tested the ‘A’ SI pump and found the recirculation flow was 10 percent lower than when it was last measured. The licensee declared both pumps inoperable and took the unit to cold shutdown. On August 25, 1992, the licensee opened the ‘B’ SI pump recirculation line and removed a single piece of white plastic, about the size of a nickel (21 mm), from the inline orifice. Previously, on July 8, 1992, the licensee had declared the ‘B’ SI pump inoperable after a quarterly in-service inspection surveillance test found that it was producing a recirculation flow of 11.4 Liters (3 gallons) per minute, rather than the required 132.5 Liters (35 gallons) per minute. On July 9, 1992, the licensee shut down the plant to determine the cause of the low flow. The licensee removed the recirculation line for the B SI pump and found that debris was obstructing the inline orifice (Ref B.20).

6. There are several other examples of debris found in Safety Injection Systems, or blockage of suction strainers reported in NUREG/CR-6808 Chapter 9 (Ref B.21). These examples cover both BWRs and PWRs. A listing of generic communications that describe other ECCS suction strainer concerns for both BWRs and PWRs is available on the NRC web site http://www.nrc.gov/reading-rm/doc-collections/#gen.

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B.18 Information Notice No. 88-28: Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage" dated May 19, 1988.

B.19 Information Notice 95-47 Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage, dated October 1995.

B.20 NRC Information Notice 92-85: "Potential Failures of Emergency Core Cooling Systems Caused by Foreign Material Blockage" dated December 23, 1992.

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APPENDIX C: CHARACTERISTICS OF INSULATION MATERIALS RELEVANT TO ECCS STRAINER BLOCKAGE

There are a large number of different commercially available insulation products. These differ from one another not only by generic type (fibrous glass wool, mineral wool, needled ceramic fiber, microporous materials) and by manufacturer but also in more measurable properties and characteristics. Some of these properties and "as fabricated" characteristics have a strong effect on the primary function of the insulation (thermal performance), but certain properties are important when evaluating potential effects related to nuclear plant safety.

This Appendix describes the physical and chemical properties of various types of insulation materials used in NPP containment, with emphasis on those properties that can affect strainer head loss.

C.1 Fiberglass

Most of the fiberglass encountered is of two types:

- Fibrous glass wool insulation
- E-type fiberglass yarns used in textiles and as a reinforcement

There is also filter-media fiberglass, used in air filters, and S-glass, used as reinforcement for plastic airplane parts or other applications requiring exceedingly high strength materials.

C.1.1 Fibrous Glass Wool

Generally speaking, this type of fiberglass is almost always used as thermal and/or acoustical insulation. It may be seen as a shredded, very low density (0.6 pounds per cubic foot) material, a fluffy soft board, rigid hard board, or rigid molded material. In all of these cases, it is made by dry batching silica and other inorganic chemicals in a large electric furnace, then pressing the molten glass mixture through thousands of tiny orifices.

In the fiberglass manufacture, the mounting of the orifices is either rotated or oscillated as the fibers are drawn out of the orifices, causing the new fibers to harden and break off, falling into a stream of sprayed liquid organic chemical "binder". The binder coats the individual fibers, bonding them at certain locations to one another. In an uncured state, this "binder" is tacky; the fibrous mat has almost no definable shape. A conveyor carries the fiberglass mat to an oven. The thickness and pack density, and uniformity of the final product will be a function of variables such as the number of orifices, the rate of fiber formation per orifice, and the speed of the conveyor.

The oven, which may use both convection and radiation, "fluffs' the uncured pack to the desired thickness (usually a little thicker than nominal) and cures the organic binder. Depending on the pack density and the percentage of binder content by weight, the final product may be soft and fluffy (residential building insulation) or rigid and firm (duct board product). Any facing material, such as aluminum foil, kraft paper, or fabric, is first sprayed with an adhesive and then pressed onto the cured fibrous glass wool pack, often in

a continuous manner at the exit of the curing oven. Final product dimensions are determined by cutting tolls, typically in line with the process machinery.

C.1.1 E-Type Textile Fiber Glass

Unlike fibrous glass wool, "E-glass" fibers are made as continuous yarns. Molten glass is forced through a "bushing" with many tiny orifices to create fibers which are then drawn together and simultaneously sprayed or coated lightly with an organic "sizing" compound. These are then rapidly twisted together to form a yarn, passed through an oven for curing of the sizing compound, and wound onto a bobbin. These bobbins of yarn are then shipped to weavers, who weave fiberglass fabric on large standard industrial looms.

Chopped strands, which are frequently used to reinforce plastics, are created by chopping the yarns every inch or so, bailed together, and shipped to companies manufacturing reinforced plastic or concrete products. This process tends to be messy, resulting in a large number of chopped strands scattered around the chopping area. These are periodically swept up, packaged, and sold to a company that has needling equipment. There, these chopped strands are needled into a felt mat that is about 1/2 inch or 1 inch thick. This is one of the few thermal insulation products made from E-glass fibers. The organic content (i.e., the sizing compound content) on needled fiberglass felt insulation is typically only about 0.5% by weight

C.1.3 Glass Fiber Properties

Glass fibers differ from one another due to differences in the following properties:

- glass chemical composition;
- fiber diameter - this may vary from 1.25 microns to 10 microns and is determined by the size of the orifices;
- fiber length - this may vary from 1/4 inch to several inches in wool to infinite lengths for E-glass fibers;
- binder type and percent - on fibrous glass wool this is typically a phenolic resin with percentages varying from 1% to 15% by weight;
- fiber tensile strength - this is very high for E-glass fibers, around 300,000 psi. For wool fibers, this is much lower (i.e., less than 100,000 psi) due to the rough physical treatment the fibers are subjected to in the forming hood.

C.1.3.1 Fibrous Glass Wool Pack Properties

The thermal performance of fibrous glass wool is primarily a function of pack thickness, pack density (typically 0.6 to 12 pcf), fiber density, and fiber emissivity. In general, fibrous glass wool insulation functions by reducing air convection and thermal radiation heat transfer. Its thermal conductivity is limited by the thermal conductivity of air. If the pack thickness, insulation thermal conductivity behavior with temperature, insulation cold surface emissivity, hot surface temperature, ambient air temperature and air movement, and configuration are known, then the thermal performance of fibrous glass wool insulation is highly predictable and the heat transfer is approximately one dimensional. Fibrous glass wool insulation will not perform as expected if any of the following occur:

- the pack thickness is reduced, perhaps by physical abuse;
- metal or other high thermal conductivity material is used as a encapsulator or as a structural material, creating a "thermal bridge" from the hot surface to the cooler ambient;
- gaps are left, or are formed, resulting in excessive air convection and thermal radiation heat transfer through the gaps;
- air spaces between the insulation and the hot surface allow air circulation movement from the hot surface, through insulation gaps, of the cooler ambient.

Following is a list of important characteristics, the properties that they affect, and a description of each.

Fiber Diameter: When the fibers are formed during manufacturing, their mean diameter is controlled. The greater the fiber diameter, the fewer fibers there are per unit volume for a given pack density and the smaller the overall fiber surface area per unit volume. Larger fiber diameters will generate a lower headloss behavior for water flowing through a bed of these fibers collected on an ECCS strainer. Fiber diameter will also have an impact on the pack compressive strength and the pack parting, or tensile, strength. There is no standardized test method for this characteristic.

Fiber Tensile Strength: This characteristic is not easily measurable; the pack parting strength, which is easily measurable, is discussed later. There is no standardized test method for this characteristic: it is controlled in the manufacturing process.

Organic Chemical Binder: The type and amount of chemical binder gives the fibrous pack much of its resilience, compressive strength, and parting strength. While the type of binder is generally proprietary information of the manufacturer, its percent by weight is easily measurable. In commercial products, this value may vary by ± 50% of the nominal; its value should be controlled more closely (± 10%) to properly control the pack properties affected by binder percentage considered to be critical characteristics for nuclear safety, or it should be removed before testing. There are no standardized test methods for these characteristics. Binder composition is controlled in the manufacturing process.

Inorganic Chemical Content: The exact inorganic chemical content of the fibers is proprietary information maintained by the manufacturer, but these materials are typically made of various amounts of silica, aluminum, calcium, magnesium, boron, soda, potassium, iron, titanium and strontium; some manufactures add fluorine. The composition affects the mechanical properties of the fibers (such as tensile strength and modules of elasticity) and the chemical properties (leachability, solubility). The manufacturer controls chemical content by controlling the batch formulation of the raw materials. There is no standardized test method for this characteristic, but it can readily be determined by standard chemical analysis techniques.

Pack Density: The mass per unit volume for the fibrous pack, which is directly controlled in the manufacturing process. For a given applied thickness of insulation, the pack density will be a major determining factor in the mass of material eventually collected on a strainer following a LOCA. The actual density of commercially available products often varies as much as 25% from the nominal density. For the purposes of testing and analysis, this value should be known much more exactly; this property can be measured as per ASTM C167.

Compressive Strength and Resilience (of the Pack): These properties of the fibrous pack are functions of fiber mechanical properties, binder type and content, fiber diameter, and pack density. These two properties can vary widely from one fibrous material to another. The greater the compressive strength, the lower the headloss because the fibers will maintain larger fiber-to-fiber distances, allowing water to flow through the pack more easily. Therefore, this is a significant property that should be controlled, for a given fibrous insulation, to allow for an accurate post-LOCA headloss calculation. These properties can be measured as per ASTM CI65.

Parting Strength (of the Pack): Parting strength, or pack tensile strength, is a function of individual fiber tensile strength and diameter, pack density, and organic binder type and content. The greater the parting strength, the "stronger" the insulation and consequently, in a LOCA, the less shredded the impacted thermal insulation materials are likely to become. This property can be measured as per ASTM C686.

Resistance to Flow: A fluid flowing through a fibrous pack will encounter resistance to flow (such as from fibrous insulation debris collected on the number on ECCS strainers). This is a complex function of the void space between the fibers, the fiber diameters, the thickness of the fibrous pack, and of course, fluid characteristics. There is no standardized test method for this property.

Thermal Conductivity: This most important property of thermal insulation, in its insulating role, is a function of fiber diameters, fiber lengths, fiber chemistry, binder type and content, and, of course, properties of air. This property is not relevant to the ECCS strainer blockage issue, but can be measured

using ASTM CI77.

As insulation manufacturers make a fibrous insulation material, they can control the fiber diameter, fibrous tensile strength, binder type and content, fiber length, fiber chemistry, and wool pack formulation (density and thickness; ASTM CI67). As a result, the following insulation pack properties will also vary: thermal conductivity (ASTM C177), resistance to fluid flow parting strength (ASTM C686), and compressive strength and resilience (ASTM C165).

Table C-1 summarizes the dependence of ECCS variable on insulation pack properties and shows that these, in turn, depend on certain characteristics of the material.

C.1.3.2 Effects of High Temperature

When fiberglass materials, both E-glass and fibrous glass wool, are sufficiently heated, their glass structure expands permanently and they lose some strength. In addition, the organic binders (on the wool) and sizing compounds (on the E-glass) decompose into gases, mostly carbon dioxide and water vapor. The exact temperature at which this occurs varies, but binder decomposition will reduce the compressive strength of the wool pack. Due to the thermal gradient through the wool pack, only the part of the binder that has exceeded the temperature required for decomposition will decompose. Therefore, the pack compressive strength generally does not decrease by more than 20%, depending on the percentage of binder, the type of binder, and the temperature conditions. Generally, fibrous glass wool insulation products are not rated for use at surface temperatures higher than 1000 °F.

E-glass yarns, used to weave fiberglass fabrics, are typically rated for use to a maximum temperature of 1200 °F. However, a fiberglass fabric that has been exposed to only 600 °F will retain a higher tensile strength than one that has been exposed to 1200 °F.

The thermal decomposition of the organic sizing compound also makes the fabric less flexible. The fusing together of the yarns, which increases with temperature, will decrease the strength of the fabric.

At temperatures of about 1400 °F, fiberglass of any form melts (i.e., flows) and therefore ceases to serve any useful function. At even higher temperatures in molten glass, some crystallization may occur; this is called devitrification.

Table C-1: Dependence of ECCS Variables on Insulation Pack Properties and Material Characteristics

ECC Behavior	Insulation Pack Properties	Important Characteristics of Fibrous Insulation Materials
Debris Generation	Parting strength	Fiber diameter Binder type and content potential Fiber chemistry Fiber tensile strength Fiber length Wool pack density and thickness
Debris Transport	Resistance to flow	Fiber diameter Fiber length Binder type and content Wool pack density and thickness
Sedimentation Rate	Resistance to flow	Fiber diameter Fiber length Binder type and content Wool pack density and thickness
Head Loss	Resistance to flow	Fiber diameter
	Compressive strength	Fiber length Binder type and content Wool pack density and thickness

C.1.3.3 Effects of Gamma and Neutron Radiation

Gamma and neutron radiation, such as might be encountered in a nuclear containment, will, in sufficient intensity, decompose organic binders and sizing compounds. There has been little research on glass fibers themselves, although testing on common boron-silica glass formulations has shown a change in the close order structure of the glass and a resultant decrease in Young's modulus at high neutron doses. There is also a noticeable change in the optical properties, but structurally the effect is probably not as great as the effect of organic decomposition.

C.1.3.4 Effects of Water

Water flowing continuously past fiberglass fibers will leach out some of the inorganic chemicals. In cold, chemically neutral water, this effect is minimal, but alkaline water will more rapidly leach certain of the inorganic compounds, leaving fibers that can be significantly reduced in tensile strength. There are likely no fiberglass products that do not undergo some degradation in tensile strength as a result of being exposed to hot, alkaline water; this behavior is generic to fiberglass.

C.2 Mineral Wool

Although the definition and usage can vary, the term "mineral wool" typically refers to two types of insulation material:

- Rock wool (Stone wool) - a man-made material consisting of natural minerals like basalt or diabase. An increasing proportion is recycled material in the form of briquettes;
- Slag wool - a man-made material from blast furnace slag (the scum that forms on the surface of molten metal).

It should be noted that Rockwool is a commercial product, which adds to the confusion over terminology.

Inorganic rock or slag are the main components (typically 98%) of mineral wool, the remaining 2% is generally a thermosetting resin binder and a little oil. The final product is a mass of fine, intertwined fibers with a typical diameter of 6 to 10 micrometers. Its thermal insulating properties have the same origins as those of glass fiber insulation.

The raw materials are measured and sent to a melting furnace, where they are melted at temperatures typically between 1,300 to 1,500 °C. The droplets of melt exiting the furnace are spun into fibers. Droplets fall onto rapidly rotating flywheels or the mixture is drawn through tiny holes in rapidly rotating spinners. Small quantities of binding agents are added to the fibers. The structure and density of the product are tailored according to its final usage. The mineral wool is then hardened in a curing oven at around 200 °C. The mineral wool is cut to the required size and shape, for example into rolls, batts, boards, or it can be customized for use with other products. Off-cuts and other mineral wool scraps are recycled back into the production process.

C.2.1 Refractory Ceramic Fiber (RCF)

Refractory ceramic fiber (e.g., Kaowool, manufactured by Morgan Thermal Ceramics) can be considered a form of mineral wool. These are aluminosilicate fibers; for example, Kaowool is produced from kaolin, a naturally occurring alumina-silica clay. A small amount of organic binder is generally added. They have good resistance to tearing, high flexibility, good resistance to thermal shock, with very low thermal conductivity and low thermal mass. They can be spun or blown into bulk, air-laid into a blanket, folded into modules, converted into papers, boards, and shapes, die-cut into gaskets, twisted into yarns, woven into rope and cloth, and blended into liquid binders for mastics and cements.

C.3 Calcium Silicate

C.3.1 Composition and Manufacture

Calcium silicate (often referred to by its shortened trade names Cal-Sil or Calsil) is the chemical compound Ca_2SiO_4, also known as calcium orthosilicate and sometimes formulated $2CaO.SiO_2$. It is a white powder with a low bulk density and high physical water absorption, and is one of a group of compounds obtained by reacting calcium oxide and silica in various ratios (often from limestone and diatomaceous earth).

Calcium silicate is commonly used as a safe alternative to asbestos for high temperature applications. It evolved circa 1950 from earlier high-temperature thermal insulations: 85-percent magnesium carbonate and pure asbestos insulation. Calcium silicate insulation was originally typically reinforced with asbestos fibers, but by the end of 1972, most North American manufacturers had switched to glass fiber, plant fibers, cotton linters, or rayon. North American–manufactured calcium silicate now contains no asbestos.

The material is manufactured and sold in three different forms: preformed block, preformed pipe, and board. Calcium silicate is noted for its high compressive strength, corrosion-inhibiting properties, and high-temperature structural integrity. It can withstand continuous temperatures up to either 1,200 °F (Type I, for pipe and block) or 1,700 °F (Type II, fire endurance boards). Industrial grade piping and equipment insulation is often fabricated from calcium silicate.

Calcium silicate insulation is made from amorphous silica, lime, reinforcing fibers, and other additives mixed with water in a batch-mixing tank to form a slurry. This slurry is pumped to the preheater, where it is heated to boiling and quickly poured into molds. After a few minutes, the material is removed as a wet and fragile solid. These formed pieces are placed into an indurator (a steam pressure cooker) for several hours, where the chemical reaction takes place to form calcium silicate. The pieces are then placed into a drying oven. After drying, the pieces are trimmed, slit into two or more pieces, and packaged.

The molded, cured insulation material is essentially a micro-crystalline material with more air space than solid space (greater than 90 percent air). Millions of tiny air spaces separated by low-thermal-conductivity material give calcium silicate its insulating characteristics. Very little infrared radiation is able to pass

through it, so it is an effective high-temperature insulation material. As such it can be considered a class of microporous insulation.

C.3.2 Relevant Characteristics for Strainer Performance

C.3.2.1 Debris Generation

American Society for Testing and Materials (ASTM) C533, "Standard Specification for Calcium Silicate Block and Pipe Thermal Insulation," establishes minimum acceptable standards for both Types I and II. Type I is rated to a maximum-use temperature of 1,200 °F and has a maximum density of either 15 lbs/ft^3 or 22 lbs/ft^3, whereas Type II is rated to 1,700 °F and has a maximum density of 22 lbs/ft^3. The as-manufactured compressive strength for both types is greater than 100 psi at a 5-percent deformation, the highest of any non-structural high-temperature insulation material in the ASTM materials specifications. The maximum linear shrinkage, after exposure to the maximum use temperature, is only 2 percent, and the flexural strength is greater than 50 psi for both types. Maximum allowable mass loss values in the ASTM specification are 20 percent and 40 percent after tumbling for 10 minutes and 20 minutes, respectively, demonstrating its resistance to breakage.

Calcium silicate insulation is typically covered with a protective jacketing: conventional aluminum sheet, stainless steel sheet, PVC sheet, glass cloth with weather barrier mastic, or a multi-ply laminate. To prevent water intrusion, a bead of sealant should be used on sheet metal jacketing overlaps.

C.3.2.2 Head Loss

Calcium silicate particulate is relatively fine (Figure C-1). Detailed SEM characterization of pulverized calcium silicate (Figure C-2) showed that the calcium silicate particles in the samples had dimensions that ranged from the sub-micron to perhaps 100 microns; the larger particles consisted of agglomerates of smaller particles suggesting that the larger particles could further break into smaller particles. In addition, larger pieces of calcium silicate are subject to substantial dissolution, which is both turbulence and temperature dependent, i.e., an increase in either temperature or turbulence has been shown to enhance the disintegration of the calcium silicate.

Head-loss tests were conducted at LANL with debris beds of calcium silicate only at three debris loadings and at two temperatures (Figure C-3). Significant head loss was measured for all the calcium silicate debris beds formed on the 1/8-in.-mesh screen, even the thinnest bed with a theoretical bed thickness of only ~0.02 in. As a significant fraction of the screen area was effectively uncovered, it was concluded that even higher head losses would have occurred if the bed had been truly uniform. If the calcium silicate had been totally pulverized before insertion into the test, its accumulation would likely have been less than shown in these tests where the debris was not completely turned into fine particulate.

Figure C-1: SEM Micrograph of Powdered Calcium Silicate [C.8]. The calcium silicate insulation was obtained from Performance Contracting Inc. (PCI), Lenexa, Kansas in the form of molded blocks, which were broken up by hand–crushing with a mortar and pestle.

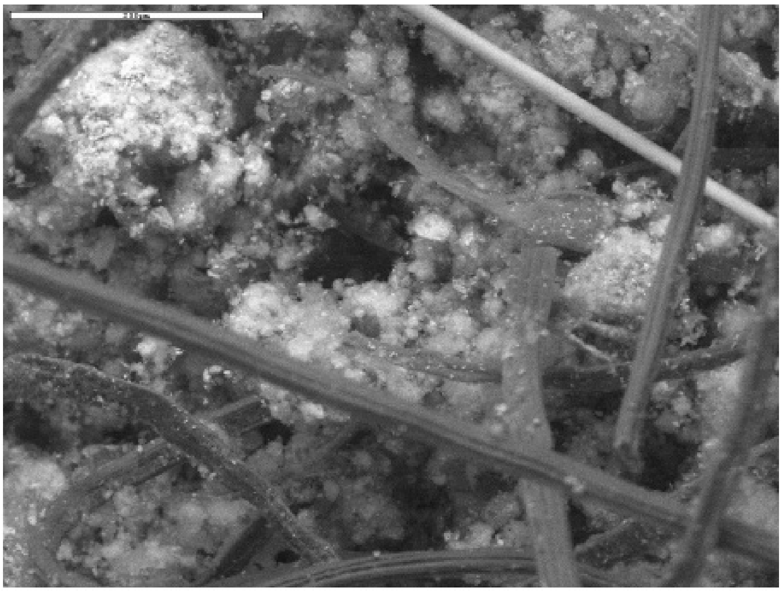


Figure C-2: SEM Micrograph of Calcium Silicate [C.7]. The scale white bar in the upper left corner represents 200 µm. The calcium silicate particles are mixed with fibers added to the insulation to provide strength.

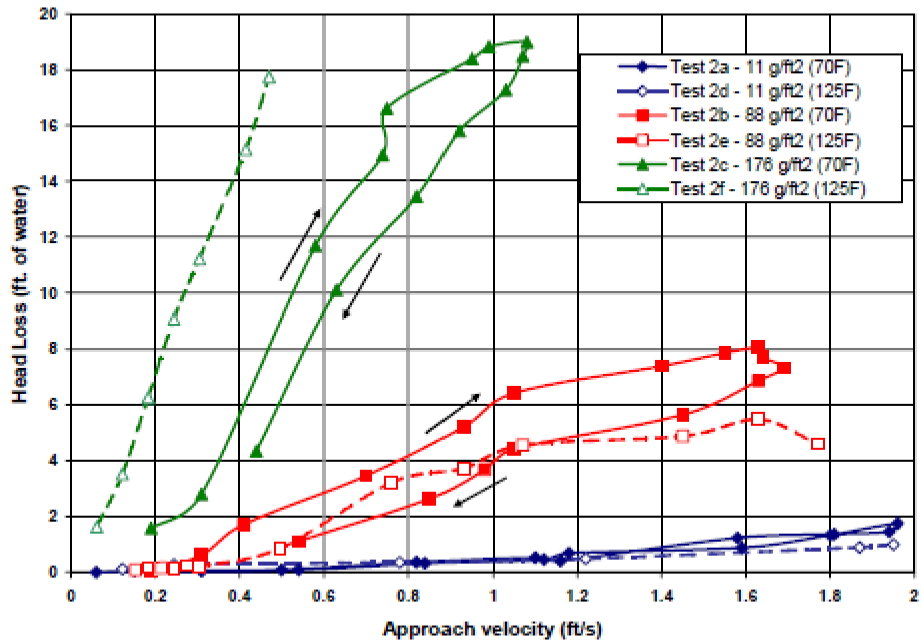


Figure C-3: Head-loss Measurements for Three Different Quantities of Calcium Silicate at Two Different Water Temperatures [C.7].

Figure C-4 shows the results of head loss testing at ANL. Calcium silicate and NUKON were heated outside the test loop for 30 minutes at 60 °C (140 ºF) in borated water (2800 ppm B and 0.7 ppm Li). After the debris was added to the loop, the head loss increased very rapidly, within the first six minutes (or after approximately one test loop recirculation) after introducing the debris.

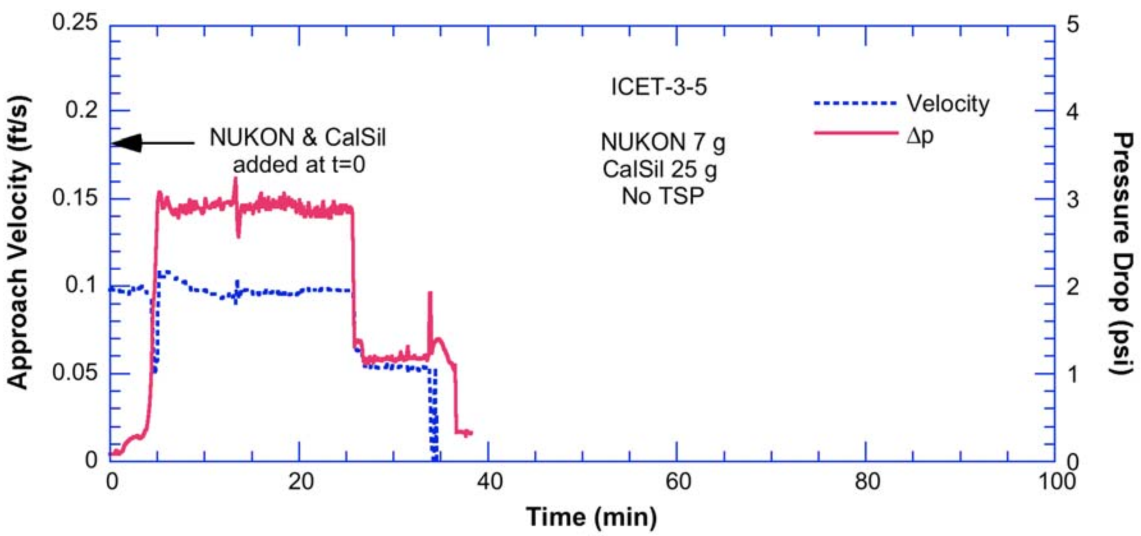


Figure C-4: Bed Approach Velocity and Differential Pressure across the Screen as a Function of Time for Test ICET-3-5 [C.8].

NUREG/CR-6913/ANL-06/41 concluded that the head losses associated with pure physical debris beds of NUKON and calcium silicate are generally smaller than those that occur across debris beds in which some of the calcium silicate has been replaced with a corresponding amount of calcium phosphate precipitates.

For a screen loading corresponding to 0.71 kg/m^2 of calcium silicate and an ~12 mm thick NUKON bed (0.71 kg/m^2), the pressure drop across the physical debris bed in benchmark testing in chemically inactive environments is approximately 1.4 psi at an approach velocity of 0.1 ft/s. With TSP, and thus calcium phosphate precipitates present, the same debris loading caused the pressure drop across the bed to be greater than 5 psi for the same approach velocity.

C.3.2.3 Chemical Effects

In tests to study the dissolution of the calcium silicate in the containment sump prior to the onset of recirculation, a slurry of calcium silicate and NUKON was presoaked at 60 °C in a boric acid, lithium hydroxide (LiOH) solution for 30 minutes. It was noted that at high calcium silicate concentrations (≥ 6 g/l), the total amount of calcium silicate dissolution is limited by the solubility of calcium silicate (about 200 ppm). Regardless of the initial pH or the rate of addition of TSP, the pH of solution rises to about 7, primarily because calcium silicate contains sodium silicate as an impurity. Sodium silicate is very soluble, and as it dissolves, the dissolved sodium causes the pH of the initial boric acid/LiOH solution to increase. At lower calcium silicate concentrations, the increase in pH due to the dissolution of the sodium silicate impurity is much smaller, reducing Ca release.

C.4 Microporous Insulation

C.4.1 Composition and Manufacture

ASTM C168 (Standard Terminology Relating to Thermal Insulation) defines a microporous insulation as *"Material in the form of compacted powder or fibers with an average interconnecting pore size comparable to or below the mean free path of air molecules at standard atmospheric pressure. Microporous insulation may contain opacifiers to reduce the amount of radiant heat transmitted."*

A microporous insulation consists of about 90% air, contained in minute 'cells' formed between nanometer-sized particles, generally amorphous (fumed) silica, sometimes with refractory oxides and glass reinforcing fibers added. Microporous insulation products are designed to provide maximum resistance to the three relevant modes of heat transfer: solid conduction, gaseous conduction and radiation.

Convection cannot occur in a microporous material due to the absence of sufficiently large air volumes.

Solid conduction is minimised since approximately 90% of the volume is void space where only less efficient gaseous conduction can take place. In addition, the nano-sized particles making up the material have very restricted contact with one another, limiting thermal pathways; the amount of heat conducted is directly proportional to the cross section of the conduction path. The heat paths through the solid matrix are very tortuous and long, which decreases the rate at which heat can flow by solid conduction; the amount of heat conducted is inversely proportional to the length of the conduction path.

Gaseous conduction is restricted by the microporous effect, which restricts collisions between air molecules that lead to heat transfer by ensuring that the voids in the material are smaller than the mean free path of the air molecules (approximately 100 nm at atmospheric pressure). Under these circumstances most of the collisions an air molecule experiences are with the walls of the pores, a process which transfers little energy. The thermal conductivity of microporous materials is actually lower than the thermal conductivity of still air; this unique property of microporous insulation gives these materials a significant decrease in thermal conductivity over conventional insulations.

Radiation**,** the major mode of heat transfer at higher temperatures, is minimized by formulating the material (e.g., by addition of opacifiers) to be almost entirely opaque to infra-red radiation. Opacifiers are specifically designed to reflect, refract and re-radiate radiation energy, preventing it from propagating easily through the microporous material. As a result, the thermal conductivity rises only slightly with increasing temperature and the performance advantage over conventional insulations becomes more pronounced as the operating temperature increases towards 1000 °C (1832 °F).

C.4.2 Characteristics Affecting Strainer Head Loss

Microporous insulation debris has the potential to adversely impact head loss in a manner comparable to or worse than calcium silicate debris. Like calcium silicate, these materials contain both particulate and fibrous components that can lead to formation of a thin debris bed on a sump strainer without the presence of significant quantities of additional fibrous debris.

In a US NRC Trip Report detailing a visit to ARL to observe chemical effects tests being conducted for the Watts Bar ECCS strainer and a new test protocol, information regarding the effect of the microporous insulation Min-K is documented [C.6]. In the test, the first addition of Min-K resulted in the head loss increasing by about 2.7 ft. A second Min-K addition resulted in a head loss increase of over 2 ft, and third (and final) Min-K addition resulted in a similar increase in head loss. After all Min-K was added, the total head loss was about 12 ft, with a clean strainer contribution of about 4.2 ft. Therefore, the debris head loss was about 7.8 ft. The trip report concludes that "*A significant head loss occurred with no debris that is considered fibrous added to the test tank. The majority of the head loss was due to Min-K which has previously been considered to be a particulate debris type. Min-K contains significant amounts of fiber that apparently provide a fibrous bed for particulates to be filtered on*".

The particle size of destroyed microporous insulation is a key question. One US licensee [C.5] used information provided by the insulation vendor to conclude that particle size of the fumed silica (SiO_2) in Microtherm debris would be 20 µm, based upon the assumption that the fumed silica would break into three-dimensional branched chain aggregates that are mechanically tangled into approximately spherical agglomerates. Information provided by the insulation vendor suggested that this was appropriate because the amount of dispersion energy typically provided by a high-shear mixer along with the use of chemical dispersants is necessary to reduce the particle size further.

However, when considering the potential head loss contribution from Microtherm, the assumed particle size distribution is potentially non-conservative (i.e., the assumed minimum particle sizes may be too large). US NRC staff believe that an actual LOCA jet may be capable of fragmenting some of the SiO_2 into submicron-range particles (recall that the particle size of the constituent silica particles in these materials is on the order of 10 nm). The smaller particle sizes may result in increased head loss by packing tightly together in a fibrous debris bed matrix. It is important that a validated technical basis for any assumed particle size distribution be provided.

The porous structure of microporous insulation material makes it extremely hydroscopic. As a result, it absorbs liquid quickly and readily, and, when saturated, suffers an irreversible loss of its superior thermal performance properties (approximately 25+%, depending upon the product form). Natural humidity and water vapor (testing performed using 100% humidity at 100 °F for 24 hours) do not affect the microporous structure. Hydrophobic options to combat the material's inherent hydroscopic qualities are available in many product forms. These hydrophobic materials give added protection to the material's microporous structure, but have service temperature use limits of approximately 900 °F. After the hydrophobic components burn out, the microporous structure continues to remain intact, but becomes hydroscopic again.

The hydroscopic and highly porous nature of these materials suggests that in alkaline water the SiO_2 could be rapidly attacked, leading to disintegration of the material.

C.5 Reflective Metal Insulation

C5.2.1 Composition and Manufacture

The US National Insulation Association defines reflective insulation as *"Insulation depending for its performance upon reduction of radiant heat transfer across air spaces by use of one or more surfaces of high reflectance and low emittance."* Reflective insulations trap air to reduce heat transfer using layers of steel, aluminum, paper or plastic. The low emittance metal surface of reflective insulation also blocks up

to 97% of radiative heat transfer. Reflective insulation is lightweight, has low moisture-transfer and absorption rates, does not contain substances that will off-gas, and shows no change in thermal performance from compaction or moisture absorption.

In nuclear applications, RMI is an engineered insulation system of individually designed segments, constructed of stainless steel (usually austenitic) sheet metal or aluminum. RMI uses a heavier gauge outer shell to hold its shape. The interior consists of numerous layers of lighter gauge foils carefully spaced and designed to prevent gaps and fit tightly to other segments and mating pieces.

RMI might not insulate as well as fibrous insulation and performance varies between manufacturers, but current designs are effective enough for their use in containment systems. RMI usually takes longer to install, remove, and reinstall, is heavier to support on pipes and equipment, is thicker so it has more interferences, and is generally more costly than other insulation options. However, as it contains no fibers, there is no health risk associated with ingestion of contaminated airborne particles by maintenance personnel. In addition, the exterior can be made water shedding and self-draining, so that its thermal performance is unaffected by water, unlike fibrous insulation (which slumps when wetted) or microporous materials whose pores are easily wetted, and this also means that RMI will not hold water in contact with pipes, which can promote oxidation corrosion cells.

C.5.2 Characteristics Affecting the ECCS Strainer Clogging Issue

Most of the RMI debris generated by the LOCA jet will be large enough that it is likely to remain near the break location; the transported RMI fragments sink typically to the bottom of the containment pool and not arrive to the strainers, especially when the sump strainers have large surface area (now used in many plants) which implies very low flow velocities. RMI materials should not corrode under the conditions normally encountered in containment, and compared to conventional insulation systems of Cal-Sil or fibers, RMI is not expected to degrade under the radiation and operating conditions of the nuclear environment and does not contributes to “chemical effects”.

C.6 References:

C.l American Society for Testing and Materials, 'Test Method for Measuring Compressive Properties of Thermal Insulation," ASTM C165, Philadelphia, PA.

C.2 American Society for Testing and Materials, 'Test Method for Thickness and Density of Blanket or Batt Thermal Insulations," ASTM C167, Philadelphia, PA.

C.3 American Society for Testing and Materials, 'Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus," ASTM C177, Philadelphia, PA.

C.4 American Society for Testing and Materials, 'Test Method for Parting Strength of Mineral Fiber Batt- and Blanket-Type Insulation," ASTM C686, Philadelphia, PA.

C.5 “San Onofre Nuclear Generating Station Unit 2 and Unit 3 GSI-191 Generic Letter 2004-02 Corrective Actions Audit Report”, US NRC ADAMS Accession Number ML070950240.

C.6 “Staff Observations of Testing for Generic Safety Issue-191 during a July 12 To July 14, 2010 Trip to the Alden Test Facility for PCI Strainer Tests”, Adams Accession Number ML102160226.

C.7 “GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation”, NUREG/CR-6874/LA-UR-04-1227.

C.8 “Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191”, Argonne National, NUREG/CR-6913, ANL-06/41.

C.8 “Specialized Reflective Metal Insulation for use in Nuclear Containment Applications”, Jon

Householder, Performance Contracting Inc., presented at the NIA 2011 Annual Convention, March 23–26, 2011, Tucson, Arizona.

APPENDIX D – EXPERIMENTAL INVESTIGATIONS AND TEST FACILITIES

This appendix briefly describes the various test facilities developed to study ECCS and CSS recirculation reliability, and the experimental investigations that have been performed. It has been divided into various categories for convenience, but it should be noted that many of the facilities listed are multi-purpose or perform integrated testing and could be listed in several categories:

Each description has the same general format, providing details on the tests, any documentation available, an abstract, objectives and a summary of the findings.

SUMP SCREEN HEAD-LOSS & DEBRIS GENERATION

Title:	Ringhals 1: Strainers system 322/323 Ref. 4.34
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 92:B56
Document length:	46 pages
Date:	1992-12-18
Nature of study:	Experimental
Phenomenon studied:	Deposit and pressure drop experiments during parallel flow through a small filter surface and on a half-scale for a complete filter; the backflushing function has also been verified

Abstract: Vattenfall Utveckling has been commissioned to propose and test new strainer designs, together with Ringhals nuclear power plant. The experimental program consisted of two types of experiments. The first experiment was one of deposit and pressure drop in connection with parallel flow through a small filter surface. These experiments were carried out as a design basis for the subsequent half-scale experiments involving an entire strainer system.

The verification experiments on half scale 1:2 involved three different strainer designs. Design 0 corresponds to the outlet point for suction at the top of filter 1, that is, all the water from the other five strainers passes through the first strainer, which can be back-flushed. Design Mod 1 is Design 0 equipped with 4 wings and a ceiling of the back-flushable strainer. Design Mod 3 involved major modifications so that the suction line is connected between the strainer that can be back-flushed (strainer 1) and the other strainers (strainers 2-6). Furthermore, a swirl device has been installed to improve the back-flushing. The four wings and ceiling were used to facilitate the back-flushing.

Test objective: The deposit and pressure drop tests were designed to provide information required for the design of the half-scale model involving an entire strainer system. The objective of the test was to resolve the following issues:

- Determine the quantity of fibres passing through at different mesh sizes;
- Measure the pressure drop as a function of the deposit degree and flow rate;
- Possible compaction and further pressure drop;
- Measure the differences between cold (20 °C) and hot (89 °C) water.

For the verification experiments on a half scale, the purpose of the tests was:

- To determine pressure drop over a clean strainer system;
- To identify the quantity of insulation in the strainer system when the pressure drop over the strainers reaches the limit for back-flushing;
- To test the back-flushing capabilities of strainer 1. To establish the cleanliness of the strainer after back-flushing as a function of the back-flushing flow rate and back-flushing time;
- To determine the pressure drop over a recently back-flushed filter system (only strainer 1 is back-flushed).

Findings: Deposit and Pressure Drop Experiments: The initial experiments clearly show that the mineral wool is compressed at high loads so that the pressure drop increases. The surface loads (approach velocity, m/s) that had previously been selected (for Ringhals 1 et al.) are on the order of a factor of 10 too high. The filter capacity is heavily dependent on the surface load. Given a pressure drop of 2 m of water, Rockwool is more sensitive to surface load than fiberglass wool (Transco). With a surface load of 0.02 m/s, considerably larger quantities of Transco material (expressed in terms of nominal thickness) can be deposited on the strainer than of Rockwool.

The effect of temperature on pressure drop can be related to the change in kinematic viscosity of the water. Results show that a factor of two reduction in pressure drop occurs when the water temperature is increased from 20 to 60 °C.

Tests were conducted in the small rig to determine the amount of Rockwool insulation that is transported through a strainer to a fine secondary strainer at different rates (surface loads) for different strainer surfaces. Results indicate that maintaining low rates (velocities) is essential in order to allow as little as possible of the fine material to enter the ECC spray systems.

Verification experiments on a half scale 1:2: Tests were carried out on Design 0 and Mod 3 for pressure drop. When the strainers are clean, there is no noticeable difference in pressure drop between the two. In a direct comparison of the three different strainer designs, given a constant flow rate, the Mod 3 design produces the least pressure drop for a given insulation quantity.

Both Mod 1 and Mod 3 are considered to fulfil the requirements on pressure drop, fibre quantity, operating times before back-rinsing, and the possibility for back-flushing, with a good margin. A design based on Mod 3 results in a greater certainty and a more developed back-flushing function. No fibers remain on the filter after back-flushing and no large fiber deposits remain on the connecting pipe from strainers 2-6. The performance with the wings worked so exceptionally well that the deposit loosens when the suction flow is reduced to zero. The installation of the rotor means that the entire strainer is thoroughly cleaned during back-flushing.

Debris data: The debris used in these experiments was Rockwool and Transco K. For the deposit and pressure drop experiment, aged Rockwool was placed between 8-mm and 10-mm meshes and shredded with a water jet from a high-pressure nozzle. The Transco K was shredded with hydraulic pumps. For the verification tests on a half scale, the Rockwool was divided into suitable portions and shredded by using high-pressure water jet and left to soak in barrels until the experiment. The Transco K was aged for 24 hours at 285 °C and then shredded with a hydrapulper.

Notation: Some diagrams use insulation nominal thickness (m) instead of mass (kg/m²) versus flow rate (approach flow velocity, m/s) for a pressure drop of 2 m of water, the pressure drop that was selected for back-flushing. A nominal thickness of e.g. 0.1 m means 4 kg/m² for Transco and 10 kg/m² of Rockwool.

Title:	Ringhals 1 – Pressure Drop on Screens from Thermal Insulation Debris
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 93:B6
Document length:	11 pages
Date:	1993-03-30
Nature of study:	Experimental
Phenomenon studied:	Head loss tests on fibre glass insulation fragmented in different ways including steam jet dislodgement

Abstract: The report gives a summary of the head loss tests on Transco K fibre glass insulation debris performed by Vattenfall Utveckling AB at the Älvkarleby Laboratory in the small scale 1-D test rig. These tests were used in the design process for new screening systems in parallel to the half scale 3-D design and verification tests for the five BWRs in Sweden that were stopped after the Barsebäck incident.

Results from water jet and steam jet (80 bar, 280 °C) fragmented insulation were presented and compared to only cut insulation (the method used in the tests for the RG at that time). Highest pressure drops were found using steam jet dislodgement.

Similar tests were then performed for a combination of fibers and particulates (Caposil), see report VU-S 93:B16 (Jonas Wilde).

Test setup: A small circulation flow loop with a pump, a magnetic flow meter, valves and a small tank with a mixer and an electric heater was used for these one-dimensional tests. The test section was 100 mm in diameter and located in the middle of a cylindrical tank. The vertical intake to the test section with the horizontal screen consisted of a funnel elevated above bottom and included a short pipe before the test screen. In most of the tests perforated plates were used as screens, but in some tests also a finer secondary screen was used to collect passing fibres.

The fibre insulation (panels of Transco K, density 40 kg/m³) had been temperature treated in an oven at 285 °C. The insulating material was mainly white, but also darker areas were observed, which was interpreted as some binder still was present.

The water jet fragmented insulation debris was obtained using a high pressure nozzle. The water jet was eroding a panel of insulation held by a net. All material was collected and stored under water before a test.

The steam jet fragmented insulation was obtained at steam blow-outs performed by Studsvik Material AB. Loop pressure at start of each test was 80 bar (8 MPa) and steam temperature was 280 °C. The inner diameter of the steam pipe was 16 mm and the thickness of the blanket and the pillows were about 90 mm. The debris after each test was collected by washing the test tank with demineralised water, and stored in cans for the head loss tests.

For comparisons with tests performed by IIT, Chicago for Transco Products, pieces (cubes 1 inch side) were cut and used in our rig as well as a sample of "as-fabricated" material cut from a panel to fit the test section. The mixer was started to suspend the material in the smaller water tank before the pump was started and correct flow rate was set to give the approach velocity (range 0.01-0.1 m/s). The test continued until the pressure drop specified (normally 2 mow) was reached. The fiber material collected on the screen was dried at 90 °C for 24 hours before it was weighed.

Findings: The tests gave an indication that steam jet fragmented insulation had a higher pressure drop. In the dislodgement tests it was observed that the smaller the distance between the steam pipe and the blanket the smaller the particles of the debris. On the other hand, a scanning electron microscope (SEM) inspection did not indicate any structure differences between the water jet and steam jet fragmented pieces.

The cut insulation matched quite well the IIT data whereas the water or steam jet dislodged material had a quite higher pressure drop, i.e. only about a half or quarter expressed as nominal thickness was needed to

reach the pressure drop 2.0 mow.

In some cases the same batch was used for two or three tests, as the available amount of fibres was very small. It gave a possibility to evaluate the influence of “fines” in the first test compared to a second one. A factor of 2 higher head loss was indicated in a first run compared to a second.

These early tests showed that earlier head loss design criteria were non-conservative. The new data could explain the high head loss experienced in the Barsebäck incident.

Title:	Ringhals 1 – Strainers System 323, Stage 2 Deposit and Back-flushing Tests, Scale 1:2
Authors:	M. Henriksson, B. Johanson
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 93:B29
Document length:	38 pages
Date:	1993-10-22
Nature of study:	Experimental
Phenomenon studied:	Deposit tests, improved back-flushing tests, Caposil insulation tests

Abstract: In a joint project between Sydkraft, ABB and Ringhals during the spring of 1993, research was carried out concerning the reactor pressure vessel insulation (Caposil HT1) influence on the ECCS suction strainers. Calculations based on results from steam dislodgement tests and deposit tests showed that at large scale pipe breaks inside the biological barrier fibres and Caposil can be released in such extent that back-flushing is required after 1 hour. A series of tests were carried out in scale 1:2 regarding a complete system of strainers in ECCS system 323.

Test setup: The tests were performed in a circular tank with diameter 5 m and water depth 3.5 m (~69 m³). Two pumps were available for suction and back-flushing respectively. The suction flow is re-fed to the pool through a slotted pipe with inclined downwards-directed openings that give a rotation of the water to hinder sedimentation.

Findings: The tests showed that, under the given test conditions, the margins to back-flushing before 10 hours ought to have been satisfactory. The tests also show that the present duration time of the flushing (3 minutes) is sufficient to get a clean strainer.

Debris type: Glass wool (Transco K, 40 kg/m³), Newtherm 1000 (asbestos-free variant of Caposil HT1)

Mode of debris generation: The glass wool was aged at 285 °C in an oven for 24 hours and after that disintegrated in water with a spinning blade (hydrapulper). The prepared insulation was stored in drums with water. This procedure was based on experiences gained from head loss tests in a 1-dimensional small scale model with fibrous insulation that had been fragmented in various ways (mechanically, water jets and steam jets respectively). See for example reports VU-S 93:B6 and VU-S 93:B8 by Greta Wilhelmsson and Hernán Tinoco and paper by Mats Henriksson at the OECD Workshop "Debris Impact on Emergency Coolant Recirculation", Albuquerque 2004. The particulate material Newtherm was achieved by a high pressure water jet eroding a panel of the insulation, simulating a pipe break near the reactor vessel insulation.

Debris size: Small clusters to single fibres and particulates.

Further information: The second test series with larger content of particulates was presented in report VU-S 94:B9 (Mats Henriksson, Bernhard Johanson). Similar test were also made for Barsebäck 1 and 2 and Oskarshamn 1 and 2.

Title:	Barsebäck 1 och 2, Oskarshamn 1 och 2 – System 322/323 Provning av Permanenta Silar (Testing of Permanent Strainers)
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 93:B12 (in Swedish)
Document length:	28 pages
Date:	1993-05-28
Nature of study:	Experimental
Phenomenon studied:	Head loss, back-flushing

Abstract: After the Barsebäck 2 strainer incident, temporary solutions for the strainers in system 322/323 were used in both Barsebäck and Oskarshamn. The permanent strainer systems, based on the development work made for Ringhals 1, were tested at the Älvkarleby Laboratory.

Test setup: The tests were performed in a 15.0 m³ test rig and performed in a half-length scale 1:2, which means that the strainer area at testing was 25 % of the real strainer area. A complete strainer system was tested, consisting of one short back-flushable cylindrical strainer and several (5 or 6) long cylindrical strainers. The back-flushing was performed with water.

Findings: The tests showed that the function of the back-flushable strainer with wings was so good that the debris cakes came off already when the flow was throttled down to zero. The debris cakes (in the shape of four packages) sank and remained lying on the bottom.

Debris type: Glass wool (Transco K, 40 kg/m³).

Mode of debris generation: The glass wool was aged at 285 °C in an oven for 24 hours and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Forsmark 1 och 2 – Silar System 322/323 (Forsmark 1 and 2 – Strainers System 322/323)
Authors:	G. Wilhelmsson, H. Tinoco
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 93:B8 (in Swedish)
Document length:	37 pages
Date:	1993-04-26
Nature of study:	Experimental
Phenomenon studied:	Different types of insulation, deposit and pressure drop tests, fibre penetration and verification of back-flushing function (with air or water as back-flushing medium)

Abstract: Tests have been performed in four different models and several combinations of insulation material have been tested. Deposits and pressure drop tests at parallel flow through a small filter area have been performed in a smaller model. Such tests have also been performed in three larger models in full and half-scale for complete strainer systems. In the three larger models verification tests for the back-flushing function have also been conducted. Some modifications to the original strainer systems were also tested. The pressure drop dependence on deposit quantity, velocity and material was also studied. Fiber penetration was measured downstream the strainer using isokinetic sampling.

Findings: Head loss is a function of loading and velocity but also strongly dependent on the material characteristics of the fibrous insulation. Data are presented. Back-flushing with air driven water volume worked in some cases, in other cases back-flushing with air worked reasonable.

Using water instead of air (nitrogen in plant) improved the result of the back-flushing of the trapezoidally-folded perforated plates considerably compared to only using air.

A plane strainer area improves the back-flushing results considerably as compared to a folded area.

Debris type:	Mineral wool with binder (Rockwool), mineral wool without binder (Rockwool and Laxå), glass wool (used Transco from Ringhals, thermally aged Transco (24 hours at 280 °C at engineering workshop) and softened Glava (10 hours at 400 °C)).
Mode of debris generation:	Disintegration in water by spinning blade (hydrapulper).
Debris size:	Small clusters to single fibers.
Further information:	Similar test were also made for TVO 1 and 2. See reports VU-S 93:B10 by Greta Wilhelmsson and Hernán Tinoco and VU-S 93:B11 by Hernán Tinoco.

Title:	Ringhals 2 – Provavseende Sedimentering, Resuspension och Transport av Glasfiberisolering i Reaktorinneslutningen. (Tests on Sedimentation, Re-suspension and Transport of Fiber Glass Insulation in the Containment.)
Authors:	R. Karlsson, J. Persson and B. Johanson
Company:	Vattenfall Utveckling AB
Document ID:	VU-S 94:B3 (in Swedish)
Document length:	37 pages
Date:	1994-04-08
Nature of study:	Experimental
Phenomenon studied:	Sedimentation, re-suspension, secondary fragmentation from falling water, loading on strainer

Abstract: Investigation of different fragmentations, sedimentation and transport including strainer loading (head loss tests) in a situation with a secondary fragmentation at the water surface caused by a falling water plume (weir and jets at a higher elevation). The flow pattern in the containment was studied in parallel by CFD simulations, see report VU-S 94:B5 (Farid Alavyoon).

Test setup: The transport tests were performed in a large laboratory flume using a 2-dimensional wall jet at the bottom.

The secondary fragmentation by the falling water was studied in a large tank (D=5 m) during the fill up phase to a water depth of 1.8 m.

The head loss tests were performed in the large tank using a vertical, cylindrical Wing Strainer 0.43 m² (Ringhals type, scale 1:2) during the circulation phase directly after the filling phase was finished and the secondary fragmentation had occurred. Also the loading of a flat mesh type strainer was studied.

Findings: Insulation material will be further disintegrated by the falling water (jet or weir) and suspended in the water body, meaning that quite large amounts of fibers will possibly load the strainers. The tests also showed that a mat of fibre was created on the flat strainer mesh causing a high pressure drop.

Head loss tests in a small 1-dimensional test rig and half-scale tests with a Ringhals 1-type Wing Strainer confirmed that the head loss was about of the same magnitude as earlier found for steam fragmented glass fiber insulation.

The tests with the vertical Wing Strainer in the large test tank showed that the fibre bed expanded and fell off as four discrete packages when the flow was throttled down to zero.

Debris type: Glass wool (MIT NG2)

Mode of debris generation: Various, including fragmentation by steam at 30 bar (Karlshamn power station) and a secondary disintegration at the water surface by a falling plume that entrains air starting a circulation that brings insulation to the plunging point.

Debris size: Various.

Title:	Ringhals 2, Funktion hos Recirkulationssilar (Function of Strainers) Prov 1, Gräns för Självrengöring (Test 1, Limit for Self-cleaning)
Authors:	J. Persson
Company:	Vattenfall Utveckling AB
Document ID:	US 95:8 (in Swedish)
Document length:	29 pages
Date:	1995-04-26
Nature of study:	Experimental
Phenomenon studied:	Limits for self-cleaning at zero flow rate

Abstract: The beginning of this project was that the requirements for the strainer function at Ringhals 2 had been evaluated and new strainers designed which were adjusted for the functional requirements and available space. This report shows the model tests performed to evaluate the limit for self-cleaning, i.e., what thickness is required for the debris bed to always release from the strainer when the flow rate is throttled down to zero.

Test setup: Tests were made with a quadrant of a cylindrical, vertical wing strainer at scale 1:1. The approach velocity was 0.5 cm/s. The water was de-ionised initially but thereafter boric acid and trisodium phosphate were added. All tests were performed at room temperature.

Findings: All tests were performed with very thin debris beds and low pressure drop in contrast to earlier tests with thicker beds and more normal pressure drops which entail a compression of the debris bed. In spite of this, self-cleaning was always obtained in some form, which implies that the limit for self-cleaning, with respect to debris bed thickness, is within the test interval (12-15 mm) but not distinctly defined.

Debris type: Mixtures of glass wool (Knauf ET) and Rockwool.

Mode of debris generation: The insulation was aged at 285 °C in an oven for 24 hours, shredded manually into 2-10 dm^3 pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Ringhals 2, Funktion hos Recirkulationssilar (Function of Strainers) Prov 3, Tryckfall vid Dimensionerande Förhållanden (Test 3, Pressure Drop at Dimensioning Conditions)
Authors:	J. Persson
Company:	Vattenfall Utveckling AB
Document ID:	US 95:9 (in Swedish)
Document length:	17 pages
Date:	1995-05-14
Nature of study:	Experimental
Phenomenon studied:	Pressure drop

Abstract: The beginning of this project was that the requirements for the strainer function at Ringhals 2 had been evaluated and new strainers designed which were adjusted for the functional requirements and available space. This report show the model tests performed to evaluate the limit for self-cleaning, i.e. what thickness that is required for the debris bed to always release from the strainer when the flow rate is throttled down to zero.

Test setup: The tests were made with a model segment of horizontal strainer in scale 1:1. The segment was made barely 2 m long, which made the strainer area per floor area the same in the model as in the prototype. Water was sucked through the strainers and re-entered the test setup by a plane weir, simulating water falling over edges in floor openings. In one test the sedimentation and transport of fragments of metallic insulation and also possible interaction between the fibrous insulation and the metallic fragments were studied.

Findings: The tests with fibrous insulation showed increasing high pressure drops when the strainer area and circulation flow was decreased. This might indicate that the larger fragments settle while the small form a very compact deposit on the strainers.

The metallic fragments settled quickly and showed no tendency to transport with the flow or to interact with the fibrous insulation.

Debris type: Mixtures of glass wool (Knauf ET) and Rockwool.

Mode of debris generation: The insulation was aged at 285 °C in an oven for 24 hours, shredded manually into 2-10 dm^3 pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Ringhals 2 – Hydraulic Model Tests of Nuclear Reactor Containment Recirculation Sump with a New Strainer
Authors:	M.E. Henriksson, J. Persson
Company:	Vattenfall Utveckling AB
Document ID:	US 95:11
Document length:	16 pages
Date:	1995-05-14
Nature of study:	Experimental
Phenomenon studied:	Air ingestion

Abstract: As part of the qualification test program for the new ECCS strainers at the PWR plant Ringhals 2, possible air ingestion caused by air pulling vortices was studied using a reduced scale 1:3.5 hydraulic model of the strainers and important areas of adjacent parts of the containment. A relatively large scale was selected for the test due to possible scale effects in modelling vortices. Experiences from similar testing were incorporated, especially those from the extensive US studies for the NRC concerning reactor containment recirculation sumps of the PWR type used at that time.

Test setup: Tests were performed in a large circular stainless steel tank. An appropriate scale was selected that was large enough to avoid scale effects in modelling the hydraulic phenomenon of concern, vortices, and an appropriate area of the containment with major obstacles was included in the model. Various water levels were tested at velocities according to the Froude criteria as well as exaggerated velocities up to prototype velocities. The sensitivity to flow distortions (from additional blockages) was also investigated.

Findings: Main conclusions were that as far as vortexing is concerned, the proposed design of the new strainer system using long horizontal cylindrical strainers in combination with vertical self-cleaning strainers of Ringhals 1-type was found to perform satisfactorily for all operating conditions considered. The likeliness of air ingestion from vortices formed in the sump or in areas adjacent to it would be small.

Debris type: Not included, only clean water was used.

Title:	Hydrauliska prov med Metallfragment som Bildats vid Ångblåsning (Hydraulic Model Tests with Metallic Fragments formed by High Pressure Steam Jets)
Authors:	J. Persson
Company:	Vattenfall Utveckling AB
Document ID:	US 95:26 (in Swedish)
Document length:	20 pages
Date:	1995-11-13
Nature of study:	Experimental
Phenomenon studied:	Hydraulic characteristics of metallic insulation

Abstract: The project involved analysis of how metallic insulation behaves at postulated pipe breaks and how fragments of metallic insulation can disturb the emergency core cooling function at dimensioning accident cases. Fragments from steam-eroded metallic insulation were tested with regard to hydraulic characteristics, i.e., how the fragments settle and are transported in water, including the possibility for reaching the strainers.

Test setup: Four different types of tests were performed; transport tests, deposit tests, turning tests and sinking tests. The first three types of tests were performed in a 15 m long channel (laboratory water flume) with a water depth of 0.8 m and a width of 0.8 m and the sinking tests were made in a 2.4 m high quadratic tank (1.2 x 1.2 m).

Findings: In the deposit tests it was seen that the fragment shape was of significant importance since the fragments with pointy edges stuck to the strainer at approach velocities down to 0.04 m/s. The transport tests showed that velocities higher than 0.09 m/s are required in order for the fragments to move with the flow. The sinking test showed that all the fragments sank with a velocity higher than 0.1 m/s.

Debris type: Metallic reflective insulation, RMI (Darchem, Grünzweig & Hartmann).

Mode of debris generation: Steam jet eroded at 100 bar.

Debris size: Range from ~4 cm to ~10 cm (crinkled), one fragment 50 x 50 cm and one whole sheet.

Title:	Oskarsham 1-2. Återisolering med Gullfiber. Jämförande Silprov. (Re-insulation with Gullfiber. Comparative Strainer Tests)
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	UX 96:F1 (in Swedish)
Document length:	11 pages
Date:	1996-01-25
Nature of study:	Experimental
Phenomenon studied:	Insulation material

Abstract: Comparative head loss tests between standard glass fibre insulation Gullfiber 6212 and nuclear glass fibre insulation Transco K were performed with a vertical cylindrical strainer.

Test setup: The tests were performed in a tank with diameter 5 m. The water depth in the tank was 2.0 m. The vertical cylindrical strainer was 250 mm in diameter and the perforated envelope surface was 475 mm high. The holes sizes were 2.5 mm in a triangular pitch with a porosity of 20.2 %.

Findings: The test with Transco showed good agreement with earlier results with respect to the pressure drop over the debris bed. At the test with Gullfiber a three times higher pressure drop was obtained.

Debris type: Gullfiber 6212, Transco K.

Mode of debris generation: The insulation was aged at 285 °C in an oven for 24 hours and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Vattenfall Utveckling AB / ABB Proof-of-Principle Strainer Testing – Panel Design
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	UX 96:F3
Document length:	37 pages
Date:	1996-07-31
Nature of study:	Experimental
Phenomenon studied:	Panel strainers

Abstract: The report describes tests on the Panel strainer as part of the Proof-of-Principle (POP) test program performed as a joint effort between ABB Atom AG, Combustion Engineering, Inc. and Vattenfall Utveckling AB for the development of ECCS suction strainers for BWRs in the USA.

Test setup: The Panel strainer had a full-scale trapezoidal surface with perforations on the flat surfaces. The operability of the strainer was tested under conditions consistent with tests of other strainer designs using sludge, heat-treated insulation and recipe material conforming to that requested by the BWROG. Debris per unit area for certain approach velocities was simulated as the main parameter and the strainer was operated under specified flow rates in order to collect the debris on the strainer surface. The strainer performance was recorded for each debris type and combination tested.

Findings: The main conclusion is that a strainer approach velocity of 0.1 ft/s (0.03 m/s) could be suggested when designing Panel strainers for BWR plants in the US. Prescribed debris types, amounts and concentration are in accordance with the assumptions presented as valid for the Reference plant. For a flow rate of 10,000 gpm (631 l/s), a trapezoidal surface area of about 225 ft^2 (21 m^2) with a porosity of 23 % should be needed. The projected area will be about half that value.

Application: The test results can be used in the design of Panel strainers for conditions in the Reference plant. Concentrations of sludge, and heat-treated fibreglass insulation corresponding to conditions stated for the Reference plant were used: 10^6 gallon (3785 m^3) condensation pool; 10,000 gpm (631 l/s) flow rate; 500 lbm (226.8 kg) iron oxide (60 ppm by weight); and 187 lbm (84.8 kg) heat-treated fibreglass insulation (22 ppm by weight). Twice these concentrations were also used in one test.

Debris type: Sludge (black iron oxides, 95 % Grade 2008 and 5 % Grade 9101-N-40), NUKON base wool insulation (nuclear grade), and miscellaneous material (rust flakes, epoxy paint chips, sand, duct tape pieces, tie wraps, plastic sheets and rubber shoe covers).

Mode of debris generation: The insulation was aged at 545 °F (285 °C) in an oven for 24 hours, shredded manually into pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Vattenfall Utveckling AB / ABB Proof-of-Principle Strainer Testing – Passive, Self-cleaning Wing Design
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	UX 96:F4
Document length:	53 pages
Date:	1996-07-31
Nature of study:	Experimental
Phenomenon studied:	Passive, Self-cleaning Wing strainers (vertical and horizontal orientation)

Abstract: The report describes tests on the Passive, Self-cleaning Wing strainer as part of the Proof-of-Principle (POP) test program performed as a joint effort between ABB Atom AG, Combustion Engineering, Inc. and Vattenfall Utveckling AB for the development of ECCS suction strainers for BWRs in the USA.

Test setup: The cylindrical Passive, Self-cleaning Wing strainer model is 6.6 ft (2 m) in length and has a full-scale diameter of 1 ft (0.3 m). The holes sizes are 1/8 inch (3 mm) at a 1/4 inch (6 mm) pitch, which gives a total strainer area of 20.4 ft² (1.9 m²). Both vertically- and horizontally-oriented strainers were tested. The operability of the strainer was tested under conditions consistent with tests of other strainer designs using sludge, heat-treated insulation and recipe material conforming to that requested by the BWROG. Debris per unit area for a certain approach velocity was simulated as the main parameter and the strainer was operated under specified flow rates in order to collect the debris on the strainer surface. The strainer performance was recorded for each debris type and combination tested. Water samples were taken at intervals during the test and analyzed.

Findings: It was hoped to run the tests to determine if a critical velocity for self-cleaning exists. Desired conditions would be that the debris bed falls off on its own when the cake reaches a certain mass. The tests have demonstrated that self-cleaning first occurred at zero flow. On horizontal strainers, fins are proposed to be located on the lower half of the strainer, this arrangement would allow for cleaning of one-quarter of the system. Sacrificial areas of the strainer act to clean the pool water and keep the insulation on the strainer. Particulate material is trapped gradually in the bed with an increasing pressure drop over the strainer.

Application: The test results can be used in the design of Passive, Self-cleaning Wing strainers for conditions in the Reference plant. Concentrations of sludge, and heat-treated fiberglass insulation corresponding to conditions stated for the Reference plant were used: 10^6 gallon (3785 m³) condensation pool; 10,000 gpm (631 l/s) flow rate for largest strainer and a total flow rate of 30,000 gpm (1893 l/s) for all strainers; 500 lbm (226.8 kg) iron oxide (60 ppm by weight); and 187 lbm (84.8 kg) heat-treated fiberglass insulation (22 ppm by weight). Twice these concentrations were also used in one test.

Debris type: Sludge (black iron oxides, 95 % Grade 2008 and 5 % Grade 9101-N-40), NUKON base wool insulation (nuclear grade), and miscellaneous material (rust flakes, epoxy paint chips, sand, duct tape pieces, tie wraps, plastic sheets and rubber shoe covers).

Mode of debris generation: The insulation was aged at 545 °F (285 °C) in an oven for 24 hours, shredded manually into pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibers.

Title:	Vattenfall Utveckling AB / ABB Proof-of-Principle Strainer Testing – Bi-stable Design
Authors:	M. Henriksson
Company:	Vattenfall Utveckling AB
Document ID:	UX 96:F5
Document length:	14 pages
Date:	1996-07-31
Nature of study:	Experimental
Phenomenon studied:	Bi-stable strainer

Abstract: The report describes tests on the bi-stable strainer as part of the Proof-of-Principle (POP) test program performed as a joint effort between ABB Atom AG, Combustion Engineering, Inc. and Vattenfall Utveckling AB for the development of ECCS suction strainers for BWRs in the USA.

Test setup: The bi-stable strainer model is a self-cleaning strainer system with fins and needs neither a change in suction flow nor back-flushing for cleaning. In this design, a flexible bi-stable wall is installed inside the vertical wing strainer. The free edge of the flexible wall is closed against either of two opposing arch-shaped seats in the strainer. As the filter bed develops over one side of the strainer, the pressure difference between the two sides increases. When a certain pressure drop is obtained, the bi-stable wall is forced to the other side. The pressure pulse, in combination with the fins, disengages the filter bed so that the strainer surface is cleaned, making this side ready for the next change in position of the bi-stable wall.

A half-scale model strainer was tested. The model was 2 ft (600 mm) in length and had a diameter of 1.2 ft (375 mm). The holes sizes were 1/8 inch (3 mm) at a 1/4 inch (6 mm) triangular pitch, which gave a total strainer area of 7.5 ft^2 (0.7 m^2) and a porosity of 23 %. The operability of the strainer was tested with fibrous insulation only.

Findings: The performance of the bi-stable strainer was successfully demonstrated in three separate tests. The insulation was shown to fall off after the flip of the wall on two occasions.

Debris type: NUKON base wool insulation (nuclear grade).

Mode of debris generation: The insulation was aged at 545 °F (285 °C) in an oven for 24 hours, shredded manually into pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibers.

Title:	Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris
Author:	G. Zigler et al.
Company:	Science and Engineering Associates, Inc. and Siemens for the U. S. NRC
Document ID:	SEA No 95-970-01-A:2, includes NT 34/95/e32
Date:	May 1996
Document Length:	198 pages
Nature of Study:	Experimental and analytical
Phenomena Studied	RMI insulation debris generation and transport in BWRs

Abstract: The NRC sponsored a debris generation test of RMI-type pipe insulation to obtain insights and data on the effects of RMI for US plants. These tests were performed at Siemens AG/KWU in Karlstein, Germany. Prior to the NRC-sponsored tests at this facility, Swedish utilities conducted 16 separate tests on the RMI commonly used in European nuclear stations manufactured by Grünzweig and Hartmann or Darchem Engineering. The NRC test was performed using RMI cassettes common to US nuclear plants provided by Diamond Power Specialty Company, the manufacturer of Mirror^R RMI cassettes. The jet impingement test was performed with saturated steam at 80 bar (1160 psi) and an initial temperature of approximately 293 ^oC (559 ^oF) to simulate BWR conditions.

Findings: The NRC test was performed with high-pressure (80 bar), saturated steam. The facility consisted of a tall vessel and a blowdown line with a double rupture disk and orifice (break plane) mounted at its end. Target insulation materials were installed on a 10-in. pipe that was positioned downstream of the simulated break at distances up to 25 break-pipe diameters. The orientation and position of the target pipe relative to the jet centerline could be changed to examine the effects of an asymmetric jet impingement. The test was conducted in May 1995. Most of the RMI debris was recovered and categorized by size and the location where it was found. Approximately 94% of the debris was larger than 6.35 mm (¼ inch).

Settlement of the RMI debris and BWR suction strainer head loss due to RMI debris are evaluated in Appendices to the report.

A total of seven saturated water tests and nine saturated steam tests were performed in the Swedish test program. This test program was completed in early 1995. The following observations were recorded in separate publicly distributed report number GEK 77/95 by Vattenfall Energisytem:

- All insulation panels directly impacted by the steam jet (up to L/D = 25) were destroyed;
- Insulation outside the core of the steam jet was not fragmented;
- The degree of destruction caused by saturated water jets was much less than that caused by saturated steam jets;
- Damage tended to take the form of crumpling the RMI panels rather than fragmenting them into small pieces. Panel disintegration was observed (with a water jet) only when the target became stuck in the mounting trestle and remained in the core of the jet during the 30-s blowdown. In this case, a small percentage of the panel was fragmented.

Title:	Air Jet Impact Testing of Fibrous and Reflective Metallic Insulation
Author:	J.H. Munchausen
Company:	Continuum Dynamics, Inc
Document ID:	CDI report 96-06 (This report is included in BWROG URG, Volume 3)
Date:	September 1996
Document Length:	253 pages
Nature of Study:	Experimental and analytical
Phenomena Studied	RMI and Fibrous Insulation Debris generation for BWRs

Abstract: This set of experiments on fibrous and RMI was performed to determine failure characteristics of insulation materials when exposed to jet impingement forces similar to what would result in a LOCA at a BWR. Continuum Dynamics, Inc (CDI) under contract to General Electric Nuclear Energy (GENE) undertook this series of Air Jet Impact Tests (AJIT) at Colorado Engineering Experimental Station, Inc. (CEESI)

Findings: A total of 77 tests were performed on various insulation materials from many manufacturers, aluminum RMI, stainless steel RMI, fibrous insulation and lead shielding. The tests were performed to simulate BWR LOCA conditions using approximately 76 bar (1110 psig) air at ambient temperatures. The test durations were 5 to 6 seconds. The tests were conducted in the orientation determined to be most conservative with respect to debris generation. For example, tests on unjacketed NUKON fibrous insulation with the Velcro attachment seam facing the exhaust nozzle produced less transportable debris that a test where the Velcro seam was located on the side of the target pipe opposite the exhaust nozzle. This was determined to be caused by the insulation blanket being immediately removed from the target pipe. As a result the tests of unjacketed fibrous insulation were typically conducted such that the fastening mechanism was not directly in line with the exhaust nozzle.

Tests of RMI resulted in the opposite conclusion. Tests of RMI systems with the seam or latch & strike in plane with the exhaust nozzle generated more debris as a result of the air jet having the capability of opening the cassettes and exposing the internal foils to the jet.

Another conclusion discussed in this report is the relative destruction potential of an air jet versus steam versus saturated water. GENE concluded that the stagnation pressure for an air jet is conservative with respect to a steam jet and that the stagnation pressure of a steam/water mixture is less than that of a steam-only discharge. Therefore the test results of the AJIT are conservative with regard to a saturated water test.

Title:	Drywell Debris Transport Study
Author:	D. V. Rao, C. Shaffer, and E. Haskin
Company:	Science and Engineering Associates, Inc. for the U. S. NRC
Document ID:	NUREG/CR-6369, Vol. 1, 2 & 3
Date:	September 1999
Document Length:	494 pages
Nature of Study:	Experimental and analytical
Phenomena Studied	Insulation debris transport in BWRs

Abstract: This report describes results of the drywell debris transport study. The objective of the study was to develop a methodology for estimating the fraction of LOCA-generated fibrous insulation debris that would be transported from the location of their generation in the drywell to the suppression pool.

Findings: Experiments and analytical studies were undertaken to compile the necessary knowledge base on debris transport during blowdown, washdown of debris by ECCS water flow, and debris sedimentation on the drywell floor. Logic charts were used to link both experimental and analytical results. The results of the study were used to delineate plant features and transport phenomena that dominate debris transport in the BWR drywell. A separate logic chart was developed for each postulated accident scenario and generic plant type analyzed. The logic charts can be modified to take into account effects of the plant-specific features. The overall method is comprehensible to engineers who are not experts in the subject of debris transport. Also, it is sufficiently flexible that new evidence and assumptions, related to debris size and distribution, can be easily accommodated.

Title:	Summary Report on Performance of Performance Contracting Inc.'s Sure-Flow ™ Suction Strainer with Various Mixes of Simulated Post-LOCA Debris, Revision 1 and Revision 0
Author:	R. Biasca and G. Hart
Company:	Performance Contracting Inc.
Document ID:	N/A
Date:	September 1997
Document Length:	23 pages Rev 1, 28 pages Rev 0
Nature of Study:	Experimental
Phenomena Studied	Impact on head loss from RMI and fibrous insulation debris with particulate debris

Abstract: Performance Contracting Inc.'s (PCI) Sure-Flow Suction Strainer was developed to attach to the ECCS pipe inlets for BWRs to reduce head loss to the suction of the ECCS pumps. This report summarizes additional qualification head loss tests conducted for the manufacturer in 1996 on the Prototype No. 2 model. The initial qualification testing was performed in 1995 and is addressed in CDI Report No. 95-09 which is included in the BWR URG. The PCI Sure-Flow Suction Strainer is a stacked-disk type of design

Findings: A series of 12 head loss tests were performed at the EPRI facility in Charlotte, North Carolina. These tests were conducted by Continuum Dynamics Inc. (CDI). For this series of tests various quantities of fibrous debris from NUKON, stainless steel foils from RMI and particulate from iron oxide were introduced into the test fixture.

NUKON was prepared by a leaf shredder. Up to 300 lbs was used for these tests.

The size of the RMI foils was based on the results of the CEESI air jet tests and the steam jet tests at Siemens-KWU.

RMI debris increased head loss by less than 1 ft. of water.

100 lbs of corrosion product particulate has a significant effect on strainer head loss.

Title:	Jet Impact Tests-Preliminary Results and Their Application
Author:	J. Russell et al.
Company:	Ontario Power Generation and Kinectrics
Document ID:	Engineering Report N-REP-34320-100000 Revision 00
Date:	April 2001
Document Length:	41 pages
Nature of Study:	Experimental
Phenomena Studied	Jet impact effects on calcium silicate insulation

Abstract: This is a report on the jet impact test program which was initiated to provide a better understanding of insulation damage mechanisms resulting from fluid emanating from a broken pipe. The jet impact tests performed to date were specifically for freely expanding jets impacting on aluminum clad calcium silicate insulated pipe.

Findings: 15 short duration (10 seconds) jet impact tests were performed using saturated water at 10 MPa (1450 psi) and 310 ^{o}C (590 ^{o}F). Results have shown that the orientation of the seam to the jet is a critical factor to be considered. The observed damage mode has exclusively been shearing of the cladding and, with this mode of failure, it has been shown that the test results can be scaled to larger pipe breaks and targets. A numerical method for applying the test results to both small (feeder) and large (primary heat transport system piping) sized breaks for limited as-tested conditions is presented. Adding a second layer of cladding has resulted in a very favourable reduction in the distance where damage occurs. This is expected because the susceptible mode of failure is eliminated by staggering the longitudinal seams to ensure that the jet cannot impact both seams. The effect of jet reflections on reducing the energy and hence the destructive forces of the jet has not yet been determined.

Title:	GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6762, Volume 1
Date:	August 2002
Document Length:	213 pages
Nature of Study:	Parametric Evaluation
Phenomena Studied	Debris transport

Abstract: This report documents a parametric evaluation of operating U.S. PWR plants that was conducted, as part of the resolution of GSI-191, to assess whether or not ECCS recirculation sump failure is a plausible concern. The purpose of the GSI-191 study is to determine if the transport and accumulation of debris in a containment following a LOCA will impede the operation of the ECCS in operating PWRs. In the event of a LOCA within the containment of a PWR, thermal insulation and other materials in the vicinity of the break will be damaged and dislodged. A fraction of this material would be transported to the recirculation (or emergency) sump and accumulate on the screen thereby forming a debris bed. Excessive head loss across this bed could prevent or impede the flow of water into the core or containment.

Findings: The parametric evaluation identified a range of conditions in which PWR ECCS could fail in the recirculation mode of operation; thereby forming a credible technical basis for making a determination that sump blockage is a generic concern for PWRs. However, the likelihood that sufficient quantities could transport and accumulate on the recirculation sump screen to severely impede recirculation flow is plant specific. The primary limitation of the parametric evaluation was a general lack of plant specific data. A review of PWR plant design features and limited plant specific data did, however, indicate that adverse conditions exist in several plants.

Title:	GSI-191 Technical Assessment: Development of Debris Generation Quantities in Support of the Parametric Evaluation
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6762, Volume 3
Date:	August 2002
Document Length:	48 pages
Nature of Study:	Parametric evaluation
Phenomena Studied	Debris generation

Abstract: This report documents the debris generation analysis that supported a parametric evaluation of operating U.S. PWR plants to access whether or not ECCS recirculation sump failure is a plausible concern. This evaluation was part of the NRC GSI-191 study to determine if the transport and accumulation of debris in a containment following a LOCA will impede the operation of the ECCS in operating PWRs. The parametric evaluation identified a range of conditions in which PWR ECCS could fail in the recirculation mode of operation. These conditions stem from the destruction and transport of piping insulation materials, containment surface coatings (paint), and particulate matter (e.g., dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. The methodology used to estimate quantities of insulation debris generated by a LOCA depressurization jet was an essential part of the parametric evaluation.

Findings: This report documents the methodology, assumptions, and data used to determine the quantities of debris generated that were used in the parametric evaluation. The plant-specific data, required for credible debris generation estimates, were limited for most plants. The evaluation performed detailed debris generation estimates for a volunteer plant for which the data were readily available and then the limited insulation data of the other plants were used to essentially scale the results of the volunteer plant to each of these other plants. Substantial uncertainty associated with the debris generation estimates is inherent due to the complexity of the analysis and the availability of appropriate data. Due to limitations of information, these estimates are not considered best-estimate plant-specific values. Instead, they represent a credible range of debris generation estimates for the industry as a whole.

Debris quantities were calculated for a number of potential break locations. The 95th percentile debris generation volumes then were developed for application to each of the 69 parametric cases.

Title:	GSI-191 Technical Assessment: Development of Debris Transport Fractions in Support of the Parametric Evaluation
Author:	S. G. Ashbaugh and D. V. Rao
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6762, Volume 4
Date:	August 2002
Document Length:	32 pages
Nature of Study:	Parametric evaluation
Phenomena Studied	Debris transport fractions

Abstract: This report documents the debris transport analysis that supported a parametric evaluation of operating U.S. PWR plants to assess whether or not ECCS recirculation sump failure is a plausible concern. This evaluation was part of the Nuclear Regulatory Commission GSI-191 study tasked to determine if the transport and accumulation of debris in a containment following a LOCA will impede the operation of the ECCS in operating PWRs. The parametric evaluation identified a range of conditions in which PWR ECCS could fail in the recirculation mode of operation. These conditions stem from the destruction and transport of piping insulation materials, containment surface coatings (paint), and particulate matter (e.g., dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. The methodology used to estimate quantities of insulation debris transported to the recirculation sump screen was an essential part of the parametric evaluation.

Findings: The transport fractions estimated were based on available experimental and analytical data and were focused on fibrous insulation debris. Both favorable and unfavorable transport fractions were estimated for small LOCAs with the sprays active and inactive, and for medium and large LOCAs. The transport fractions considered the size of the debris generated, the depressurization driven air and steam flow transport, the subsequent containment spray washdown transport, and the sump pool debris transport. Substantial uncertainty associated with the debris transport estimates is inherent due to the complexity of the analysis and the availability of appropriate data. Due to limitations of information, these estimates are not considered best-estimate plant-specific values. Instead, they represent a plausible range of debris transport estimates for the industry as a whole.

Title:	GSI-191: Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6770
Date:	August 2002
Document Length:	371 pages
Nature of Study:	DBA simulations
Phenomena Studied	Thermal-Hydraulic Response to a LOCA

Abstract: This report documents the results of calculations performed, as part of the resolution of the NRC GSI-191, to simulate RCS and containment thermal-hydraulic response to a number of accidents that could potentially cause insulation debris to be collected on the sump screen.

The calculations were performed using the NRC-approved computer codes RELAP5 and MELCOR. These calculations identified important RCS and containment thermal hydraulic parameters that influence the generation and/or transport of debris in PWR containments. The calculations determined the time-dependent system response parameters. The system responses were used to construct accident progression sequences that form the basis for strainer blockage evaluations and probabilistic risk evaluations.

Findings: Computer codes (RELAP5 and MELCOR) have been used to simulate RCS and containment thermal-hydraulic response to a number of accidents that may potentially cause insulation debris to be collected on the sump screen. The calculations were performed with three primary objectives.

1. Identify important RCS and containment thermal-hydraulic parameters that influence the generation and/or transport of debris in PWR containments.

2. Perform plant simulations using NRC computer codes to determine the value of each parameter as a function of time and, where applicable, as a function of the assumed system's response. Of particular interest are plant simulations of small and medium LOCAs for which information regarding accident progression is not readily available.

3. Use the calculated plant response information to construct accident progression sequences that form the basis for strainer blockage evaluations and probabilistic risk evaluations.

In considering the results presented here, it should be recognized that the RCS and containment models used, although representative of a class of PWRs, do not altogether reflect the uniqueness of any particular plant. RCS and containment responses to the accidents studied would likely differ sizably between plants dependent on numerous specific factors. Many of the noteworthy RCS and containment specifics included in the models used in the subject analyses are identified in this report. The reader should be mindful of the modeling specifics when considering the course of the accident simulations presented.

Title:	Separate-Effects Characterization of Debris Transport in Water
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6772
Date:	August 2002
Document Length:	115 pages
Nature of Study:	Experimental
Phenomena Studied	Debris transport

Abstract: This report documents the results of experiments conducted to measure specific debris transport properties for a selection of potential types of debris. The purpose of the study is to determine if the transport and accumulation of debris in a containment following a LOCA will impede the operation of the ECCS in operating PWRs. The properties measured by these experiments included: 1) the terminal settling velocity in quiescent pools and in water pools in planar motions; 2) the minimum fluid velocity at which an individual stationary fragment resting on the containment floor would begin to move; 3) the minimum fluid velocity required to induce "bulk scale" movement of a population of debris fragments; and 4) the minimum fluid velocity required to lift a fragment of debris over a vertical curb that impedes forward motion along the floor. In all cases, these velocities were measured in terms of the pool average velocity. Experiments were also conducted to examine the variability in transport properties due to flow turbulence.

Findings: This research program is the experimental determination of the transport characteristics of various types of LOCA-generated debris within a PWR containment. The data presented here focuses exclusively on debris transport on the containment floor. The experiments described in this report measured the following properties for several types of debris:

- Terminal settling velocity in quiescent pools and in water pools in planar (lateral) motion;
- Incipient tumbling velocity (i.e., the minimum fluid velocity at which an individual stationary fragment resting on the containment floor would begin to move);
- Bulk tumbling velocity (i.e., the minimum fluid velocity required to induce "bulk-scale" movement of a population of debris fragments);
- Lift-at-the-curb velocity, i.e., the minimum fluid velocity required to lift a fragment of debris over a vertical curb (typically 4 or 6 in. in height) that impedes forward motion along the floor.

In all cases, these velocities are measured in terms of the pool average flow velocity. Variations in pool velocity as a result of (for example) large-scale turbulence may cause significant variability in measured values for these threshold velocities. Experiments were performed in planar and turbulent flow conditions (and repeated several times) to evaluate and quantify the degree of data variability in such circumstances.
In addition to the transport properties listed above, experiments were performed that measured other important characteristics of post-LOCA debris behavior. Among these are:

- The buoyancy characteristics of fibrous debris fragments, i.e., the rate at which low density fiberglass insulation fragments become sufficiently saturated with water to sink into the pool as a function of temperature;
- The disintegration rate of calcium silicate insulation when submersed in hot water;
- The extent to which the threshold velocities, listed above, are affected by the simultaneous presence of other types of debris (i.e., mixtures of fiber fragments and calcium silicate).

Title:	GSI-191: Integrated Debris-Transport Tests in Water Using Simulated Containment Floor Geometries
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6773
Date:	December 2002
Document Length:	96 pages
Nature of Study:	Experimental
Phenomena Studied	Insulation debris transport in PWRs

Abstract: This report documents the results of experiments conducted to examine insulation debris transport under flow and geometry configurations typical of those found in PWRs. This work was part of a comprehensive research program to support the resolution of GSI-191. Among the GSI-191 program research tasks is the development of a method to estimate debris transport in PWR containments and the quantity of debris that would accumulate on the sump screen for use in plant-specific evaluations. Predicting the transport of debris within the sump pool is an essential part of that methodology. The analytical method proposed by the Los Alamos National Laboratory to predict debris transport within the pool is to use CFD combined with experimental debris transport data to predict debris transport and accumulation on the screen. The three dimensional tank tests were conducted to test debris transport under conditions that simulate flow regimes relevant to a typical PWR plant. These tests provided insights into the relative importance of the various debris-transport mechanisms and are directly applicable to creating or validating models capable of estimating debris transport within a PWR plant containment sump.

Findings: Based on a determination of the physical processes governing the transport of debris on the containment floor, two types of small-scale tests were conducted to support the analytical methods: (1) separate-effects tests (NUREG/CR-6772); and (2) three-dimensional (3-D) tank tests (reported here). These tests were conducted at the University of New Mexico Open-Channel Hydrology Laboratory. The 3-D tank tests were conducted in a large tank with provisions to simulate a variety of PWR containment and sump features. In this manner, debris transport was studied in such a way that all the separate effects studied in the separate-effects testing could be integrated into tests that were more typical of PWR geometries.

The important physical processes that took place in the 3-D tank tests included settling of debris in turbulent pools, tumbling/sliding of settled debris along the floor, re-entrainment of debris from the containment floor, lifting of debris over structural impediments, retention of debris on vertical screens, and the further disintegration of debris as a result of sump-pool dynamics. The integrated phenomena included early debris transport as the sump filled and later debris transport after a steady-state flooded condition was achieved. The flow regimes established during the tests included quiescent, turbulent, and rotational flow in geometries comparable to the complexity of PWR containment floors. The tests provided insights into the relative importance of the various debris-transport mechanisms and are directly applicable to creating or validating models capable of estimating debris transport within a PWR plant containment sump. Further, these tests provided debris particle tracks and bulk debris transport data that are necessary to validate CFD code applications to estimate debris transport within a PWR plant containment sump.

Title:	Experiments on the Integral Test Facility “Erlanger Wanne”
Authors:	I. Ganzmann et al.
Company:	AREVA NP GmbH
Document ID:	Various
Date:	From 2003 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Vertical debris transport; horizontal debris transport; debris sedimentation; Pressure loss on sump strainers; back flushing; down stream effects (FA deposition); chemical effects; long term effects

Abstract: In 2003 AREVA NP Technical Center extended its Thermal Hydraulic Platform by the integral test facility “Erlanger Wanne”. The facility is designed to investigate processes following a LOCA in the region of the reactor sump as well as downstream the sump strainers. The following parameters have been considered: the debris transport and sedimentation behavior in the reactor sump region; pressure loss caused by debris agglomeration on the sump strainer; the influence of strainer geometry and size of the strainer openings on the pressure loss; back-flushing ability of sump strainers; pressure loss caused by debris bypassing the sump strainer (downstream effects); the influence of erosion and corrosion processes on the pressure loss behavior.

The experimental studies led to the development of an accepted procedure to handle a LOCA for KWU PWR plants. For the EPR™ the efficiency of the debris retention concept in case of a LOCA was demonstrated.

Test Facility Capabilities:

Scaling Vertical:	1:1 (sump height, strainer height, leak position)
Scaling Horizontal:	1:20 to 1:60, (depending on sump design)
Test flume:	Height 3 m; width 1.5 m; length 5 m; volume 22 m³
	Austenitic Material
Operating Temperature:	80 °C max.
Mass flow:	40 kg/s max.
Strainer design:	All kinds of strainer design applicable
Fuel element Section:	FA (fuel assembly) section to handle one or more FAs downstream sump strainer; flow direction in FA up- or downstream, pressure loss measurement on FA components
Debris preparation:	Fibers heated at 300 °C for 24 h, mechanically or high pressure water jet fragmented; particulates (e.g. paint, concrete, Microtherm) sieved to different size classes
Measured Variables:	Flow rate (strainer and FA) online
	Water temperature online
	Water pH online
	Water turbidity online
	Water conductivity online

Pressure loss strainer online

Pressure loss FA components online

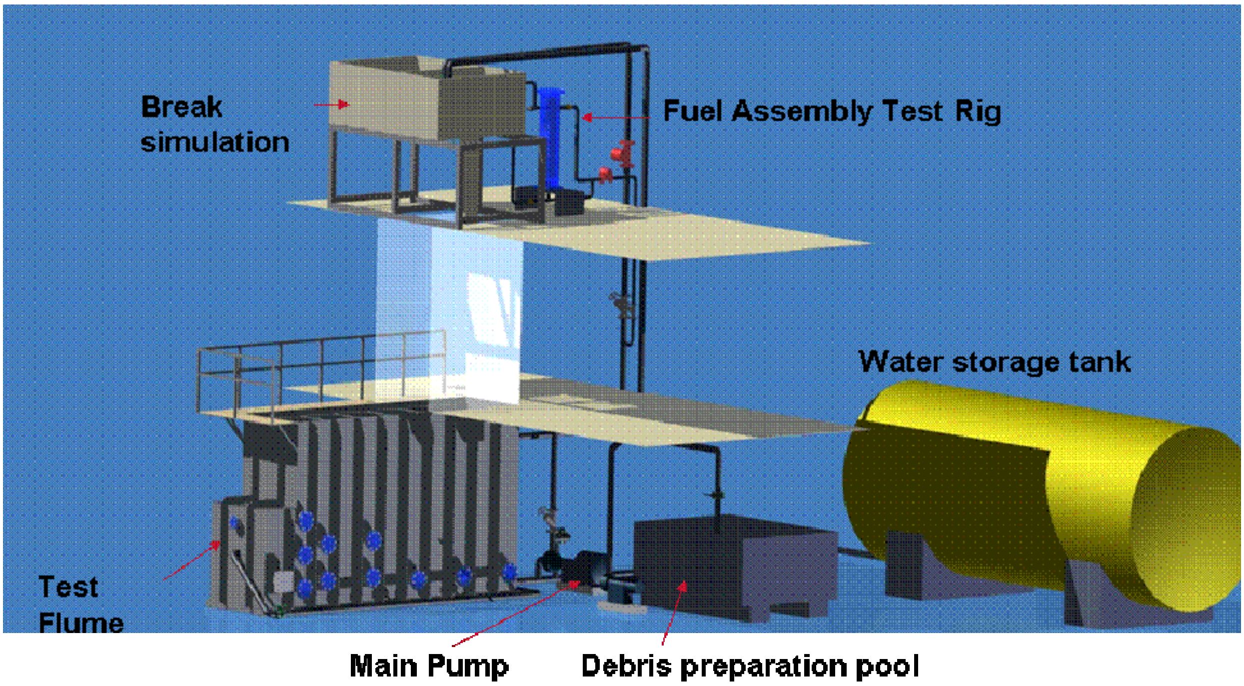
Water solid content offline after sampling

Water ion concentration offline after sampling

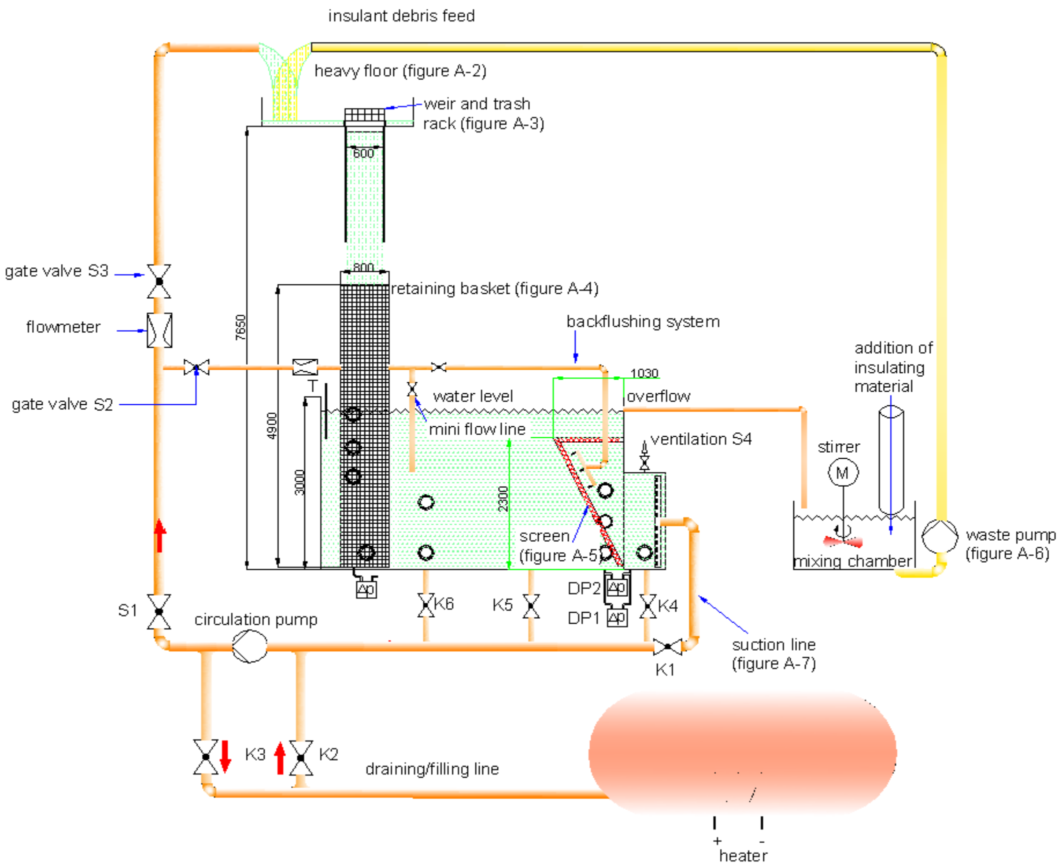
Tests performed:

In total more than 200 tests have been performed in the "Erlanger Wanne" test facility with different focus:

- Pressure loss evaluation on sump strainer and sedimentation behavior of different fibrous insulation materials (mineral wool used in KWU plants, different suppliers, different year of production, different production facilities), short term, up to 8 h;
- Pressure loss evaluation on sump strainer and sedimentation behavior of different fibrous insulation material **mixtures** (mineral wool used in KWU plants, different suppliers, different year of production, different production facilities), short term, up to 8 h;
- Downstream effect testing (pressure loss on fuel element) for different strainer mesh size and different strainer shape in combination with pressure loss evaluation on sump strainer;
- Challenging of back flushing operation depending on back flushing flow rate and fiber bed pressure loss;
- Long term tests regarding chemical and downstream effects by use of borated water and zinc-coated ferritic steal (walking grids); influence on pressure loss on strainer and FA components;
- Qualification of the debris retention concept for the AREVA EPR™.



Erlanger Wanne Test facility 3-D view



Erlanger Wanne Test facility set up EPR configuration

Title:	Uncertainties in the ECC Strainer Knowledge Base – The Canadian Regulatory Perspective
Authors:	C. Harwood, Vinh Q. Tang (Canadian Nuclear Safety Commission), J. Khosla (Nutech Safety Assessment Inc.), D. Rhodes and A. Eyvindson, Atomic Energy of Canada Limited
Document ID:	NEA workshop proceedings, Debris Impact on Emergency Coolant Recirculation, p. 149, Albuquerque (NM)
Date:	2004 February 25-27
Document Length:	9 pages
Nature of Study:	Summary conference paper
Phenomena Studied:	Head loss

Abstract: When the Canadian Nuclear Safety Commission (CNSC) became aware of concerns relating to the collection of debris at suction strainers for ECC systems following the incident in Barsebäck, Sweden, it issued a notice to Canadian utilities requiring them to review their ECC strainer capability in view of the potential increase in pressure drop, and address any deficiencies. During this review a number of uncertainties in need of resolution were identified, principally directly related to the head loss across the strainer (both in the short and long term), as well as a few secondary issues such as the likelihood of air ingestion. Canadian utilities contracted AECL, through the CANDU Owners Group, to perform extensive fundamental testing to establish the important parameters governing ECC strainer performance. AECL expanded upon this knowledge base with additional tests to confirm proposed designs for specific applications. This testing produced a substantial body of knowledge that was used by the Canadian utilities to support their final ECC strainer design solutions in their submissions to the regulator. This paper discusses these uncertainties and their resolution. It also identifies the remaining uncertainties in the ECC strainer knowledge base, as it applies to CANDU stations, and how various conservatisms were used to offset these uncertainties.

Findings: Short term head loss tests were performed in either a medium or a large scale facility. The medium scale facility consists of a Jacuzzi-sized tank with a strainer screen. An external pump draws the water through the screen, past a heat exchanger and filter bag (both of which can be valved in or out of the system) and back into the tank. A stirring mechanism is used to keep the debris in suspension. The water temperature can be controlled, and temperature, flow and pressure drop across the screen are measured continuously. The large scale facility consists of a large lined tank (approximately 1.5 m deep, 2.5 m wide and 5 m long) connected to a large piping system, large enough to hold approximately 15 m^2 of strainer surface area. Flow rates up to 240 L/s and temperatures from 20 °C to 55 °C can be tested.

A large number of tests were performed for durations of up to ten days using a variety of debris types and combinations, flow rates and temperatures. The method of debris fabrication (e.g., shredding, grinding) was varied to determine its effect on the head loss. Test results were compared to values predicted using a published head loss correlation, and significant discrepancies between the measured and predicted values were noted. A CANDU-specific correlation was developed and used to predict short term (2 day) head loss across a strainer for a given approach velocity, water temperature, material volume and type. The new correlation was limited to use over the range of approach velocities from 0.006 m/s to 0.01 m/s. A small number of long term tests with durations ranging from 20 to 90 days were performed to confirm that the short term test results could (in some cases) be extrapolated to a longer period. The possibility of ingesting air into the ECC system through the strainer was identified early on as a concern, due to its potential harmful effect on the ECC pumping capability. Conservatism was applied to the results of these tests when identifying strainer requirements for the stations by using the minimum possible water level when specifying the maximum strainer elevation.

Title:	Emergency Core Cooling Strainers - The CANDU Experience
Authors:	A. Eyvindson and D. Rhodes (Atomic Energy of Canada Limited), P. Carson (New Brunswick Power), G. Makdessi (Ontario Power Generation)
Document ID:	NEA workshop proceedings, Debris Impact on Emergency Coolant Recirculation, p. 149, Albuquerque (NM).
Date:	2004 February 25-27
Document Length:	12 pages
Nature of Study:	Summary conference paper
Phenomena Studied:	Head loss

Abstract: The Canadian nuclear industry developed a substantial knowledge base with support from various organizations, including the CANDU Owners Group, AECL and the CANDU utilities. Work included debris assessments at specific stations, debris characterization, transport, head loss measurements across strainers, head loss models and investigations into paints and coatings. Much of this work was performed at AECL's Chalk River Laboratories (CRL) and used to customize strainer solutions for several CANDU stations. This paper summarizes the CANDU experience, describing problems encountered and lessons learned from strainer implementation at stations.

The following key points were identified for consideration during any station assessment or strainer implementation:

- A realistic testing model and method is essential for accurate predictions of head loss, and the limits of the model must be understood;
- Assessment of station debris must be sufficiently conservative to overcome uncertainties in debris generation and transport models;
- Appropriate and reliable data (e.g., flow rate, layout, size of test model, method of debris generation and deposition, test duration), with true representation of the various field conditions, is necessary to select the appropriate strainer solution;
- Flexibility in the strainer design permits adaptability to different plant layouts and schedules, while maintaining basic design qualification;
- Innovative header design can improve strainer efficiency;
- Reducing the strainer footprint-to-surface area ratio is desired; and
- Detailed review of specific station layout is critical prior to final design, fabrication and installation.

Debris similar to that found in the stations was obtained for the testing. Visual examination and scanning electron microscope imaging was performed to provide a baseline. A variety of small-scale tests were then performed at CRL, including measurement of material strength and density, the deposition rate of particulate and fibrous debris, the effect of temperature on the material structure, and the effect of particulate size on generic clogging. Several bench-top flow loops were set up to observe flow passage through a strainer. Information generated served to direct future testing.

The potential for the formation of hollow core vortices was examined to ensure that air ingestion due to vortices was not possible. A number of tests were performed in which the submergence of the strainer was fixed and the flow rate was varied to see if a vortex would form. This was done for several difference submergence levels and debris loading conditions.

Samples of debris types common to CANDU stations (fibrous debris (fibreglass), calcium silicate, marinite, rust, dust, dirt and paints (coatings)) were obtained from stations and from commercial suppliers, using the same suppliers as the stations where possible. Fibre diameters from different sources were compared. For head loss testing, a leaf shredder was used to break the fibrous debris into smaller pieces, which were then soaked prior to insertion in the test tank. Calcium silicate was broken up using an impact hammer. The effect of the different sizes was evaluated in the testing. Other experiments were performed

to determine the rate of erosion of calcium silicate pieces exposed to flowing water to determine if significant debris could be generated by erosion of large pieces of material that fall into the flow during an accident but are not transported to the strainer. This could lead to delayed deposition of calcium silicate on the strainer, leading to different results than for a fully-mixed debris bed.

Paint chips were prepared at CRL and added to the debris mixture for the tests. A detailed test program was performed to evaluate the performance of paints and coatings typically used in CANDU stations under accident scenarios to determine if, during an accident, the coatings would be likely to degrade to a degree that could impact strainer performance. This testing involved irradiation, exposure to high-temperature, high pressure transients, and long-term testing.

Title:	Ringhals 3-4. Head Loss and Self-cleaning Tests on a Modified Wing Strainer (Project Sil-05) Report No 1
Authors:	M. Henriksson, H. Lindqvist
Company:	Vattenfall Utveckling AB
Document ID:	U 05:50
Document length:	32 pages,
Date:	2005-06-01
Nature of study:	Experimental
Phenomenon studied:	Self-cleaning, particulate material, high temperatures, long-time tests.

Abstract: Tests have been performed on a new and somewhat modified design of the Wing Strainer that was installed at Ringhals 2 in 1995. The tests were carried out on a quarter of a modified Wing Strainer at full scale 1:1 with various temperatures, flow rates and combinations of fibrous insulation and particulate material. This was done in a PWR environment after a LOCA; boric acid (H_3BO_4) and tri-sodium-phosphate (Na_3PO_4) corresponding to accident conditions were added to the de-ionized water in the test tank. The purpose of these tests has been to study possible effects on head loss over strainer due to degradation of fibrous insulation (glass wool, nuclear grade) and to verify self-cleaning of the conical Wing Strainer.

Test setup: The test facility consists of an insulated stainless steel tank (D = 2.0 m, H = 2.0 m) connected to a flow loop with two variable speed pumps, flow meters, temperature controlled heaters on the outside of the tank and stainless steel piping, mainly DN 150. The Wing Strainer has a conical shape with a radius increasing with height above the outlet pipe at the bottom of the strainer. It is attached to the same pump suction line as the horizontal, sacrificial strainers. One quarter of the Wing Strainer was tested at full-scale 1:1 and mounted about 300 mm above the tank bottom. The total strainer area of a complete Wing Strainer is 2.0 m^2, so the quarter model has an area A = 0.5 m^2. The size of the holes is 3 mm at a 6 mm pitch.

Findings: The tests showed that at the low velocities to be used for the new strainer systems, the effect on pressure drop from softening of the glass fibres is expected to be small during long time operation (several weeks) at elevated temperatures up to 60 °C or even at 80 °C during shorter periods. Self-cleaning is expected to occur when flow rate is throttled down to zero if the pressure drop over the debris bed is kept low, below 50 mbar (0.5 meters of water pillar) and if self-cleaning is performed within a few days, preferably every 24 hours. At the plant it is suggested that the pumps are shut down for at least two minutes, preferably for 5 minutes. It is also expected that the new test data for pressure drops over the strainer debris bed can be used for the sizing of the strainer system.

Debris type: Transco glass wool insulation, nuclear grade (density 35 kg/m^3) and Rockwool (type Paroc, density 100 kg/m^3), sludge (black iron oxides, 95 % Grade 2008 and 5 % Grade 9101-N-40).

Mode of debris generation: All fibrous insulation was aged by heat treatment of the insulation blankets (285 °C, 24 h in an oven), the blankets were then manually shredded into pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Ringhals 3-4. Head Loss and Self-cleaning Tests on a Modified Wing Strainer (Project Sil-05) Fiber Deterioration, Report No 2
Authors:	M. Henriksson, H. Lindqvist
Company:	Vattenfall Utveckling AB
Document ID:	U 05:64
Document length:	32 pages,
Date:	2005-07-06
Nature of study:	Experimental
Phenomenon studied:	Fiber deterioration

Abstract: Tests have been performed on a new and somewhat modified design of the Wing Strainer that was installed at Ringhals 2 in 1995. The tests were carried out on a quarter of a Wing Strainer at full scale 1:1 with various temperatures, flow rates and combinations of fibrous insulation and particulate material. This was done in a PWR environment after a LOCA; quantities of boric acid (H_3BO_4) and tri-sodium-phosphate (Na_3PO_4) corresponding to accident conditions were added to the de-ionized water in the test tank. Possible effects on head loss over strainer due to degradation of fibrous insulation (glass wool, nuclear grade) and verification of self-cleaning of the conical Wing Strainer were studied.

Test setup: The report presents data from the water sampling in the test tank and in the suction line downstream of the Wing Strainer during the tests. The deterioration of the fibers was measured as the amount of dissolved silica (SiO_2), magnesium (Mg) and calcium (Ca). The water samples were analyzed at Ringhals NPP by photometric analyzer and by atomic absorption.

Findings: The results indicate that in the longest test, 18 days (412 h) at 60 °C about 25 % of the magnesium in the fibers was dissolved in the water and over 10 % of the calcium, but less than 0.1 % of the silica. Those values are based on the concentration in the water and do not take into account any possibilities for re-crystallization. It should be noted that the Ca-concentration after 100 h was as high as it was at the end of the test.

The results from the two tests at the highest temperature, constantly 80 °C, indicated that about 30 % of the magnesium was dissolved within 2 days and about 20 % of the calcium.

Debris type: Transco glass wool insulation, nuclear grade (density 35 kg/m³) and Rockwool (type Paroc, density 100 kg/m³), sludge (black iron oxides, 95 % Grade 2008 and 5 % Grade 9101-N-40).

Mode of debris generation: All fibrous insulation was aged by heat treatment of the insulation blankets (285 °C, 24 h in an oven), the blankets were then manually shredded into pieces and after that disintegrated in water with a spinning blade (hydrapulper).

Debris size: Small clusters to single fibres.

Title:	Ringhals 3-4. Possible Air Ingestion at the Strainers (Project Sil-05)
Authors:	M. Henriksson, H. Lindqvist
Company:	Vattenfall Utveckling AB
Document ID:	U 05:61
Document length:	11 pages
Date:	2005-06-22
Nature of study:	Experimental
Phenomenon studied:	Air ingestion

Abstract: As part of the qualification test program for the new ECCS strainer system at Ringhals 3 and 4, studies have been made of possible air ingestion caused by air pulling vortices using a reduced scale 1:3.5 hydraulic model.

Test setup: Tests were performed in a large circular stainless steel tank. The model consisted of an appropriate area around one location of the outlets for containment spray systems (SP 322) and emergency core cooling systems (ECCS 323). Major obstacles in the containment were included in the model. (Compare with the study for Ringhals 2, report US 95:11 for test methodology.)

Findings: The main conclusion was that as far as air ingestion from vortexing was concerned, the proposed design of the new strainer systems using long horizontal cylindrical strainers in combination with vertical, conical self-cleaning strainers was found to perform satisfactory for all operation conditions. The likeliness of air ingestion from vortices would be small for all water levels above the brim level.

Debris type: Not included, only clean water.

Title:	GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation
Author:	C. J. Shaffer et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6874
Date:	May, 2005
Document Length:	155 pages
Nature of Study:	Experimental
Phenomena Studied	Insulation Debris Transport in PWRs

Abstract: This report documents experiments conducted to determine the head-loss characteristics associated with calcium silicate insulation debris accumulated on a sump screen. These experiments were performed under the direction of Los Alamos National Laboratory in facilities operated by the Civil Engineering Department of the University of New Mexico. Experiments confirmed that calcium silicate insulation could degenerate into very fine particulates in the containment environment after the occurrence of a LOCA, and that debris beds formed by a combination of fine calcium silicate particulates and fibrous insulation on a sump screen can cause substantial head loss across the sump screen. Recommended head-loss parameters to be used in the NUREG/CR-6224 correlation were established with consideration of uncertainties in test parameters and variability in the manufacture of the particular brand of calcium silicate insulation tested. Using these recommended input parameters (e.g., specific surface area and particle density), the NUREG/CR-6224 correlation predicts reasonably well conservative head losses as demonstrated by comparisons with experimental data obtained in this study. Debris accumulation on a simulated (vertical) PWR sump screen was examined for several different types of LOCA-generated debris, including shredded fiberglass, crushed calcium silicate insulation, mixtures of NUKON™ and calcium silicate, and crumpled stainless-steel foils from the interior of reflective metal insulation. Results from this research enhance the understanding of head-loss characteristics important to the resolution of GSI-191.

Findings: The tests provide data and qualitative insights not available from earlier experimental work in two respects. First, head loss across a debris bed consisting of fragments of calcium silicate insulation had not been measured in prior experiments sponsored by the NRC. Second, prior experimental work did not explicitly examine the geometric configuration(s) with which transportable forms of LOCA-generated debris would collect on a typical PWR recirculation sump screen. A prior industry examination of calcium silicate head-loss characteristics performed to support the redesign of recirculation strainers in a BWR suggested that the head loss caused by this material could be disproportionately higher than that of other forms of insulation debris with comparable mass/volume. When it was recognized that the specific design features of recirculation sump screens differ considerably among the fleet of U.S. PWRs, experimental data were needed to understand the basic configuration with which debris would collect on a typical PWR sump screen. Therefore, tests were conducted to observe the geometric pattern with which debris would accumulate on a prototypic screen in representative configurations.

Significant findings from the current experiments are the following:

1. Debris accumulation on a simulated (vertical) PWR sump screen was examined for several different types of LOCA-generated debris, including shredded fiberglass, crushed calcium silicate, mixtures of NUKON and calcium silicate, and crumpled stainless-steel foils from the interior of RMI. With the exception of RMI foils, debris was observed to accumulate on the screen in a relatively uniform manner for conditions in which the local fluid velocity was significantly greater than the bulk transport velocity of debris fragments.
2. Head-loss measurements were made in a closed-loop test facility located at the University of New

Mexico. Before conducting experiments with debris containing calcium silicate, qualification tests were run to measure the head loss caused by debris that has been examined in prior studies (in other test facilities). In particular, tests were performed to measure head loss caused by shredded NUKON fiber and mixtures of NUKON fiber and a sand-and-concrete-dust particulate. Measurements were compared to predictions of the head loss using the NUREG/CR-6224 correlation.

3. The application of the NUREG/CR-6224 head-loss correlation to a bed of debris requires certain parameters (e.g., specific surface area) as input to the correlation. These parameters were determined for NUKON insulation debris and for some other materials, such as BWR suppression pool corrosion products, but not for many types of insulation and particulate debris typically found in PWR containments.
4. Tests conducted using only calcium silicate fragments to form the debris bed demonstrated that calcium silicate debris can accumulate on a 1/8-in. mesh screen and cause substantial head loss without the aid of another form of fiber to hold it in place.
5. Measured head losses for mixtures of calcium silicate and RMI were higher than those measured for the base RMI debris.

Title:	Characterization and Head-Loss Testing of Latent Debris from Pressurized-Water-Reactor Containment Buildings
Author:	B.C. Letellier et al.
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6877
Date:	July, 2005
Document Length:	122 pages
Nature of Study:	Experimental
Phenomena Studied	Head loss tests with latent debris

Abstract: To properly evaluate the performance of a PWR ECCS containment recirculation capability, it is necessary to estimate the total amount of debris that may be present in the containment pool during the recirculation phase. To be as accurate as possible, it is important to include a reasonable estimate of the latent dirt and foreign material that can be found in containment, in addition to the debris generated by a high pressure pipe rupture. Past and recent testing has shown that even small volumes of fibrous debris present on an ECCS sump screen can filter particulates present in the sump pool very effectively, leading to the formation of composite debris beds that can produce significant pressure losses. Debris present during routine operations that is subjected to containment spray and pool transport may be a significant contribution to the particulates and/or fiber material that compose the sump screen debris bed.

To investigate the significance of this issue, Los Alamos National Laboratory (LANL) performed experiments to characterize the material composition and the hydraulic flow properties of actual plant debris samples.

This study was performed from August 2003 to June 2004. The purpose of the study was to quantify parameters critical to the proper application of the NUREG/CR-6224 head-loss correlation, such as specific surface area. Micro filtering, optical microscopy, and organic dissolution chemistry tests were performed to fractionate the fibrous and particulate components. Most tests were performed at the geochemistry laboratory of the Isotope and Nuclear Chemistry Facility at LANL, which has the necessary analytic equipment to make direct measurements of the hydraulic flow properties and to handle potential low-level radioactive waste streams. Hydraulic parameters representative of latent particulates were measured by testing larger quantities of surrogate debris in a vertical-flow test loop at the University of New Mexico. In addition to our attempt to provide the first quantitative characterization of PWR latent debris properties, this study provides a model of participation and cooperation between the US PWR industry and the NRC. Five volunteer plants contributed samples collected during their recent condition assessment surveys. Descriptions of test procedures and quantitative results are provided in the applicable sections of this report.

Findings: Hydraulic parameters representative of latent particulates were measured by testing larger quantities of surrogate debris in a vertical-flow test loop at the University of New Mexico. This apparatus permits measurement of pressure drop (head loss) across a debris bed of known composition under a range of water velocities. Hydraulic parameters can be inferred from differential pressure data by iteratively applying predictive correlations until the model results envelop a variety of observed behavior. Surrogate particulate debris was generated by dry sieving soil and sand into a range of particle diameters using different sieve sizes and by recombining mass fractions to match the size distribution measured in the plant samples. The micro-flow characteristics of the surrogate also were compared to those of the plant debris by measuring packed-bed flow conductivity.

All analyses are based on the assumption that proportional debris compositions are approximately constant even if the total inventory varies during an outage or during a plant lifetime. These samples represent the best information to date regarding latent containment debris but may not capture the full range of variability present in the population of nuclear power plants. Furthermore, the quality of the debris samples varied widely because of differences in collection methods and sample locations.

Title :	Experimental Study of Head Loss Induced by LOCA-Generated Debris at Containment Sump of Westinghouse Two Loop Plant (Kori Unit 1)
Author:	Young Wook Chung
Company:	FNC Technology Co., LTD, Korea Hydro & Nuclear Power Co., LTD
Document ID:	ICAPP 2007, Paper No. 7475
Date:	December, 2006
Document Length:	7 pages
Nature of the Study:	Experimental
Phenomena Studied:	Head loss through insulation, coating and latent debris on strainer screen surface

Abstract: To assess debris-induced head loss in the sump screen, experimental studies have been widely conducted and the results have shown that head loss depends on amount of debris, specific surface area, mixture porosity of debris bed, debris type, and so on. Based on the experimental results, empirical correlations have been developed. Plant specific head loss data were obtained with a test facility that is a closed-loop type. A vertical test section was fabricated with 6 inch chlorinated polyvinyl chloride (CPVC) pipe. The ratio of length to diameter at the vertical test section was about 30. Experimental results showed that the head loss across a NUKON™ debris bed with theoretical thickness greater than 4 inch was predicted conservatively by the NUREG/CR-6224 correlation. Head loss tests with a debris composition representative of a Westinghouse two loop plant showed that the NUREG/CR-6224 correlation predicted a higher head loss than the experimentally measured head loss.

Test Setup: The test facility was designed as a closed loop type with a vertical test section which was fabricated from CPVC pipe. The ratio of L/D of the vertical test section was about 30. A return path of the loop needed to keep the flow velocities high enough to minimize settling of sludge particles in the loop and was fabricated from 2 inch stainless steel pipe. A transparent section was fabricated from a clear polyvinyl chloride (PVC) pipe and was inserted into the vertical test section. The transparent section was used to observe formation of the debris bed and to measure the bed thickness. The inner diameter of the clear PVC pipe is 165 mm, which results in a screen area of 0.196 ft^2. The test screen was a perforated metal plate that supports the debris bed and was located at the middle of the transparent section. The perforated metal screen was positioned at the position 20 L/D upstream and 10 L/D downstream in the vertical section. The perforated metal screen with holes of 3 mm diameter was used to simulate the sump screen.

The flow rate in the test facility was controlled by a 15 HP variable speed motor-pump and measured with Coriolis-type flow meter. The head loss across the screen was measured with a differential pressure transmitter. Pressure taps were perforated at the position of 2 L/D and 5 L/D from the screen. K-type thermocouples were installed to measure water temperature. The test facility has been operated at higher water temperature than ambient temperature. The steel piping of the loop was insulated to minimize heat loss and a resistance heater on the pipe wall was wound to maintain water at temperature as high as 60 °C.

Findings: The types and quantities of debris of the Westinghouse two loop plant (Kori Unit 1) were obtained from a plant walkdown process and scoping analysis on debris generation and sump screen sizing calculation. Table 1 shows the debris quantities of the plant. For head loss testing with plant-specific debris, the debris quantities of the plant are to be scaled to the screen area in the head loss test facility with the following equation;

$$W_{HLT} = W_{PWR} \times \frac{S_{HTL}}{S_{PWR}}$$

where W_{HLT} is a scaled debris quantity, W_{PWR} is a debris quantity of the plant, S_{HLT} is a screen surface area of head loss test facility, and S_{PWR} is a sump screen area of the plant.

The surrogates for the debris in the the plant were selected based on the characteristic size and microscopic

density of the debris. For the coating particulate, ground silica with average size of 10 µm was used. The coating chips in the the plant are nominally sized at minimum 5 mils (127 µm) thick. For the chip surrogate, silica sand with size distribution greater than 100 µm was used. For latent debris, the surrogate debris was used with a form that three different silica sand products were blended into a mixture that represents the size distribution in according with NRC's Safety Evaluation Report to NEI-04-07.

Water temperature for testing was selected as 50 °C to estimate the head loss conservatively. Experimental results showed that the NUREG/CR-6224 correlation could be applied to NUKON™ debris bed with theoretical thickness greater than 4 inch. Head loss test with debris composition of the plant showed that NUREG/CR-6224 correlation could predict conservatively head loss across debris bed. The experiment showed that a debris bed with calcium silicate and/or particulate of about 10 µm size in NUKON™ debris had a significant effect on the head loss.

Title:	Experimental Measurements of Pressure Drop across Sump Screen Debris Beds in Support of Generic Safety Issue 191
Author:	C.W. Enderlin et al.
Company:	Pacific Northwest National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6917
Date:	January 2007
Document Length:	459 pages
Nature of Study:	Experimental
Phenomena Studied	Head loss tests

Abstract: Pacific Northwest National Laboratory (PNNL) conducted experiments to help the NRC predict the flow through debris beds consisting of fiberglass and calcium silicate particulate. The effects of debris preparation on debris bed formation and pressure drop were evaluated and a metric developed for characterizing the preparation. Testing consisted of forming the debris bed within the test loop and obtaining a steady-state pressure drop at the bed formation velocity. The velocity was then changed incrementally through several cycles—increasing and decreasing—with a steady pressure measurement obtained at each flow set point. The loop temperature was then changed and the velocity variation sequence repeated.

Findings: A total 156 tests were conducted consisting of the following test conditions: 5 screen-only tests, 11 calcium silicate-only tests, 90 NUKON-only tests, 45 NUKON/ calcium silicate tests, and 5 coatings tests. Of the 156 tests, 43 were performed in the large-scale test loop, and 16 of those tests were conducted at elevated temperatures of 129 and 180 °F (54° and 82 °C).

Two test loops with test sections 4 and 6 inches in diameter were constructed for generating debris beds and measuring the associated pressure drop. Debris beds were generated and pressure drop measurements made for beds consisting of NUKON fiberglass, calcium silicate particulate, and combinations of fiberglass and particulate.

During the test program, the effects of debris preparation on debris bed formation and pressure drop were evaluated and a metric developed for characterizing the disassociation of the debris after preparation. Testing consisted of forming the debris bed within the test loop and obtaining a steady-state pressure drop at the bed formation velocity. The approach velocity was then changed incrementally through several cycles of increasing and decreasing velocity with a steady pressure measurement obtained at each flow set point. The loop temperature was then changed and the velocity variation sequence repeated. During testing, in-situ measurements of the debris bed height were taken using an optical triangulation system developed for the test program. Selected retrieved debris beds were impregnated with epoxy and sectioned, and then subsequently imaged using scanning electron microscopy to evaluate the debris bed structure. A process for assessing the calcium silicate mass in a NUKON/ calcium silicate debris bed was employed using chemical dissolution and a calcium ion selective electrode. The test program also evaluated the effects of the debris loading sequence and flow history through the debris bed on the resulting pressure drop.

The preparation of the debris material and the constituent loading sequence during debris bed formation were shown to strongly influence the resulting pressure drop and physical integrity of a debris bed.

Title:	Development of a Pressure Drop Calculation Method for Debris- Covered Sump Screens in Support of Generic Safety Issue 191
Author:	W. Krotiac
Company:	U. S. NRC
Document ID:	NUREG-1862
Date:	February 2007
Document Length:	204 pages
Nature of Study:	Analytical-Head Loss Correlation
Phenomena Studied	Head loss across a debris bed

Abstract: U.S. and international researchers have sought to develop an analytical method to predict the pressure drop across a debris-covered sump screen. One study sponsored by the U.S. NRC, documented in NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA-Generated Debris," issued October 1995, used available test data to develop a head loss correlation to evaluate suppression pool strainer performance in BWRs. However, the tests and data used for the development of the NUREG/CR-6224 correlation focused on debris constituents that were not dominant contributors to debris beds at PWRs. A significant number of PWR plants use calcium silicate thermal insulation, often in combination with other insulation materials such as fiberglass (i.e., Nukon) or RMI.

Consequently, the NRC sponsored another study to provide test data for head losses resulting from the accumulation of calcium silicate-laden insulation debris on a PWR sump screen and to evaluate the suitability of the NUREG/CR-6224 correlation for application to PWR plants that can accumulate calcium silicate insulation in combination with other debris on a sump screen. The agency documented this study in NUREG/CR-6874, "GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation," issued May 2005. It also recognized that the available head loss test data did not include the effects of water temperature on a debris-laden sump screen, did not provide data for a broad enough range of calcium silicate and Nukon concentrations on a sump screen to address a large portion of expected PWR sump screen conditions, and did not address head loss resulting from the accumulation of coating debris on a sump screen. In addition, all previous testing involved the use of a woven metal screen to represent the sump screen. In contrast, many of the proposed PWR sump designs use perforated metal plates instead of woven metal screens and are designed for lower water approach velocities.

To support the development of an improved head loss correlation and provide test data to address these concerns, the NRC sponsored additional testing, which is documented in NUREG/CR-6917,"Experimental Measurements of Pressure Drop across Debris Beds on PWR Sump Screens in Support of Generic Safety Issue 191," issued January 2007

Findings: A set of equations has been derived to calculate the pressure drop for flow across a compressible porous medium debris bed composed of thermal insulation such as fiberglass fibers (Nukon) and calcium silicate particles. The equations account for the kinetic and viscous contributions to pressure drop. The compressibility of the porous medium debris bed is considered by initially assuming an irreversible, inelastic process followed by elastic behavior with constant compressibility. Semi-empirical relations and constants required to solve the flow and compression relations are determined using available test data. An iterative procedure has been developed to estimate the pressure drop across a debris bed composed of one debris type (e.g., fibers) by applying the flow and compression relations to a one-volume, homogeneous debris bed model. The pressure drop across a debris bed composed of two debris types (e.g., fibers and particles) depends on the distribution of the two debris types in the bed.

Predictions using the developed approaches are compared to test data.

Title:	Electrabel. Head Loss and Self-cleaning Tests of a Wing Strainer. Report on Thick Bed Tests with Only Fibres.
Authors:	M. Henriksson, M. Agrell, D. Edmarker
Company:	Vattenfall Research and Development AB
Document ID:	U 10:05
Document length:	74 pages
Date:	2010-03-19
Nature of study:	Experimental
Phenomenon studied:	Self-cleaning, thick beds

Abstract: Introductory tests were carried out on a quarter of a Wing Strainer at full scale 1:1 with typical low approach velocities. Artificially aged fibrous insulation that had been disintegrated was used. Some of the tests were run at water conditions corresponding to a PWR after a LOCA, that is, boric acid (H_3BO_3) and sodium hydroxide (NaOH) were added to the de-ionized water in the test tank. The purpose of the tests was to study possible effects on head loss over strainer due to degradation of fibrous insulation (glass wool, nuclear grade) and to verify self-cleaning of the vertical Wing Strainer.

Test setup: The test facility consists of an insulated stainless steel tank (D = 2.0 m, H = 2.0 m) connected to a flow loop with two variable speed pumps, flow meters, temperature controlled heaters on the outside of the tank and stainless steel piping, mainly DN 150.

One quarter of the strainer has been tested at full scale 1:1. It was mounted 300 mm above the tank bottom. Total strainer area of one complete strainer is 1.6 m^2, so the quarter has an area of A=0.4 m^2. The sizes of the holes were 2.5 mm at a triangular pitch of 4 mm, giving a porosity of 35.4 percent.

The test tank was filled with de-ionized water (from Forsmark NPP) and possible chemical and high temperature effects on the strainer performance were included in the test program by using water with chemicals and pre-heated insulation that simulated post-accidental recirculation conditions.

In some preliminary tests ordinary tap water was used.

Findings: The thick bed tests show that self-cleaning is expected to occur when the flow rate is throttled down to zero if the pressure drop over the debris bed is kept low, below 100 mbar (1.0 meters of water pillar). At plant it is suggested that self-cleaning should be initiated sooner (preliminary value 80 mbar) and performed within 24-48 hours. It is also suggested that the pumps be shut down during at least two minutes, preferably 10 minutes. The degree of disintegration of the fibrous insulation had a strong influence (as expected) on the pressure drop over the strainer. Thus, it is difficult to use correlations for head loss calculations in real situations.

Debris type: Glass wool (Nukon), Mineral wool (Telisol 734QN)

Mode of debris generation: All fibrous insulation was supposed to be aged by heat treatment of the insulation blankets at 343 °C for 24 hours in an oven. As it turned out, the aging was made for a shorter time and in an oven without proper ventilation. A possible result of this is that binder residue might be left in the insulation. Torn or cut pieces (about 25x25x25 mm) were disintegrated by means of a spinning blade in a water tank (hydrapulper).

Debris size: Various degree of disintegration with the hydrapulper method (speed and time), i.e. milder and stronger compared to the standard method

Title:	Electrabel. Head Loss and Self-cleaning Tests of a Wing Strainer. Thin Bed Report.
Authors:	M. Henriksson, M. Agrell, D. Edmarker
Company:	Vattenfall Research and Development AB
Document ID:	U 10:54
Document length:	81 pages
Date:	2010-03-19
Nature of study:	Experimental
Phenomenon studied:	Self-cleaning, thin beds

Abstract: Introductory tests were carried out on a quarter of a Wing Strainer at full scale 1:1 with typical low approach velocities for artificially aged fibrous insulation that had been disintegrated. Some of the tests were run at water conditions corresponding to a PWR after a LOCA; boric acid (H_3BO_3) and sodium hydroxide (NaOH) were added to the de-ionized water in the test tank. The purpose of the tests was to study possible effects on head loss over strainer due to degradation of fibrous insulation (glass wool, nuclear grade) and to verify self-cleaning of the vertical Wing Strainer, especially in combination with a new mixture of particulate material that was supposed to represent latent debris in a Belgian NPP. Very thin beds with very high ratios of particulates to fibers were studied (Mp/Mf from 2.05 to 20).

Test setup: The test facility consists of an insulated stainless steel tank (D = 2.0 m, H = 2.0 m) connected to a flow loop with two variable speed pumps, flow meters, temperature controlled heaters on the outside of the tank and stainless steel piping, mainly DN 150.

One quarter of the strainer has been tested at full scale 1:1. It was mounted 300 mm above the tank bottom. Total strainer area of one complete strainer is 1.6 m^2, so the quarter has an area of A=0.4 m^2. The sizes of the holes were 2.5 mm at a triangular pitch of 4 mm, giving a porosity of 35.4 percent.

The test tank was filled with de-ionized water (from Forsmark NPP) and possible chemical and high temperature effects on the strainer performance were included in the test program by using water with chemicals and pre-heated insulation that simulated post-accidental recirculation conditions.

Findings: None of the thin bed tests showed that self-cleaning was expected to occur when the flow rate is throttled down to zero. Instead the debris cake stuck to the strainer like some sort of gel. An explanation for this might be that chemical reactions occur between the chemicals in the water, the insulation fibres and the special mixture of particulates that was used.

Debris type: Glass wool (Nukon), Mineral wool (Telisol 734QN), particulate material (for a 1 kg batch 100 g of quarts powder was used plus sands of different grain sizes; 170 g Baskarpsand 15, 200 g Silversand 36 and 530 g Silversand 90, each one with a certain size distribution to get the specified total size distribution curve.

Mode of debris generation: The insulation was aged for 24 hours at an inside air temperature of 343 ±5 °C instead of the earlier used temperature 285 °C (originally selected for BWR plants), then cut into pieces with a pair of scissors (about 10 mm sizes) and then disintegrated by means of a thin high pressure mixing water jet in a small water tank.

Debris size: Very high degree of disintegration of the insulation to form a thin bed

Title:	Lab-scale Deep-bed Filtration Test Facility “TiFi”
Authors:	H. Kryk, H.-U. Härting
Company:	Helmholtz-Zentrum Dresden-Rossendorf
Document ID:	
Date:	From 2010 onwards
Document Length:	
Nature of Study:	Single effect experiments to parameterize and validate deep-bed filtration models for sump strainer modeling
Phenomenon Studied:	Pressure loss across strainers; compaction of fiber beds and test materials; deposition and remobilization of particles

Abstract: Within a common research project funded by the Federal Ministry of Economics and Technology (BMWi), the lab-scale deep-bed filtration test facility “TiFi” has been designed to investigate deposition and remobilization of debris (fines and corrosion particles) at fiber-laden strainers by means of single effect experiments. The studies are aimed at the development, parameterization and validation of deep-bed filtration models for numerical modeling and simulation of head loss courses across sump strainers during ECCS operation following a LOCA.

The main unit of the test facility is a strainer section (F1, see facility scheme) for the application of ex-situ generated filter cakes or mats of adequate material in order to simulate the clogged sump strainer. Special emphasis was put on the application of variable inserts for the strainer section and the installation of a bubble trap (B3) in front of the section. The supply unit of the test facility consists of two 60 L stirred tanks (B1, B2), a heat exchanger (W1) with thermostat and an impeller pump (P1) to provide the strainer section with the particle-water suspension for the examination of the deep-bed filtration behavior of the aforementioned filter materials. By means of valves and a sophisticated mode of operation, the facility can be operated in batch mode or continuous (recirculation) mode, as well. The pump is part of a control loop, which guarantees a constant mass flow during the experiments.

Test Facility Capabilities:

Liquid volume:	2 x 60 l max.
Operating Temperature:	70 °C max.
Mass flow:	800 kg/h max.
Strainer design:	Flat stainless steel strainer (mesh width 2 mm, diameter 50 mm)
Superficial liquid velocity at strainer:	113 mm/s max.
Fiber bed preparation:	Rockwool fibers tempered at 225 °C, steam jet fragmented; pads of thermally bonded polyester fibers
Debris preparation:	Corrosion particles generated during experiments at the corrosion test facility “KorrVA”; test particles Vestosint, Sphericell; ferric oxide powder
Measured Variables:	Liquid flow rate (online)
	Liquid inlet temperature (online)
	Liquid temperature at strainer (online)
	Pressure loss across strainer (online)
	Fiber bed height (online)
	Liquid turbidity upstream the strainer (online)

Liquid turbidity downstream the strainer (online)

Particle concentration (offline)

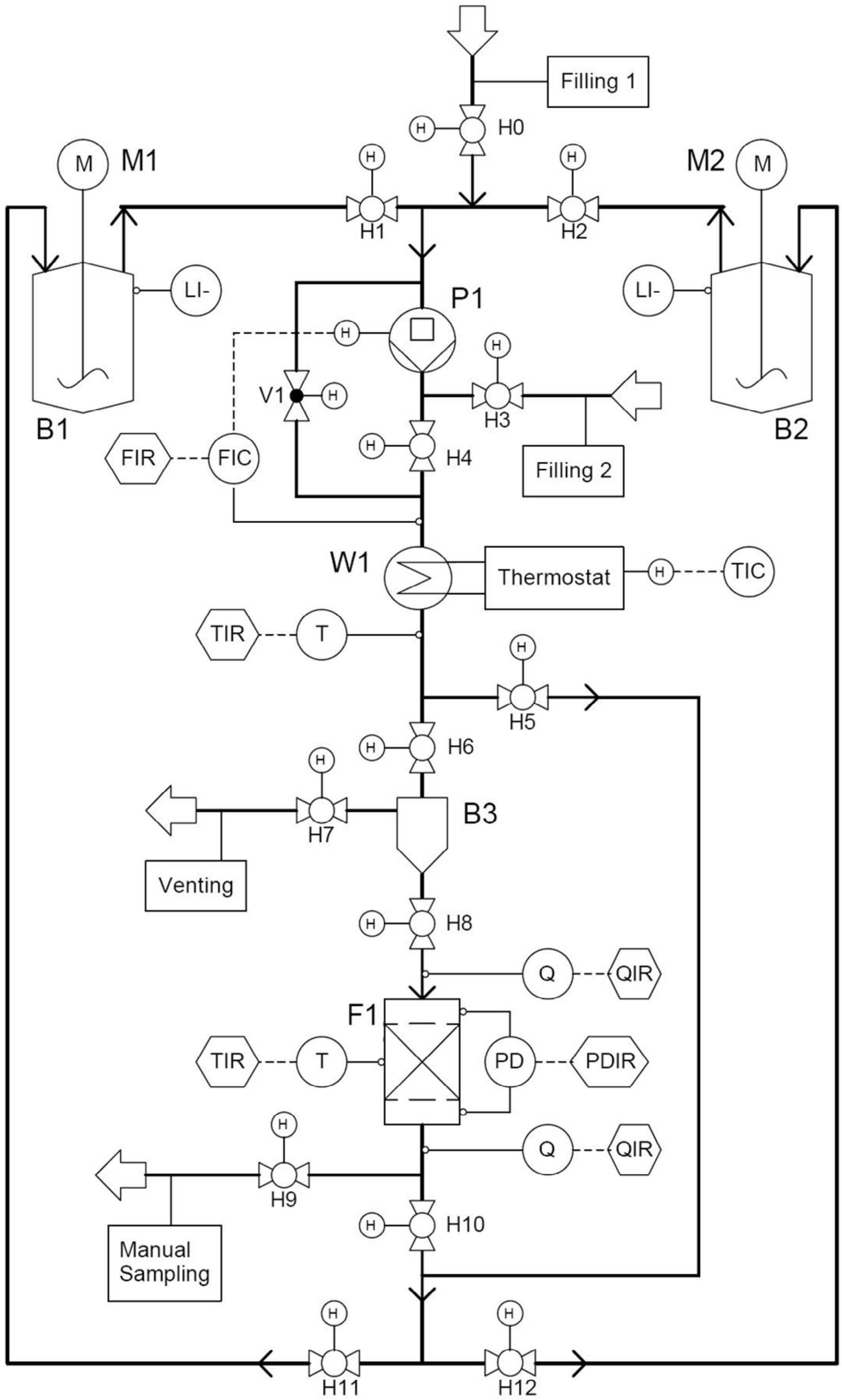
Particle size distribution (offline)

Mass of fiber bed (offline)

Tests performed:

So far, the following tests have been performed in the "TiFi" test facility with different focus:

- Head loss evaluation on sump strainer using ex-situ generated rock wool insulation material mats and pads of thermally bonded polyester fibers as fiber beds; short-term and long term, up to 24 h:
- Compaction behavior of different fiber bed materials (different bed heights and flow rates):
- Head loss courses during deposition and remobilization of different particles (Vestosint, Sphericell, ferric oxide) at fiber beds for development and test of the deep-bed filtration model.



Lab-scale deep-bed filtration test facility "TiFi" schematic

Title:	Experimental Investigation of the Trapping Efficiency of an Intermediate Trap for ECCS Recirculation Strainer using FINA (FNC INterceptor Assessment test facility)
Author:	Jong Wook Kim
Company:	FNC Technology Co., LTD, Korea Hydro & Nuclear Powr Co., LTD
Document ID:	S08NX03-F-TR-006
Date:	December, 2010
Document Length:	68 pages
Nature of the Study:	Experimental
Phenomenon Studied:	Trapping efficiency of intermediate trap for coating fragment debris to reduce the debris loading on the strainer screen

Abstract: The function and mechanism of coatings trapped by the intermediate trap (IT) was verified by measuring dynamic properties of protective coatings such as tumbling and lifting velocity, and the overall trapping efficiency. For the test, a flume test rig was developed that simulates a sectional flow path of the reactor building floor. Silica powder was used for simulating particles. The measured trapping efficiency showed that more than 70% of the coating debris can be captured before reaching the main sump screen. The result of this study has been already used for preparing design specifications of the IT of Kori Unit 1 plant and is expected to contribute to the cost-effective design changes of the remaining plants.

Test Setup: The test facility consists of a flume containing a diffuser (porous media), a flow straightener, a simulated IT, and a recirculation pump and piping. The test flume size (6 m length and 0.6 m width) was determined by CFD analyses. The simulated coating was injected at 3 m downstream and the simulated IT was placed at 5 m downstream. The recirculation pump capacity was 7000 LPM considering the operating nuclear power plant and a 50% margin was added. For the 0.6 m width and 1.0 m height of flume water flow, 7000 LPM is able to achieve a maximum flow velocity of 19.5 cm/sec. The test flume was fabricated from transparent acryl material and piping was fabricated from CPVC pipe. The diffuser was made of a sponge material in a metal frame and was netted by metal wire to prevent breakage. The simulated IT was a T-shape and its cover was perforated with holes of 2.3 mm in diameter and 4 mm in pitch. The overall dimension was 0.2 m, 0.5 m and 0.3 m for the depth, width and height, respectively. The simulated IT was fabricated entirely of stainless steel.

Findings: A series of tests were performed to characterize the dynamic properties of coatings, i.e., tumbling velocity and lifting velocity. The tumbling velocity and lifting velocity are the threshold fluid conditions necessary to induce the tumbling of the coating fragments over the IT structure on the reactor building floor and induce the lifting of the coating fragments, respectively. If the simulated particle size ranges from 0.1 to 0.15 mm, the tumbling velocity was approximately 3 cm/sec; if the size was larger than 1 mm, the tumbling velocity was 4.3 ~ 4.5 cm/sec. The test results also showed that the lifting velocity was nearly twice as large as the tumbling velocity for each case.

Tests were performed to measure the trapping efficiency while varying the average velocity of the flow in the flume. Silica power was used to stimulate particles. The measured trapping efficiency showed that more than 70% of the coating debris can be intermediately captured before reaching the main sump filter.

Title:	Experimental Investigation for ECCS Recirculation Strainer using FISTA (FNC Integral STrainer Assessment Test Facility)
Author:	Jae Seon Cho
Company:	FNC Technology Co., LTD, Korea Hydro & Nuclear Powr Co., LTD
Document ID:	S08NX03-F-TR-007
Date:	December, 2010
Document Length:	40 pages
Nature of the Study:	Experimental
Phenomenon Studied:	Head loss induced non-chemical debris and chemical products on prototype strainers

Abstract: The debris that could accumulate on the sump strainers would increase head loss across the resulting debris bed and sump strainer. Another major concern in evaluating the effects of the debris transported to these sump strainers after a LOCA is the chemical products which may form in a post-LOCA sump environment. The FISTA facility was constructed to evaluate the effect of the non-chemical debris and chemical precipitates on the head loss through recirculation sump strainer. The FISTA facility is combination facility having a flume section and a pool section. The test strainer is located and submerged in the pool section. The objective of each test is to determine the head loss associated with a plant-specific debris bed and chemicals at the specified temperature and flow rate. Differential pressure, temperature, flow rate, and turbidity data are collected and recorded while building a bed of a specific type and quantity of debris across a strainer. The tests measure the head loss of the plant-specific debris load and scaled the prototype strainers.

Test Setup: The test facility consists of a flume containing a flow straightener and a pool containing a test strainer, a recirculation pump, heater and piping. The test facility size was determined by CFD analyses. The flume region was determined as 6 m length, 1 m width and 1 m height. The pool region was determined as 2 m length, 2 m width and 2 m height. Water recirculation in the loop is realized by means of a centrifugal pump measured with a flow meter that has a capacity up to 8000 LPM. The test can be performed between 10 and 55 °C. The flow rate is adjustable by means of the frequency control of the rpm of the pump motor. The water flow rate is measured using a coriolis mass flow meter. The test facility was fabricated from transparent acryl material and piping was fabricated from stainless steel pipe. Both horizontal strainer installation and vertical strainer installation tests are made possible by two types of flow suction, in the horizontal and vertical directions.

The facility was designed to measure the head loss through the clean strainer and the head loss across the strainer with full debris loading. To get the head loss characteristics of the test strainer, the test is executed with different flow rates below and above the nominal flow rate. Clean strainer head loss at nominal flow rate shall be measured before the start of each test as part of the test setup and test initiation activities.

The amount of fiber and particulate as well as the flow rate are calculated from the plant to the test condition by a scaling factor. The plant specific values are converted to the test-specific amounts by a scaling factor.

Findings: The test matrix consists of clean head loss test, non-chemical debris test and adding chemical precipitate material test for each test strainers. The trend of head loss change is able to be measured step by step by controlling the inserted debris material and amount. In addition, the temperature effect on the head loss is able to be measured with range of 10 ~ 55 °C. The FISTA facility can do integral tests of strainer and intermediate trap coupling. This test result gives information for optimized strainer design due to reducing the debris load on the strainer screen by the intermediate trap.

Title:	Test Report: Head Loss Testing of a Prototypical Almaraz Strainer
Author:	T. Hadaway
Company:	ALION Science and Technology
Document ID:	ALION-REP-CNAT-2915-04
Date:	May 2007
Document Length:	65 pages
Nature of Study:	Experimental
Phenomena Studied	Head loss across a debris bed on a flat strainer

Abstract: The resolution strategy implemented by the PWR Spanish Almaraz NPP was to retain the existing sump flat screens and remove debris sources (fiberglass, calcium silicate and Microtherm) so that the main insulation material implemented in this plant is RMI. Additionally, the GL 2004-02 performance assessment was based on refined values for ZOI coatings; that is, 4D for epoxy and 5D for IOZ coatings, according to WCAP-16568-P for IOZ surfaces topcoated with an epoxy layer, also in accordance with NRC staff letter to the NEI of April 6, 2010.

In 2007 this plant performed the required plant-specific test plan at the ALION facilities in Warrenville (IL). The tests considered the maximum debris load with chemical precipitates, scaled according to the ratio of prototype strainer surface area to the actual plant strainer surface area. The aim of the test was to collect and record differential pressure, temperature, flow rate and turbidity data to finally obtain head loss data across the screen for debris loads up to the maximum amount analyzed.

Debris Types and Quantities: The debris load corresponded to the actual plant specific inventory, reduced according to the scaling factor. During the tests extra loads were added in order to obtain additional bounding data. The non-chemical debris was homogenously mixed in a container prior to addition to the flume and the whole load was added at the top of the flume. Visual observations were made to ensure that a vortex didn´t form along the test. The test load includes the precipitates based on WCAP-16530-NP (Feb-2006). After removal of calcium silicate and fiberglass insulation, only a minimal amount of AlOOH (0.8 kg) is considered to be formed in the sump.

The non-chemical debris mixture was as follows, along with the references given in the NRC SER:

- ISOVER as the surrogate for latent fiber, with as-fabricated density of 3.75 lbm/ft^3 (60 kg/m^3)
- Coatings Debris: Epoxy and IOZ coatings were represented by paint chips to a size based on the SER Section 3.4.3.6 related to plants that demonstrate no thin bed effect, as this case is. Paint chips of 4-6 mils thickness were sifted using a sieve with holes of diameter 2.8 mm (nominal) to obtain chips greater than the 2.0 mm screen opening. The paint chips have a density of 100 lb/ft^3.
- Dirt/Dust particulate surrogate was a material blend of silica sand representative of PWR latent dirt/dust. The size distribution of the silica sand was prepared to be consistent with the latent dirt/dust size distribution provided in the SER Table 3-4, ranging from a 37% of small fines (<75 µm) to a 28% of coarse grain (>2000 µm). The load debris incorporates results from latent debris walkdown (53 lb obtained, from which 0.55 lb is fiber).
- Stainless steel RMI was included in tests, with only small pieces (<4”x4”) in the debris load. The size distribution for testing was ½” and 2” pieces, considering that this was representative enough for the 6.1% of ¼” pieces and for the 29.4% of 1”. All RMI foils were crumpled. One test was performed with RMI to evaluate the head loss with the full debris load placed at the screen and a second test is performed without RMI.

Test setup: The test facility is intended to reproduce the Almaraz NPP flat finest 2.0 mm mesh, with a scaled screen area of 1.5191 ft^2. The flow points were selected to obtain approach velocities ranging from 0.03281 ft/s to 0.08658 ft/s, where the maximum value is corresponding to the most limiting flow conditions. The tests were performed varying the approach velocity by flow sweeps among these values. Turbidity data were recorded once per hour, at every flow sweep. The scale calculations do not take into

account any surface reduction due to latent tags because these elements have been either removed or replaced by stainless steel tags or proven to remain intact. Other test parameters are: Temperature: 29.4 ±5 ºC and pH according to actual plant conditions. As test criteria, a stabilized head loss profile (less than 1% change over a given time period) and a minimum number of flume pool turnovers (5) were specified prior to flow rate changes (flow sweeps) and prior to test termination. The flume apparatus used is capable to control the flow correspondingly to the approach velocity. The procedure includes stirring actions to avoid debris deposition in the flume volume.

The table below show a summary of the tests performed.

GOALS for each test:

- 1A: Clean screen test
- 1B: Thin bed effect sensitivity (no RMI nor *coating* from outside ZOI)
- 1B+: Extra fiber load (x10) added at the end of 1B test at maximum velocity after flow sweep
- 2A: Basis case, with RMI and *coating* from outside ZOI
- 2B: Extra fiber load (x10) added at the end of 2A test at maximum velocity after flow sweep
- 3A: Basis case without RMI. No flow sweep
- 3B: Extra fiber load (x10) added at the end of 3A test at maximum velocity. No flow sweep
- 3B+: Extra *Chemical precipitates (*x2) at the end of 3B test at maximum velocity. No flow sweep
- 4: Bounding case

ALMARAZ NPP SPECIFIC TESTS (ALION FACILITIES)

	DEBRIS LOAD (based on Almaraz design basis for GSI-191)						**REMARKS**	
Test	**Fiber**	**Coating ZOI**	**Particulate ZOI**	**RMI ZOI**	**Chemical Precipitate AlOOH**	**UQ Coating No-ZOI**	**Test Conditions**	**Test Results (ΔP max=15 ft)**
100 %	**0.004 lb**	**1.6815 lb**	**0.382 lb**	**5.85/3.3 ft²**	**0.0127 lb**	**0.4125 lb**	**-**	**-**
1A	0	0	0	0	0	0	Clean screen	Low head loss 0.033 ft
1B	100%	100% Chips	100%	0	100%	20%	High part/fiber Bed at low V	No thin bed 0.121 ft
1B+	**1000%**	100% Chips	100%	0	100%	20%	Extra test Bed at high V	**0.41 ft**
2A	100%	100% Chips	100%	100%	100%	100%	Bed at high V	No RMI impact 0.31 ft
2B	**1000%**	100% Chips	100%	100%	100%	100%	Extra test Bed at high V	**2.14 ft**
3A	100%	100% Chips	100%	0%	100%	100%	Max.debris load Bed at high V	No thin bed 0.47 ft
3B	**1000%**	100% Chips	100%	0%	100%	100%	Bed at high V	0.97 ft
3B+	1000%	100% Chips	100%	0%	**200%**	100%		**5.5 ft** Screen failure
4	**500%**	100% Chips	100%	0%	**125%**	**100%**	Bounding test Bed at high V	**5.25 ft (1.6 m)**

Findings: As shown in the table, no *thin bed* formation was detected in any case. Tests #2B, #3B+ and #4 show a high ΔP because of the high extra debris load. When comparing tests #2A and #3A, RMI showed a behavior like a "debris catcher"; that is why #4 is the bounding case, without RMI. The impact of precipitants is important and very fiber-dependent, as show #3 tests.

Test #4 was stopped after 4.5 h from the beginning. Head loss can be extrapolated obtain the best estimate at 24 h after the accident to obtain, at most ΔP=1.61 m (5.28 ft).

The duration of the tests do not allow specific assessment of long-term corrosion effects.

Title:	Test Report: Head Loss Testing of a Prototypical Ascó/Vandellós Top-Hat Strainer Array/ Test Report: Chemical Effects Prototype Testing for Ascó/Vandellós.
Author:	R. Rosten
Company:	ALION Science and Technology
Document ID:	ALION-REP-ENER-4903-03/ ALION-REP-ENER-4903-04
Date:	Feb 2007 / March 2007
Document Length:	50 pages / 31 pages
Nature of Study:	Experimental
Phenomena Studied	Head loss across a debris bed on a top-hat strainer array

Abstract: These reports contain the results of the specific tests performed by the PWR Spanish NPPs of Ascó (I and II units) and Vandellós II to validate the hydraulic performance of the ENERCON "TOP-HAT" prototype strainers installed at the sumps to support the GSI-191 performance assessment. Initially, separate tests were performed for each plant, because of their different debris inventory, but the final chemical tests were performed according to a selected configuration bounding for both plants.

The purpose of the test was to collect and record differential pressures, temperature, flow rate, turbidity data and monitor for vortex while building a debris bed across a strainer array representative of a portion of the larger arrays installed at VA2/ASCÓ NPPs. The debris mixtures used include both fibrous and particulate debris up to the maximum analyzed load. The strainer modules tested were a triple Top-Hat design developed by Enercon Services Inc. consisting of hollow concentric cylinders mounted on a square base and comprised of stainless steel perforated plates. The top-hats modules tested were dimensionally similar to the modules installed at VA2/ASCÓ NPPs, taking into account during the scaling process the differences with the real installed strainers.

The tests took place at the Alion Hydraulics Lab. Test Tank, Warrenville, IL. A total of two sets were performed on November 15-16, 2006 and November 17, 2006. The chemical effects tests were performed on December 19, 2006.

Debris Types and Quantities: The debris load corresponded to the plant specific inventory that is supposed to be released in an accident and reduced according to the scaling factor (Ascó test #1; Vandellós test #2). The inventory of particulate released from coatings was calculated based on a nominal 10D qualified coatings, with additional unqualified coatings. The chemical test needed to recalculate the debris load because the scaling factor was reduced by using a 2x1 set and shorter prototypes, which is supposed to be more conservative as it is more likely to produce a homogeneous debris bed. The technical approach to check chemical effects consisted of adding the chemical precipitates according to a production curve intended to match the actual precipitate formation that would occur in a LOCA environment. The initial time for chemical addition was chosen (3.5 h) to represent the time after the accident when all of the non-chemical debris has been transported to the sumps and a portion of the chemical debris has formed. The only chemical test performed for both Ascó and Vandellós plants took the Vandellós debris chemical load as bounding, based on the assumption that all precipitates will behave similarly to one another in the test environment, as WCAP-16530-NP states related to sodium aluminum silicate and aluminum oxihydroxide. In the same way, the slightly greater approach velocity of this plant was selected to perform the test.

Below is shown the debris load and surrogates used in the tests:

a) Non-chemical

- NUKON was used as a surrogate for fiber debris, latent fiber debris and 5% mass fiber content of Thermolag (Ascó only), accordingly to the SER. The as-fabricated density of NUKON is 2.4 lb/ft^3.

- GROUND SILICA was used as a surrogate for epoxy and alkyd coatings, as well as the particulate (95%) portion of Thermolag (Ascó). This surrogate is spherical particulate ranging in size from 1 µm to 100 µm, with a significant portion less than 10 µm (while particulate material is assumed to fail as 10 µm spheres). This could be considered conservative in case of having a thin bed, because the ground silica would tend to produce a bed with a lower porosity and higher surface-to-volume ratio than debris comprised of coating material. On the contrary, if there is no thin bed formation, it is necessary to use the coating debris fragmented in chips.
- Dirt/Dust particulate surrogate was a blend of silica sand representative of PWR latent dirt/dust. The size distribution was prepared to be consistent with the latent dirt/dust size distribution provided in the SER Table 3-4. The debris load incorporates results from a latent debris walkdown performed for Ascó I unit only, and whose results were considered applicable to both Ascó II and Vandellós II units (200 lb obtained, from which 30 lb is fiber).
- Microtherm in containment is used in powder form for the tests. No surrogate is used.
- Chips Unlimited Paint Chips 4-6 mils thick consisting of a mixture of resins and other materials. Only for test $1C^{+}$.

b) Chemical precipitates

The debris load includes the precipitates based on WCAP-16530-NP (Feb-2006). The chemical debris inventory considered in the sumps after an accident is shown in the table below. The corresponding scaling factor applied to these values determined the test debris load:

Precipitate	**Test Debris Load (lb) (kg in brackets)**	
	ASCÓ	**VANDELLÓS II**
Sodium Aluminum Silicate ($NaAlSi_3O_8$)	12.13 (5.5)	22.93 (10.4)
Aluminum Oxihydroxide (AlOOH)	11.46 (5.2)	6.61 (3.0)
Calcium Phosphate ($Ca_3(PO_4)$)	3.09 (1.4)	0.44 (0.2)

Test setup: The prototype was mounted to a plenum assembly and arranged vertically in a 2x2 array and placed in a test tank (approx. 6 ft. tall, 6 ft. wide and 10 ft. long) capable of control flow circulation. The chemical test prototype was slightly different, with a 1x2 array. The test facility was intended to reproduce the ASCÓ/VA2 NPP strainer design with annular perforated plates of 2.4 mm diameter holes, with a scaled screen area based on the ratio of the prototype screen area and the net screen area unrestricted to flow (considering latent tag blockage). The scaling factors for both plants, Ascó and Vandellós II, which are each different, depends on the test (non-chemical and chemical, because the prototype set is different) and determines the flow points, selected to reproduce the actual maximum approach velocities of 0.011 ft/s and 0.012 ft/s for Ascó and Vandellós NPP, respectively, corresponding to the most limiting flow conditions (1 RHR+CS train, 1 only sump available). The tests with total debris load were performed first at these high velocity values and, after ΔP stabilization, initiate the flow sweep down and after back up. It was considered a conservatism to maintain the maximum flow once reached after flow sweep, because in the real case, as debris bed builds on the strainer, the flow rate will decrease, and the settling on the floor would increase. Turbidity data was recorded once per hour and visual observations were made to ensure that a vortex didn´t form during the test. The non-chemical debris was homogenously mixed in a container prior to addition to the flume and the whole load was added at the top of the flume. As test criteria, a stabilized head loss profile (less than 1% change over a given time period) and a minimum number of flume pool turnovers (5) were specified prior to flow sweeps and prior to test termination. The procedure includes stirring actions to avoid debris deposition in the flume volume.

Other test parameters were: Temperature: 29.4 ±5 ºC and pH according to actual plant conditions.

Findings: As shown in the table below, no *thin bed* formation was detected in any case, according to the low head loss observed, in spite of the equivalent bed thicknesses. It can be concluded that the enhanced strainers implemented provide enough NPSH margin. Vortexing was detected at maximum approach velocity, but no air entrainment. The high turbidity data associated with head loss stabilization at a low value indicate that suspended solids in the water were not filtered by the debris bed and passed through the uncovered strainer area with no impact on the head loss. Only the paint chip addition made the head loss increase sharply from the stabilized value at the 100% load without paint chips, the rationale for selecting $1C^+$ as the bounding case. Test $1B^+$ was stopped at 1 hour before the final batch addition as it showed a stabilized head loss value. However, the $1C^+$ test was ended approximately 5 hours after completion of test $1B^+$, at a time when the head loss was not entirely stabilized, but showed a decreasing slope. During the chemical tests the pH increased as batch additions were performed, until a final value of 10.6 was reached.

The duration of the tests did not allow the specific assessment of long-term corrosion effects.

ASCÓ/VANDELLÓS II NPP SPECIFIC TESTS (ALION FACILITIES)

	DEBRIS LOAD (based on NPP design basis for GSI-191)						**REMARKS**	
Test	**Fiber**	**Particulate Coatings (Q+UQ)**	**Particulate Latent dirt/dust**	**Particulate Thermolag ZOI**	**Particulate Microthem**	**Chemical Precipitate** $NaAlSi_3O_8$, AlOOH, $Ca_3(PO_4)$	**Test Conditions**	**Test Results (ΔP max=5.38/2.2 9ft)**
100 %	**4.91/ 4.21 lb**	**114.35/123.72 lb**	**24.54/22.09 lb**	**70.40/- lb**	**15.05/30.4 7 lb**	**0.87 lb, 0.25 lb, 0.017 lb**	**-**	**-**
1A	0	0	0	0	0	0	Clean screen. High velocity	Low head loss 0.055 ft
1B	100%	100%	100%	100%	100%	0	High ratio particulate /fiber	0.167 ft. No thin bed
2A	100%	100%	100%	-	100%	0		0.0148 ft. No thin bed
$1A^+$	0%	0%	0%	0%	0%	0%	Chem. test at high V	0.036 ft
$1B^+$	100% (1.23 lb)	100% (36.1 lb)	100% (6.46 lb)	-	100% (6.46 lb)	100%	Chem. test at high V	0.065 ft
$1C^+$	100% (1.23 lb)	100% (36.1 lb)	100% (6.46 lb)	-	100% (6.46 lb)	100%	$1B^+$ plus extra 36.1 lb of paint chips load	2.02 ft

GOALS for each test:

- 1A: Clean screen test. Max. ΔP for máx. approach velocity. No vortex formation.
- 1B: Thin bed effect sensitivity (0.135” equivalent bed thickness: the material is assumed to collect uniformly on the screens)
- 2A: Thin bed effect sensitivity (0.116” equivalent bed thickness)
- $1A^+$: Chemical test. Head loss for clean prototype 2x1 set for information only.
- $1B^+$: Load scaled for the chemical prototype 2x1 set. (0.115” equivalent bed thickness).
- $1C^+$: Extra load of 36.1 lb of paint chips added after test $1B^+$ finished.

Title:	CNT1: Summary of Experimental Results for Long-term Sump Clogging Tests
Author:	H. Ludwig
Company:	AREVA
Document ID:	NEPS-G/2007/en/0034
Date:	October 2008
Document Length:	27 pages
Nature of Study:	Experimental
Phenomena Studied:	Head loss across a debris bed on a flat strainer and on a FA-spacer. Backflushing actions efficiency to remove the filter cake. Long-term corrosion effects.

Abstract: This document contains the results of KWU Trillo Spanish NPP final specific tests to provide an experimental validation of the technical approach for GSI-191 performance assessment, intended to accommodate the specific plant boundary conditions, including the different materials used in CNT, which are not identical with the materials used in other KWU plants. The influence on the transport of different insulation materials, mixtures of fibrous and particulate insulation, as well as other substances, was also specifically investigated for CNT, in order to determine the transportation rates. In the same way, the penetration of the insulation material through the strainers assumed for further analysis and the deposition in the core had to be determined on a plant-specific basis, with consideration of the worst-case assumed for this plant.

The first experimental set was conducted in 2004, with the 9x9 grids then installed at the plant. CNT provided FRAMATOME ANP with several different materials in order to obtain the experimental pressure losses and to determine the correction factors for use in further calculations. The results confirmed that finer fibers lead to a higher pressure loss, showing the most unfavorable transportation behavior because of the less sedimentation. Based on that, this was selected as the worst-case material with regard to pressure loss and transportable amount. The results also confirmed the effect of increasing the pressure loss in the FA for the lower amount of material in the sump, corresponding to the maximum number of pumps running scenario, in which the slippage through the strainers towards fuel elements is enhanced. In these tests, neither THERMOLARG nor RMI were considered as debris sources. Similarly, coatings were considered not transportable to the sump. However, further experiments included a portion of paint chips in the debris load composition.

After conducting the first tests in 2004, some important modifications implemented in CNT made it necessary to develop a new experimental background corresponding to the new specific plant configuration (change to 3x3 grids, removal of MINILEIT isolation, replacement of conventional isolation by RMI, strainers reinforcement up to a strength design value of 400 mbar and some other housekeeping actions). The specific tests for CNT were conducted in September 2007 at the SUSI test facility in Erlangen. Long term effects (corrosion) were taken into account, as well as the effect observed in generic tests that a low entrainment of mineral fiber may lead to a higher deposition of fiber in the core. Taking into account that specific fiber in CNT show greater transport rates than the generically used in KWU plants (MD2) it was considered necessary to investigate this material.

The test program described here consisted of two tests performed, as follows:

- TI: It was assumed that the minimum amount of sump entrainment and the maximum strainer area to maximize the penetration through the sumps towards the core. With this aim, the considered configuration corresponded to all RHR running.
- TII: It was assumed the maximum amount of sump entrainment and the minimum strainer area to obtain the maximum pressure loss across the strainer. Only half of the sumps were simulated in order to minimize the filtering area, corresponding to the configuration of 2 trains on.

Debris Types and Quantities for CNT:

- Release of insulating material 269.8 kg, 50% of which arrives at the sump, 134.9 kg. For TI test, a total amount of 0.3 kg of insulation debris was considered, from generic tests results adapted to CNT specific case.
- Mineral wool mixture (53% M9 Manta Spintex 342 G125 + 32% M5 Mineral Wool Coquilla Rockwool + 15% M8 Ceramic Fiber CT-23BBFV). All fibers thermally aged and fragmented by high pressure water jet across wire mesh 6x6 mm.
- Latent debris: instead of quantification it was used the generic value of 2% of the maximum amount of released insulating material; made up of iron chips, concrete crumbs and paint chips. That is, 100 g and 200 g, respectively for TI and TII tests.

Test setup: The main features of the facility are indicated below:

- The scaling applied was 1:1 in the vertical direction and, accordingly with the configuration assumptions, the scaling factor is 1:54 and 1:27, respectively for TI and TII tests.
- Flat strainer: The size corresponds to the application of scaling factor to the configuration assumptions. This leads to 0.40 m^2 and 0.53 m^2, respectively for the TI and TII tests.
- Mesh size: 3x3 mm (wire thickness 1.2 mm)
- Flow rate was adjusted according to the scaling factor and the plant configuration assumed, so that the flow velocity through the strainer is the same as the plant-specific value, 2.8 cm/s.
- Downstream effects evaluation: The facility incorporates a two full-cross section-FA dummy and a bypass duct to control and get the expected plant-specific velocity at the FA spacer level. A small range pressure transmitter is connected to them.
- Test duration for the corrosion-long term effects evaluation: Generic corrosion tests show that pressure loss across the sump screen is stable in demineralized water, as well as in boric acid if no ferritic/galvanized materials are present. On the contrary, with such materials in areas of impinging break flow, the pressure loss can increase significantly, even at neutral pH. Corrosion effects start at 10 h and the combination of corrosion-erosion of the corroding material, like gratings, in the water jet can lead to the most severe pressure drop increase at about 60 h. However, with a sufficiently thick fibrous deposit, it is expected that the pressure drop can rise after 10 h by the interaction of corrosion and erosion leading to the adsorption at the fibers bed of the corrosion particles of zinc and iron compounds. To simulate this phenomena one galvanized grid (ferritic) of 0.2 m^2 was inserted and hit by the water jet, and one galvanized grid was submerged in the sump water of about 1.5 m^2. The second, submerged grid is thought to have no significance according to previous generic tests. The test lasts more than 10 h, time for the onset of corrosion effects, and the earliest after 48 h, once stabilized the pressure drop across the strainer and FA.

Other test conditions:

- Chemical conditions: Concerning corrosion it was considered conservative 50 ºC; 2200 ppm; 0.5 ppm LiOH; deionized water.
- Backflushing actions: Simulated a 3 kg/s backflushing procedure, according to the specific CNT case, which consists of injecting compressed air into the suction line of the recirculation pump.

Test procedure:

- **TI test**:

  Mass flow across sump strainer 14.8 kg/s, corresponding to 3 pumps running and applying a scaling factor of 1:54. The resulting velocity across sump strainer is 2.8 cm/s.

  Mass flow across FA-dummies 1.5 kg/s. Low flow velocities are considered conservative concerning the ability to keep fiber on the FA surface. Velocity at FA spacer lever was 5.2 cm/s.

  A portion of the debris load, both insulation and latent debris, was inserted at the same time of filling the tank. About 2 h later, at stationary conditions, a second portion was inserted. A mistake produced

an extra 50% additional latent debris load (rust, concrete and paint chips), what was considered conservative. Once the intended water level (2.6 m) was reached the mode was switched from injection to recirculation. 50 h later the mass flow rate was set to zero, simulating the minimum flow mode of the emergency core cooling pumps. The test facility kept in operation for about 55 h. No backflushing procedure was initiated because the filter cake fell down by itself.

- **TII test**:

  Mass flow across sump strainer 19.8 kg/s, corresponding to 2 pumps running and applying a scaling factor of 1:27. The resulting velocity across sump strainer is 2.8 cm/s.

  Mass flow across FA-dummies 1.5 kg/s. The velocity at the FA was 5.2 cm/s.

  The debris load was inserted at the same time as the filling of the tank. The amounts were the maximum considered, 134.9 kg insulation and 200 g (rust, concrete and paint chips) latent debris.

  Once the intended water level (2.6 m) was reached the mode was switched from injection to recirculation. After 48 h the backflushing procedure was initiated. The backflow was maintained for 40 s and then the pump was restarted. The test facility kept in operation for about 125 h.

Findings: The test results are identified below:

- Test TI showed that the pressure drop across the strainers rises significantly only after the second addition of debris load, at a rate that is reduced after 5 h. Ten h later a new increase can be observed, caused by the corrosion particles that have been deposited on the filter cake. A stable value is reached 25 h later, at around 48 mbar. When the pump stops the filter cake is removed, which terminates the pressure drop across the sump strainer. The restart of the pump is followed by a new increase of the pressure drop, caused by the deposition of the material resuspended in the sump water. The pressure drop observed across the FA is negligible, having detected no significant deposition of mineral wool in the FA spacer.
- Test TII showed a pressure drop across the sump strainer higher than that observed in test TI because of the higher debris load. The increase of the pressure drop doesn´t show the same linear behavior as that found in the TI test because of the different structure of the filter cake, made up of fibers lying on a fine particles bed initially deposited on the filter. This cake is more compacted and allows for the FA to be clean enough to maintain a negligible pressure drop. The cake remained attached to the strainer surface even when the pump stopped after 48 h, and only the backflushing procedure initiated 10 minutes later removes this cake. After restart of the pump the slippage of the resuspended fibers through the strainers lead to an increase of the pressure drop across the FA. The stable condition reached for a pressure drop of 40 mbar across the FA corresponds to a flow velocity of 2.7 cm/s, which is considered enough to remove the decay heat in the core. The maximum pressure drop across the strainer can be observed in a value around 135 mbar. The maximum pressure loss (calculated for 25 ºC) is 216 mbar, well below the design pressure loss of 400 mbar. At the end of the test the material deposited on different areas was measured. As an example, it was observed 555 g of material at the strainers, which corresponds to a fraction of 11%.

Main results:

- Maximum ΔP 135 mbar across sump strainer (in the test boundary conditions);
- Maximum ΔP 40 mbar across FA-spacer;
- Stable ΔP, no further increase;
- Backflushing is very efficient at removing the filter cake.

POST-LOCA CONTAINMENT POOL CHEMISTRY

Title:	Small-Scale Experiments: Effects of Chemical Reactions on Debris-Bed Head-Loss
Author:	B. Letellier et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	NUREG/CR-6868
Date:	March 2005
Document Length:	120 pages
Nature of Study:	Experimental
Phenomena Studied:	Chemical reactions and effects on head loss

Abstract: Small-scale head-loss flow tests and quiescent-immersion corrosion tests were performed to determine whether post-LOCA debris generation and sump-screen head loss in a PWR containment system can be affected by chemical interactions between the ECCS water, which contains boric acid and sodium hydroxide at elevated temperatures, and (1) exposed metal surfaces, (2) inorganic zinc-based paint chips, and (3) fiberglass insulation debris.

Findings: The principal findings of this study are that: (1) temperature-dependent corrosion of zinc metal can occur at typical temperatures and pH; (2) precipitation of dissolved iron, aluminum, and zinc in excess of their low solubility limits produces transportable gelatinous material that can cause additional pressure drops across a fibrous debris bed; (3) dissolved zinc can be leached from zinc-based coatings debris; and (4) silica can be leached from typical fiberglass insulation debris and may be an important constituent of the chemical system. However, the implied progression from metal corrosion to the ultimate precipitation of a flocculent material was not demonstrated conclusively. One alternative corrosion product observed in the zinc immersion tests was a crystalline surface growth, suggesting redeposition of zinc compounds initiated in a saturated solution. Electron microscopy, energy dispersive spectrometry, and x-ray diffraction methods were employed to determine the composition of the surface corrosion product.

In addition, the tests demonstrated that gelatinous material can transport to the PWR sump screen, where it can increase the head-loss across a fibrous debris bed. Despite these results, which demonstrated that harmful chemical products can form in the sump pool, a group of independent peer reviewers concluded that the results may not provide a complete understanding of sump pool chemistry because of the multitude of chemicals that are typically present in the sump pool. The ICET research documented in NUREG/CR-6914 was initiated to address this peer review feedback.

Title:	Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191
Author:	V. Jain. et al.
Company:	Center for Nuclear Waste Regulatory Analyses for the US NRC
Document ID:	NUREG/CR-6873
Date:	April 2005
Document Length:	200 pages
Nature of Study:	
Phenomena Studied	Chemical speciation of corrosion products

Abstract: This report documents thermodynamic simulations conducted to determine whether post-LOCA debris generation and consequent sump screen head loss in a PWR containment can be affected by chemical interactions between the ECCS/containment spray water and exposed materials. Based on the measured corrosion rates, estimated exposed surface area, and exposure time, the thermodynamics simulations indicated that the formation of dominant solid phases was controlled by the presence of Nukon low-density fiber insulation, aluminum, and concrete. The predicted dominant solid phases consisted of potentially amorphous silicate phases such as sodium aluminum silicate ($NaAlSi_3O_8$), calcium magnesium silicate [$Ca_2Mg_5Si_8O_{22}(OH)_2$], calcium silicate ($CaSiO_3$), and silica (SiO_2). The results were based on the solid phases included in the thermodynamic simulation program database. The formation of actual solid phases may be different depending on the reaction kinetics. Although some constituents decreased proportionally with increasing time, the solid $NaAlSi_3O_8$ phase continued to be a dominant solid phase at all times. The formation of $NaAlSi_3O_8$ in the presence of alkaline solutions could lead to gel formation, which could result in clogging of containment area sump pump suction strainers. Thermodynamic simulations indicate that in simulated alkaline containment water at pH 10 there is no significant difference in corrosion product formation as high-temperature and pressure conditions during the initial stages of a LOCA event approach steady-state atmospheric pressure conditions. This report provides insight into, and is useful in understanding, the evolution of solution chemistry and the formation of solid phases in integrated chemical effects tests at the University of New Mexico.

Findings: One notable simplification is that the model does not consider reaction kinetics, which may affect the types and amounts of chemical species that form. However, these initial thermodynamic simulation results indicate that (1) chemical interactions could lead to the formation of gelatinous products following a LOCA; (2) the important parameters for solid formation include solution pH and temperature (among others); and (3) the presence of low-density fiber insulation, aluminum, and concrete influences precipitation of chemical species. In addition, this report provides some initial understanding of the evolution of solution chemistry and the formation of solid phases in the ongoing ICET program. However, a better understanding of the impact of modeling assumptions and simplifications, including the effect of reaction kinetics, is necessary and could be obtained by comparing simulation results with ICET observations. The NRC staff conducted follow-on research to evaluate available analytical tools with the objective of gaining an understanding of their accuracies, uncertainties, and limitations within the sump environment.

Title:	GSI-191 PWR Sump Screen Blockage Chemical Effects Tests: Thermodynamic Simulations
Author:	J. McMurry et al.
Company:	Center for Nuclear Waste Regulatory Analyses for the US NRC
Document ID:	NUREG/CR-6912
Date:	December 2006
Document Length:	219 pages
Nature of Study:	Experimental and Computer simulation
Phenomena Studied:	Chemical speciation of corrosion products

Abstract: This report summarizes chemical modeling studies and experiments performed to support the resolution of GSI–191. Along with entrained debris components, the formation of secondary precipitates and gels have the potential to impede the performance of ECCS pumps, Containment Spray System pumps, or other components downstream of the sump strainer after a LOCA. The purpose of this study was to examine the use of chemical modeling software as a tool in predicting whether secondary precipitates would be likely to form in specific post-LOCA chemical environments. Within the limits of the available thermodynamic data for the model, the software also identified which solids would be expected to form and their quantities, and it indicated how the containment water chemistry was affected by these reactions. Several existing, widely available chemical modeling programs—EQ3/6 (Lawrence Livermore National Laboratory, 1995), OLI Systems Stream Analyzer (OLI Systems, Inc., 2005), The Geochemist's Workbench® REACT (RockWare, Inc., 2004), and PHREEQC (U.S. Geological Survey, 2003)—and their accompanying thermodynamic database files were evaluated to simulate the potential formation of precipitates under post-LOCA conditions. Detailed simulations were performed for five representative post- LOCA environments, in which alkaline or neutral borated containment waters interacted with metals, concrete, and insulation materials at 60 °C (140 °F) for times up to 720 h. The modeled conditions corresponded to the ICET experiments conducted at the University of New Mexico, and results of the experiments were used to benchmark and calibrate the simulations. The input water compositions for the simulations were estimated from specified initial containment water compositions, previously derived corrosion rates for the metals of interest, and dissolution rates from new experiments involving insulation materials and concrete. The modeling programs EQ3/6 and PHREEQC were used to perform blind predictions of the experiment results. Analytical data and qualitative observations of precipitation (or lack of it) from the ICET experiments were used to refine the conceptual model. Revised dissolution rates were obtained from additional experiments at the Center for Nuclear Waste Regulatory Analyses, after which informed simulations were performed using StreamAnalyzer and PHREEQC. A more detailed simulation considered the gradual changes in chemistry of the solution water over time, based on kinetic reaction rates with the reactive materials and ongoing equilibration (precipitation) with oversaturated secondary phases.

Findings: The study determined that the most important requirements for developing more accurate chemical effects simulations were (i) a realistic estimate of starting water compositions and dissolution rates, and (ii) the availability of an adequate set of thermodynamic data, particularly for amorphous or metastable solids that would be expected to form under the simulated conditions. The study concluded that the codes as tested were broadly useful in assessing whether precipitation of secondary solid phases was likely under the specified conditions and the quantity of material that was predicted to form. In applying chemical modeling software to other plant-specific sets of conditions, the effectiveness of the simulations and confidence in their predictions would be considerably improved by a more complete characterization of source-term materials and release rates for the conditions of interest, and by development of an appropriate thermodynamic database for modeling purposes that includes more realistic amorphous or metastable solids for the conditions of interest.

The results of the study are useful in broadly assessing chemical precipitate effects in a typical containment pool. However, limitations in the thermodynamic and kinetic database used to represent PWR containment environments inhibit the development of a robust, predictive model.

Title:	Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191
Author:	J. H. Park et al.
Company:	Argonne National Laboratory for the US NRC
Document ID:	NUREG/CR-6913
Date:	December 2006
Document Length:	161 pages
Nature of Study:	Experimental
Phenomena Studied:	Chemical corrosion products

Abstract: This summary report describes studies conducted at Argonne National Laboratory on the potential for chemical effects on head loss across sump screens. Three different buffering solutions were used for these tests: trisodium phosphate (TSP), sodium hydroxide, and sodium tetraborate. These pH control agents used following a LOCA at a nuclear power plant show various degrees of interaction with the insulating materials calcium silicate and NUKON. Results for calcium silicate dissolution tests in TSP solutions, settling rate tests of calcium phosphate precipitates, and benchmark tests in chemically inactive environments are also presented. The dissolution tests were intended to identify important environmental variables governing both calcium dissolution and subsequent calcium phosphate formation over a range of simulated sump pool conditions.

The results from the dissolution testing were used to inform both the head loss and settling test series. The objective of the head loss tests was to assess the head loss produced by debris beds created by calcium silicate, fibrous debris, and calcium phosphate precipitates. The effects of both the relative arrival time of the precipitates and insulation debris and the calcium phosphate formation process were specifically evaluated. The debris loadings, test loop flow rates, and test temperature were chosen to be reasonably representative of those expected in plants with updated sump screen configurations, although the approach velocity of 0.1 ft/s used for most of the tests is 3–10 times that expected in plants with large screens. Other variables were selected with the intent to reasonably bound the head loss variability due to arrival time and calcium phosphate formation uncertainty. Settling tests were conducted to measure the settling rates of calcium phosphate precipitates (formed by adding dissolved Ca to boric acid and TSP solutions) in water columns having no bulk directional flow.

For PWRs where NaOH and sodium tetraborate are used to control sump pH and fiberglass insulation is prevalent, relatively high concentrations of dissolved aluminum can be expected. Tests in which the dissolved Al resulted from aluminum nitrate additions were used to investigate potential chemical effects that may lead to high head loss. Dissolved Al concentrations of 100 ppm were shown to lead to large pressure drops for the screen area to sump volume ratio and fiber debris bed studied. No chemical effects on head loss were observed in sodium tetraborate buffered solutions even for environments with high ratios of submerged Al area to sump volume. However, in tests with much higher concentrations of dissolved Al than expected in plants, large pressure drops did occur. Interaction with NUKON/ calcium silicate debris mixtures produced much lower head losses than observed in corresponding tests with TSP, although tests were not performed over the full range of calcium silicate that might be of interest.

Findings: Overall, the test results indicated that:

1. Significant head-loss can result from chemical reaction products formed in pool environments buffered with TSP or sodium hydroxide, as well as in pool environments containing significant quantities of dissolved aluminum;
2. Pool environments buffered with sodium tetraborate did not exhibit head-loss attributable to chemical effects;
3. Complete dissolution of calcium silicate insulation could take 1–4 days or more, depending on the dissolution rate of the trisodium phosphate buffer and the concentration of calcium silicate insulation; and

4. Precipitates can agglomerate at higher dissolved calcium concentrations.

These results provide some initial understanding and insights regarding the head-loss attributable to chemical byproducts observed in the ICET program, as well as the other sump pool environments not examined in that program.

Title:	Integrated Chemical Effects Test Project
Author:	J. Dallman et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	NUREG/CR-6914, Volumes 1 to 6
Date:	December 2006
Document Length:	
Nature of Study:	Experimental
Phenomena Studied	Simulation of chemical environment in PWR containment pools

Abstract: The ICET project documented in this report was jointly sponsored by the US NRC and the nuclear energy industry. The tests were performed at the University of New Mexico, under the direction of Los Alamos National Laboratory.

Five tests conducted in the ICET project apparatus attempted to simulate the chemical environment present inside a pressurized-water-reactor containment water pool after a LOCA. The chemical environment within the tank included boric acid, lithium hydroxide, and hydrochloric acid. TSP, sodium hydroxide, or sodium tetraborate was added to each test. The tests were conducted for 30 days at a constant temperature of 60 °C. The materials tested within this environment included representative amounts of submerged and unsubmerged aluminum, copper, concrete, zinc, carbon steel, and insulation samples (either 100% fiberglass or a combination of 80% calcium silicate and 20% fiberglass by volume). Representative amounts of concrete dust and latent debris were also added to the test solution. Water was circulated through the bottom portion of the test chamber during the entire test to achieve representative flow rates over the submerged specimens. Test solution pH ranged from just over 7 in Tests #2 and #3 to just over 8 in Test #5, and it reached almost 10 in Tests #1 and #4. Test solution chemistry varied from test to test, depending on the starting conditions and amount of material corrosion or leaching. Either particulate, flocculent, or film (webbing) deposits were observed in the fiberglass after each test. Visible changes were also seen on the metal coupons in each test. Corrosion was evident on both submerged and un-submerged coupons. The amount of sediment recovered was directly proportional to the amount of particulate debris added to the test. Tests #3 and #4 had considerably more sediment than did the other tests, primarily because of the cal-sil dust added to the tank. The top layer of Test #3 sediment contained a gel-like material. When cooled to ambient temperature, test solution in Tests #1 and #5 contained precipitates. Test solution from those two tests also exhibited a non-Newtonian tendency for shear thinning with increasing strain rate when the solution was cooled to ambient temperature.

Findings: This six-volume report documents the results of this program. Volume 1 provides a summary and comparison of the important observations and measurements among all of the tests, while Volumes 2-6 provide detailed data reports for each of the five tests. As documented, the ICET results indicate that:

1. Chemical reaction products with varied quantities, consistencies, attributes, and apparent formation mechanisms were found in each unique ICET environment;
2. Containment materials (metallic, non-metallic, and insulation debris), pH, buffering agent, temperature, and time are all important variables that influence chemical product formation; and;
3. Changes to one important environmental variable (e.g., pH adjusting agent, insulation material) can significantly affect the chemical products that form.

Recommendations: Many practical lessons were learned during ICET Test #1 that may serve to improve the quality of information obtained in subsequent tests and the efficiency with which daily operations can be managed. The following items were discussed with the NRC/industry sponsors, with input from LANL and UNM investigators for consideration as minor modifications to the ICET Test #2 plan and procedures.

- Continue the practice of daily water sampling, but reduce the frequency of comparison between filtered and unfiltered samples if the differences again become negligible. In Test #1, there was no

measurable difference in TSS, viscosity, or elemental composition after the bulk turbidity dropped;

- Given the continued increase in the rate of observed precipitation in extracted samples and the continued increase in aluminum concentrations beyond 15 days, plan all subsequent tests for a duration of 30 days;
- Acquire duplicate water baths to improve control of water temperature for extracted samples waiting for viscosity and turbidity measurement. The post-Test #1 interest in controlled temperature precipitation studies further justified the need for this equipment;
- Continue the practice of daily water sample viscosity measurements, but eliminate the requirement for replicate measurements if the same level of precision is achieved. Variations between repeated measurements under the Test #1 protocol were less than 1%;
- The presence of deposits on exposed surfaces of the fiberglass blankets and the decline of silicon concentrations in solution raised questions about realistic exposure of fiberglass debris to the test solution. SS mesh sample bags were prepared for Test #1 to confine the fibers, but deposits were noted only on fiber layers next to the mesh, even for mesh envelopes embedded in larger blankets;

For Test #2, construct a small mesh sample box (in addition to the original bags) to hold a loose collection of fiber that is not compressed on all sides.

Wrap a 1/2-in. - to 1-in.-thick mesh bag around the lower 4 in. of the drain screen to expose small amount of fiber to higher water velocities.

Title:	Aluminum Chemistry in a Prototypical Post-Loss-of-Coolant-Accident, Pressurized-Water-Reactor Containment Environment
Author:	M. Klasky et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	NUREG/CR-6915
Date:	December 2006
Document Length:	113 pages
Nature of Study:	Small-scale experiments, analysis, and literature review
Phenomena Studied	Behavior of aluminum in PWR containment pools

Abstract: An analysis of the ICET experiments has been performed by a comprehensive examination of both the test solutions and precipitates. In addition, a comprehensive review of the literature has been performed to assist in explaining the behavior of aluminum in alkaline solutions. The objective of this analysis was to elucidate the behavior of precipitate that formed when the ICET Tests 1 and 5 solutions were allowed to cool so that the behavior of other solutions with different conditions, i.e., pH, temperature, etc., could be predicted throughout the pressurized water reactor following a LOCA. This examination included supplemental analytical measurements using x-ray diffraction, ^{27}Al and ^{11}B nuclear magnetic resonance for both liquid and solid states, and quasi-elastic light-scattering measurements. Surrogate solutions were developed and compared with the analytical measurements of the ICET Tests 1 and 5 solutions. Finally, the characterization of the particle sizes and corrosion properties, including the corrosion mechanism and the corrosion rate of aluminum under LOCA conditions, has been elucidated. The current study should allow for the development of a head-loss correlation using the existing cake filtration theory, which could be used in conjunction with a corrosion model to predict system performance following a LOCA.

Findings: This report provides information about the characterization of particle sizes and corrosion properties of aluminum under LOCA conditions. It also provides information that will allow extrapolation of ICET behavior to predict the behavior of aluminum under the various pH and temperature conditions that might exist in PWR plants following a LOCA.

LANL also conducted small-scale experiments and a literature review to develop a more thorough understanding of the corrosion rates, precipitation mechanisms and precipitate characteristics of aluminum and aluminum compounds in alkaline solutions that are representative of post-LOCA PWR containment environments. This study helped explain the physical characteristics and behavior of the chemical precipitates that were observed in the ICET #1 and #5 test solutions, and provided information that could be used to predict the behavior of aluminum under various pH and temperature conditions that may exist in PWR containment pools following an accident.

Title:	Supplementary Leaching Tests of Insulation and Concrete for GSI-191 Chemical Effects Program
Author:	J. McMurry and X. He
Company:	Center for Nuclear Waste Regulatory Analyses for the US NRC
Document ID:	Technical Letter Report IM 20.12130.01.001.320
Date:	November 2006
Document Length:	57 pages
Nature of Study:	Experimental
Phenomena Studied	Chemical leaching in PWR containment pools

Abstract: The purpose of this study was to conduct supplementary and confirmatory dissolution and precipitation experiments for insulation materials and concrete using an approach similar to the one used by Westinghouse in experiments for WCAP-16530-NP. The Westinghouse study was designed to provide a consistent modeling approach to determine the types and amounts of chemical precipitates that might form for a specific set of containment materials under expected post-LOCA conditions of pH and temperature. Dissolution rates for each material class were estimated from the experiment leachate compositions, which had been sampled at three different exposure times for this purpose. In applying the chemical model for a specific plant environment, the rates are used to calculate the concentration of a solution after reaction with the solid materials in a post-accident environment for a specified amount of time. Rather than calculate how much, if any, solid phases might precipitate from a given solution composition, the model assumes that all of the dissolved material precipitates in unidentified secondary solids. This assumption, which is based on the relatively low solubility of several key solid phases of aluminum, calcium, and silicon, provides a conservative estimate of the maximum mass of secondary precipitates that could form from a given solution composition.

Findings: For this study, samples were chosen from five of the insulation material classes. The testing focused on the conditions that previously had produced the most concentrated solution for each material class, i.e., Cal-Sil, Fiber Frax Durablanket, Temp-Mat, and “high density” fiberglass.

Using an approach developed for GSI–191 for a modeling study of post-LOCA chemical effects (McMurry et al., 2006), the compositions of the leachates also were examined using a chemical modeling code and database of likely precipitates to determine if the leachates were oversaturated with respect to solid phases that had not precipitated for kinetic reasons. Overall, the test results reported by CNWRA supported that assumption.

Title:	Follow-On Studies in Chemical Effects Head-Loss Research: Studies on WCAP Surrogates and Sodium Tetraborate Solutions
Author:	C. B. Bahn et al.
Company:	Argonne National Laboratory for the US NRC
Document ID:	Technical Letter Report (ADAMS ML070580086)
Date:	February 2007
Document Length:	21 pages
Nature of Study:	
Phenomena Studied	Chemical environment in PWR containment pools

Abstract: In this study, a series of tests were performed to evaluate (1) the head-loss performance of the surrogate precipitates recommended in Westinghouse WCAP-16530-NP, relative to the precipitates generated in NRC-sponsored chemical effects tests, and (2) the long-term solubility limits and head-loss characteristics of aluminum precipitates in sumps buffered with sodium tetraborate.

Findings: The WCAP surrogate tests demonstrated that aluminum precipitates prepared in accordance with the WCAP procedure were effective in creating head-loss when deposited on a sump screen laden with a fiber bed and, therefore, may be representative of precipitates formed in the containment pool. The quantity of precipitate required to generate high head-loss was equivalent to an aluminum concentration that is 5% above the solubility limit.

The sodium tetraborate buffer experiments demonstrated that the solubility limit for aluminum compounds in a sump pool buffered with sodium tetraborate at 27 °C (80 °F) appears to be 50 ppm. Consequently, aluminum concentrations above 50 ppm begin to precipitate as aluminum oxyhydroxides.

Title:	Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191
Author:	W. J. Shack
Company:	Argonne National Laboratory for the US NRC
Document ID:	Technical Letter Report (ADAMS ML080650350)
Date:	February 2007
Document Length:	9 pages
Nature of Study:	
Phenomena Studied	Chemical environment in PWR containment pools

Abstract: There are two major steps in the WCAP process for assessing chemical effects. One is the calculation of the amount of materials dissolved into the sump and the other is production of a realistic surrogate product. The WCAP makes the conservative assumption that the precipitation products are of low solubility and all the dissolved species that can form precipitates, do.

Findings: For the most part the WCAP calculation of releases seems appropriate. The model of Ca release includes a saturation term that is not relevant if phosphate is present, but this has little practical impact for the levels of Ca of interest in practice.

The recommended Al release model significantly underestimates releases in ICET−1 over the first 15 days of operation and underestimates the dissolution data in the WCAP. Unless passivation of the aluminum or saturation of the dissolved Al occurs, it may underestimate Al releases over the entire history in Al/NaOH environments. The release model is overly conservative in environments with significant Ca.

For Al/NaOH environments an alternate release model is given in the WCAP (Equation 6-1) that seems to better reflect the available data. It should be noted that the coefficients for this equation in Rev. 0 of the report are incorrect. This release model seems to overpredict releases in sodium tetraborate environments. However, in such environments the 50 ppm level observed in the ICET–5 tests may be considered bounding for virtually all plants. The assumption that all dissolved Ca in TSP environments and all dissolved Al in other environments form precipitates is reasonable for the Ca/TSP case, but overly conservative in the Al/NaOH and Al/STB environments. Accurate prediction of solubility limits is difficult since they are sensitive to the choice of the solubility constant and pH.

The WCAP recognizes that the precipitation products developed by the proposed surrogate process are sensitive to the mixing conditions, especially the concentration, and imposes limits on the concentration. However, no good arguments are presented as to why these limitations are good enough. However, whatever differences there are between these products and the “real” products are, the surrogate products are so effective in producing head loss, that arguments over whether their capability to produce head loss is conservative or non-conservative seem moot.

Title:	Evaluation of Chemical Effects: Studies on Precipitates Used in Strainer Head Loss Testing
Author:	C.B. Bahn et al.
Company:	Argonne National Laboratory for the US NRC
Document ID:	Technical Letter Report (ADAMS ML080600223)
Date:	January 2008
Document Length:	37 pages
Nature of Study:	Experimental
Phenomena Studied	Chemical precipitate properties; head loss

Abstract: The purpose of these tests was to evaluate the properties of chemical precipitates that are used in sump strainer head loss testing by certain nuclear industry test vendors. Tests at ANL consisted of vertical loop head loss tests to evaluate precipitate filterability and bench-type tests that investigated precipitate characteristics such as particle size and settlement rate and solubility. Specific precipitates that were evaluated included aluminum oxyhydroxide (AlOOH) and sodium aluminum silicate (SAS) prepared according to the WCAP-16530-NP directions, along with precipitates formed from injection of sodium aluminate, calcium chloride, and sodium silicate according to the Control Components Inc. (CCI) test approach.

Findings: ANL had previously performed a vertical head loss loop with the WCAP AlOOH precipitate. An additional head loss test using the WCAP AlOOH surrogate but at lower concentration was performed for this report. The test confirmed that the surrogate is very effective in increasing the head loss across a glass fiber bed. The current result is consistent with that of the earlier ANL head loss test with the WCAP surrogate. In the ANL loop, only 1.5 ppm Al equivalent of surrogate (29.6 g/m^2) can completely plug a glass fiber bed. Tests with the WCAP SAS surrogate show that it is not quite as efficient as the WCAP AlOOH surrogate in increasing head loss. At low levels, the SAS surrogate tends to dissolve, especially in high purity water. However, in tap water, only 2 ppm Al equivalent SAS surrogate (172 g/m2) is needed to generate a significant head loss. The particle sizes of the WCAP AlOOH surrogates range from 13-72 μm depending on the Al concentration in the mixing tank. For the same mixing concentration, the particle sizes of the SAS surrogate are larger than those of the AlOOH surrogate. The settling rates of the surrogates are strongly dependent on particle size, and the rates are reasonably consistent with those expected from Stokes Law or colloid aggregation models.

Surrogates were also created using the CCI procedure. Although aluminum and silicate are both added to the solution, the aluminum precipitate formed by the procedure probably consists primarily of aluminum hydroxide, since it would tend to form first in the CCI procedure. The characteristics of the precipitates strongly depend on whether in the solutions are made using high purity or ordinary tap water. In borated high purity water the aluminum hydroxide precipitates form extremely small particles with sizes ranging from 100-300 nm depending on the total Al concentration. These particles are much smaller than the WCAP surrogates. Literature results suggest that the sodium silicate that is present in the CCI procedure could act as a deflocculant for the aluminum hydroxide precipitates. In borated tap water, the aluminum hydroxide precipitates are much larger than those formed in the solutions using high purity water, although they are still somewhat smaller than the WCAP surrogates. The effect of tap water on precipitate size may be attributable to the relatively high ionic strength of tap water due to dissolved cations like Ca^{2+}, Mg^{2+}, Na^+ and the presence of anions like SO_4^{2-}, Cl^-, etc. The loop head loss tests showed that extremely small aluminum hydroxide precipitates (100-300 nm) produced using high purity water do not cause significant head loss while the 5.7 ppm Al equivalent of CCI-type precipitate made in tap water exhausted the pressure drop capacity of the ANL vertical loop.

Title:	Evaluation of Long-term Aluminum Solubility in Borated Water Following a LOCA,
Author:	C. B. Bahn et al.
Company:	Argonne National Laboratory for the US NRC
Document ID:	Technical Letter Report (ADAMS ML081550484)
Date:	February 2008
Document Length:	31 pages
Nature of Study:	Experimental
Phenomena Studied	Long-term aluminum solubility

Abstract: Long-term aluminum hydroxide ($Al(OH)_3$) solubility tests were conducted in solutions containing 2500 ppm boron (B), and an aluminum (Al) concentration ranging from 40-98 ppm using aluminum nitrate or sodium aluminate as the Al source. The solution pH values were adjusted to achieve target pH ranging from 7.0 to 8.5. The solution temperature was cycled to obtain a temperature history more representative of ECCS temperatures during operation in the recirculation mode after a LOCA in a PWR.

Findings: The observed Al solubility as a function of temperature and pH was close to predicted results for amorphous precipitates in a borated environment, which are higher than the solubility expected for crystalline forms of aluminum hydroxide. Precipitates were observed to form either as fine, cloudy suspensions, which showed very little tendency to settle, or under certain conditions, as flocculated precipitates, which were formed at the inner surface of the test flasks. The flocculated precipitates have an average diameter of 4-6 µm.

Title:	Evaluation of Head Loss by Products of Aluminum Alloy Corrosion
Author:	C. B. Bahn et al.
Company:	Argonne National Laboratory for the US NRC
Document ID:	Technical Letter Report (ADAMS ML082340870)
Date:	August 2008
Document Length:	71 pages
Nature of Study:	Experimental
Phenomena Studied	Head loss due to aluminum alloy corrosion

Abstract: Previous ANL head loss tests for $AI(OH)_3$ precipitates that can potentially form in sump solutions with high levels of dissolved aluminum (Al) have been performed with surrogates proposed by industry or by forming precipitates in situ with aluminum nitrate, $Al(NO_3)_3$ as the source of dissolved Al. In a post-LOCA environment, however, the precipitates would be formed in situ with the source of the Al being dissolution of Al by corrosion of Al metal and NO_3^- would not likely be present in amounts comparable to those encountered when $Al(NO_3)_3$ is the source of dissolved Al.

Findings: The objective of these tests was to compare head loss associated with precipitate formation from aluminum coupon corrosion with those using WCAP-16530-NP precipitates or with precipitates formed in situ as a result of chemical injection. The head loss tests were performed in the ANL vertical loop with 6061 Al alloy and "commercially pure" 1100 Al plates immersed in borated solution. The Al release rate from 6061 Al alloy in borated water at pH=9.35 (at room temperature) and 140 °F with a flow rate of 0.1 ft/s was similar to predictions based on data from bench top tests and low-flow rate tests with 1100 and 3003 Al alloys. However, the Alloy 1100 corrosion rate was higher than predicted based on data from benchtop tests and appeared to be flow dependent.

Alloy 6061 allowed to corrode in a flowing loop created a significant head loss at an Al concentration of 116 ppm with a pH of 9.35 and a temperature of 140 °F. An additional increase in the head loss was observed when the temperature was lowered from 140 to 80 °F. Post-test examination revealed that grayish black particles were trapped in the glass fiber bed.

Stagnant bench top corrosion tests with Alloy 6061 also showed grayish black particles, which were released from the coupon surfaces rather than being generated as a precipitate from the solution. Based on microscopic analyses, it was concluded that the grayish black particles are intermetallic particles present in the alloy that are released by corrosion of the alloy matrix. The intermetallic particles are primarily (FeSiAl) ternary compounds ranging in size from a few tenths of a micrometer to 10 micrometers. ANL bench top tests and other loop tests show that the solubility limit' for $Al(OH)_3$ at pH=9.35 (at room temp.) and 140 °F is significantly greater than 116 ppm Al. This indicates that the head loss at 140 °F was induced by the intermetallic particles present in the 6061 Al alloy. As the temperature of the loop was decreased additional head loss was experienced due to the formation of $Al(OH)_3$ from the decrease in temperature i.e., the dissolved aluminum exceeded its concentration limit at the lower temperature.

With an Al concentration of 118 ppm in the loop from corrosion of 1100 Al plates, no significant increase in head loss was observed at 140 °F. Post-test examination for the glass fiber bed and bench top test results confirmed that Fe-Cu enriched intermetallic particles were present in the 1100 Al, which were released and captured in the bed during the loop test. The differences in head loss behavior associated with the intermetallic particles may be attributed to the fact that the sizes of the intermetallic particles in 6061 Al alloy are typically larger than those in 1100 Al alloy. At the Al concentration of 118 ppm no significant increase in head loss was observed in the 1100 Al test until the temperature was decreased to 100 °F. This increase appears to be induced by Al hydroxide precipitation, not by intermetallic particles. Once the head loss began to increase, a rapid increase in head loss was observed even though the temperature was increased from 100 to 120 °F.

Title:	Test Facility Regarding the Chemical Behavior of Debris Material
Authors:	I. Ganzmann et al.
Company:	AREVA NP GmbH
Document ID:	Various
Date:	From 2008 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Pressure loss on sump strainer screens; debris slippage through sump strainers; debris behavior at higher temperatures; debris behavior depending on water chemistry; long term effects

Abstract: In 2008 AREVA NP Technical Center extended its Thermal Hydraulic Platform by two separate effect test facilities. The facilities are designed to investigate the behavior of debris mixtures concerning pressure loss evaluation at strainers and material behavior (decomposition) at higher temperatures in the presence of chemical agents (e.g. boron acid). Tests can be performed during long term for several weeks.

Test Facility Capabilities:

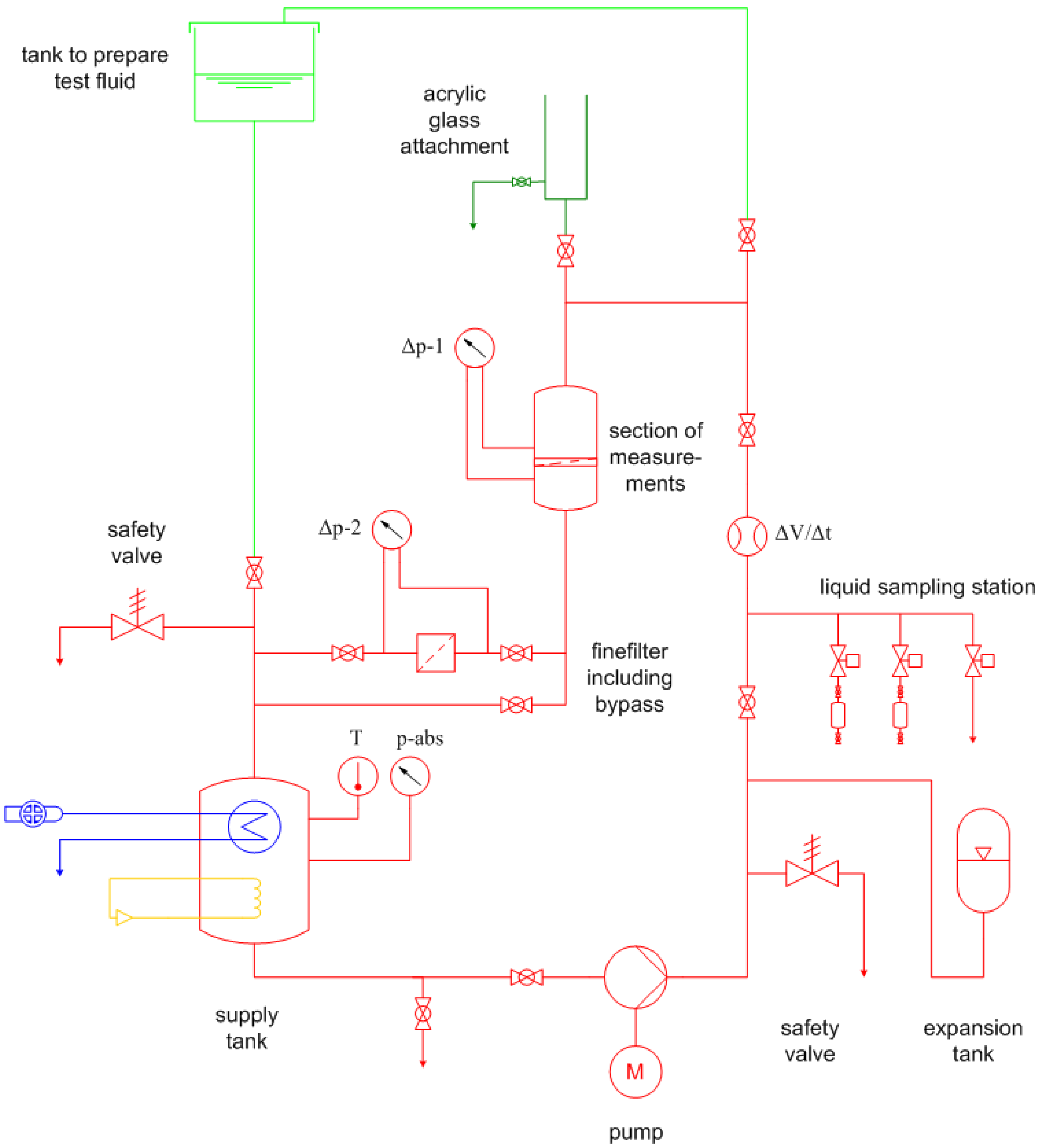
Scaling:	Small scale
Test section:	Tube DN100 equipped with filter section
	Austenitic Material
Operating pressure:	3 bar max.
Operating temperature:	120 °C max.
Mass flow:	1 kg/s max.
Strainer screen design:	Wire mesh or perforated plates
Debris preparation:	Fibers heated at 300 °C for 24 h, mechanically or high pressure water jet fragmented; particulates (e.g. paint, concrete, Microtherm) sieved to different size classes
Measured variables:	Flow rate (strainer) online
	Water temperature online
	Pressure loss strainer online
	System pressure online
	Semi-automatic sampling system
	Water solid content offline after sampling
	Water ion concentration offline after sampling

Tests performed:

A number of tests have been performed since 2008 with different focus:

- Pressure loss evaluation on sump strainer screens for debris mixtures in dependence on mixture composition, water temperature and flow velocity (self compression of debris bed);

- Behavior of (mostly fibrous) debris material depending on water temperature and presence of chemical agents (e.g. boron acid). Evaluation of fiber decomposition, dissolved ions (e.g. Si) and pressure loss.



Test Facility Schematic

Test Facility Picture

Title:	Peer Review of GSI-191 Chemical Effects Research Program
Author:	P.A. Torres
Company:	US NRC
Document ID:	NUREG-1861
Date:	December 2006
Document Length:	221 pages
Nature of Study:	Peer review
Phenomena Studied	Chemical effects research

Abstract: This report describes the chemical effects peer review assessment process and summarizes its significant findings. It is important to mention that this peer review is not a consensus review. Each reviewer was asked to provide an individual evaluation based on his or her particular area of expertise. The research projects addressed by the peer review included ICET and ICET follow-up testing and analysis conducted at Los Alamos National Laboratory, chemical speciation prediction conducted through the Center for Nuclear Waste Regulatory Analyses at Southwest Research Institute, and accelerated chemical effects head loss testing conducted at Argonne National Laboratory.

The chemical effects peer review evaluated the technical adequacy and uncertainty associated with the RES-sponsored research results, and identified outstanding chemical effects issues. The final assessment reports from the peer reviewers are included as appendices to this NUREG-series report.

Findings: This report documents a peer review to evaluate the technical adequacy and uncertainty associated with the RES-sponsored chemical effects research. Toward that end, five reviewers with expertise in related fields critiqued the following chemical effects research programs:

- Integrated chemical effects tests conducted at LANL (NUREG/CR-6914)
- Chemical testing and analysis conducted at LANL (NUREG/CR-6915)
  Chemical speciation prediction conducted through CNWRA at Southwest Research Institute (NUREG/CR-6912)
- Accelerated chemical effects head-loss testing conducted at ANL (NUREG/CR-6913)

The peer reviewers identified additional chemical effects phenomena for consideration. NRC staff is evaluating these phenomena in a manner consistent with the general resolution of technical issues related to GL 2004-02. The results of that evaluation will be documented in reports.

Title:	Phenomena Identification and Ranking Table Evaluation of Chemical Effects Associated with Generic Safety Issue 191
Author:	R. Tregoning et al.
Company:	US NRC
Document ID:	NUREG-1918
Date:	February 2009
Document Length:	334 pages
Nature of Study:	PIRT evaluation
Phenomena Studied	Chemical effects research

Abstract: Both the NRC and industry have sponsored research to provide additional information and develop some guidance for evaluating chemical effects. The NRC convened an external peer review panel to review the NRC-sponsored research conducted through the end of 2005 and to identify and evaluate additional chemical phenomena and issues that were either unresolved or not considered in the original NRC-sponsored research.

A phenomena identification and ranking table (PIRT) exercise was conducted to support this evaluation in an attempt to fully explore the possible chemical effects that may affect emergency core cooling system performance during a hypothetical LOCA.

Findings: The PIRT was not intended to provide a comprehensive set of chemical phenomena within the post-LOCA environment. Rather, these phenomena should be combined with important findings from past research and informed by ongoing research results. It is anticipated that knowledge gained by ongoing and completed research will be considered along with the PIRT recommendations to identify and resolve existing knowledge gaps so that a more accurate chemical effects evaluation can be performed.

The PIRT panel identified several significant chemical phenomena. These phenomena pertain to the underlying containment pool chemistry; radiological considerations; physical, chemical, and biological debris sources; solid species precipitation; solid species growth and transport; organics and coatings; and downstream effects. Several of these phenomena may be addressed using existing knowledge of chemical effects in combination with an assessment of their implications over the range of existing generic or plant-specific post-LOCA conditions. Other phenomena may require additional study to understand the chemical effects and their relevance before assessing their practical generic or plant-specific implications.

Title:	Final Report-Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant
Author:	C.H. Delegard et al.
Company:	Pacific Northwest National Lab for the US NRC
Document ID:	NUREG/CR-6988
Date:	March 2009
Document Length:	125 pages
Nature of Study:	Evaluation
Phenomena Studied	Chemical environment in PWR containment pools

Abstract: Experimental testing and other studies have been completed to determine the impacts of cooling water composition, debris sources, and materials corrosion on the nature of the debris, presuming no fuel cladding failure. However, historical, ongoing, and planned testing and analysis studies were evaluated, as documented in NUREG-1918 and 10 further topics related to chemical effects were identified that deserve additional consideration.

The 10 topical areas are radiation effects (particularly on material corrosion), differences in concrete carbonation between tested systems and existing containment structures, effects of alloy variability between tested and actual materials, galvanic corrosion effects, biological fouling, co-precipitation, and other synergistic solids formation effects, inorganic agglomeration, crud release effects (types and quantities), retrograde solubility and solids deposition, and organic material impacts. Sufficient data or prior related studies were available to sufficiently address some of the questions raised in the 10 topic areas. However, within these 10 broad areas, topics meriting additional consideration also were identified and are the focus of this report.

Findings: The PIRT exercise in 2006 provided a comprehensive evaluation of possible chemical effects in a post-LOCA containment environment. The PIRT was primarily focused on identifying phenomena that both may potentially affect ECCS functionality and also were not well understood within the context of the post-LOCA environment in light of recent and ongoing NRC and industry-sponsored research. The PIRT process first identified over 100 phenomena, 41 of which were judged to be highly significant by at least one PIRT team member. The staff then evaluated these 41 phenomena, and identified approximately 16 of these issues that are potentially deleterious to ECCS performance and merited additional analysis by the NRC to understand their significance. These issues were combined into the following 10 distinct topics: radiological effects, concrete carbonation, alloy corrosion, galvanic corrosion, biological fouling, co-precipitation and other synergistic phenomena, inorganic agglomeration, crud effects, retrograde solubility and solids deposition, and organic materials. These topics were further evaluated, as summarized in this report, using information available in the literature and by performing conservative calculations as appropriate. This more detailed evaluation identified several phenomena with knowledge gaps that could be studied further to have a more realistic understanding of ECCS performance following a LOCA. The phenomena evaluated in this report with the highest potential significance include synergistic solids formation between organic compounds and inorganic solids, radiolytic effects, biological effects, and retrograde solubility. These effects are also highly plant-specific, and their significance is a function of parameters such as pH buffer, aluminum concentrations, insulation materials, containment cleanliness, quantity of unqualified coatings, and sump strainer submergence.

Title:	Investigation of Chemical Effects on Emergency Core Cooling Filtration Head Loss after Loss of Coolant Accident
Author:	J. S. Cho
Company:	FNC Technology Co., LTD, Korea Hydro & Nuclear Power Co., LTD
Document ID:	KOPEC/NED/TR/08-015
Date:	December, 2009
Document Length:	68 pages
Nature of the Study:	Experimental
Phenomenon Studied:	Head loss induced non-chemical debris and chemical products on strainer screen surface

Abstract: Integrated tests of head loss through an emergency core cooling filter screen were conducted simulating the thirty day chemical environment after LOCA conditions. A test apparatus with five individual loops with each chamber was established to test chemical product formation, and head loss through a sample filter was measured. The screen area in each chamber was 78.54 cm^2 and containment materials could be scaled down according to plant specific conditions. A series of tests was performed to investigate effects of containment spray, presence of calcium silicate with TSP, and the composition of materials. The results showed that the head loss across the chemical bed with even a small amount of calcium silicate insulation instantaneously increased as soon as TSP was added to the test solution. Also, the head loss across the filter screen was greatly affected by the spray duration. Long-term spray conditions generated twelve times larger head loss than short-term spray conditions. The test results also showed that the head loss increase is fast in the early stage because of the high dissolution and precipitation of aluminum, and zinc. Later on, after passivation of aluminum and zinc by corrosion, the head loss increase was much slower and mainly induced by materials such as calcium, silicon, and magnesium leached from NUKON™ and concrete.

Test Setup: A chemical head loss test apparatus was constructed which can predict realistic head loss by chemical effects by simulating plant specific chemical environmental conditions after loss of coolant accident. The apparatus can maintain containment pH and temperature conditions of a specific plant with a recirculating water system and measure head loss across filter screen with relevant materials that generate chemical byproducts. In addition, the apparatus is able to simulate containment spray duration, which is a driving factor producing chemical reaction of specific containment materials.

The apparatus consists of five chambers which have individual loops. Each test loop was equipped with the test chamber, recirculation pump, heater, water chemistry measurement box, piping and valves with sampling tabs. The simulated screen was installed at each chamber with an area of 78.54 cm^2 and mesh size of 2.38 mm (3/32 inches) and the specific containment materials were inserted to the specimen installation rack, where the amount of each material was scaled down according to plant specific sources of materials. The head loss across the screen, flow rate, temperature, pH, oxidation-reduction potential (ORP) and water conductivity were measured online through a data acquisition system. The water was sampled periodically both upstream and downstream of the screen and its composition was analyzed with Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES).

Findings: All the test series consisted of three different 30-day tests with different conditions. The first variable test parameter was spray duration time, which determines the amounts of materials exposed to the test solution; two different times were considered. Test #1 simulated short-term spray conditions where an operator switches off spray operation at 3,600 seconds after starting recirculation. Test #2 was for a long-term spray condition where the spray was maintained for 30 days. Test #3 was to obtain the pure pressure drop across screen by a test material bed that has no chemical effects. For this test #3, chemicals additives were not added into the test solution. The test conditions are summarized in Table 1.

It was found from the three types of tests that the head loss across the screen was greatly affected by spray duration. Long-term spray conditions generated twelve times larger head loss than the short spray

condition.

The test results also showed that the head loss increase can be divided into two stages. In the first stage, head loss sharply increases because of dissolution and precipitation of aluminum and zinc. The duration of the first stage depends on the amounts of material exposed to the containment water solution. After passivation of aluminum and zinc by corrosion, i.e., in the second stage, head loss increases slowly and is caused mainly by materials such as calcium, silicon, and magnesium leached from NUKON™ and concrete.

Table 1. Test conditions

Test ID	Test #1	Test #2	Test #3
Remarks	Short Spray	Long Spray	Non-Chemical
Materials	NUKON Coating (surrogates) Latent Materials	NUKON Coating (surrogates) Latent Materials	NUKON Coating (surrogates) Latent Materials
Materials Inducing Chemical Bed	Aluminum Zinc Concrete	Aluminum Zinc Concrete	N.A.
Spray Buffer	TSP	TSP	N.A.
Additives to Solution	H_3BO_3, LiOH, HCl	H_3BO_3, LiOH, HCl	N.A.
Temperature (°C)	90~40	90~50	90~45
Water Volume (L)	41.24	41.24	41.24
Flow rate (Lpm)	1.06	1.06	1.06
Effective Spray Duration	3600 sec	30 days	0

Title:	Lab-scale Corrosion Test Facility “KorrVA”
Authors:	H. Kryk
Company:	Helmholtz-Zentrum Dresden-Rossendorf
Document ID:	
Date:	From 2009 onwards
Document Length:	
Nature of Study:	Experiments for determination of chemical long-term effects
Phenomenon Studied:	Pressure loss across sump strainers; effects of corrosion processes on cooling water chemistry and pressure loss

Abstract: Within a common research project, funded by the Federal Ministry of Economics and Technology (BMWi), the lab-scale corrosion test facility “KorrVA” was designed to investigate the influence of corrosion of hot-dip galvanized containment internals on cooling water chemistry and head loss across sump strainers during ECCS operation following a LOCA.

The design of the corrosion facility is based on a downscaled version of the ECCS and the sump geometries of typical PWRs (KONVOI). Thus, it represents the ECCS operation during a LOCA in a simplified manner. The experimental unit of the modular test facility consists of a spraying section (representing the leakage) including samples of hot-dip galvanized steel gratings or small plates and a bath section (representing the sump) with a liquid volume of about 60 l. The impact of the leakage flow onto the sample surface as well as the area impacted can be varied by using different types of nozzles (e.g. full-cone, flat spray). The bath section includes a strainer unit (inner diameter 50 mm) with a mat of appropriate insulation fiber samples that represent the clogged sump strainer. Additionally, corrosion samples can be inserted into the bath section to investigate the corrosion behavior of submerged sump internals. A supply unit, consisting of heat exchanger, thermostat and circulation pump, provides the experimental unit with the liquid media (coolant) for each experiment at the desired process parameters.

Test Facility Capabilities:

Volumetric Scaling Factor:	Approx. 1:16,000 (based on KONVOI design)
Test Flume:	Volume 60 L, acrylic glass
Operating Temperature:	70 °C max.
Mass Flow:	600 kg/h max.
Strainer Design:	Currently: Flat stainless steel strainer (mesh width 2 mm, diameter 50 mm)
	Generally: All kinds of strainer design applicable
Fuel Element Section:	No fuel element section
Corrosion Samples:	Hot-dip galvanized steel samples (plates, gratings, max. 300 x 300 mm)
Debris Preparation:	Rockwool fibers tempered at 225 °C, steam jet fragmented; corrosion particles generated during corrosion of hot-dip galvanized steel samples
Measured Variables:	Coolant flow rate (online)
	Coolant sump temperature (online)
	Coolant inlet temperature (online)
	Coolant outlet temperature (online)
	Pressure loss across sump strainer (online)

Coolant primary pressure (online)

Coolant conductivity (online)

Coolant pH (offline)

Coolant cation concentration (offline)

Coolant anion concentration (offline)

Particle concentration (offline)

Particle size distribution (offline)

Mass loss of corrosion sample (offline)

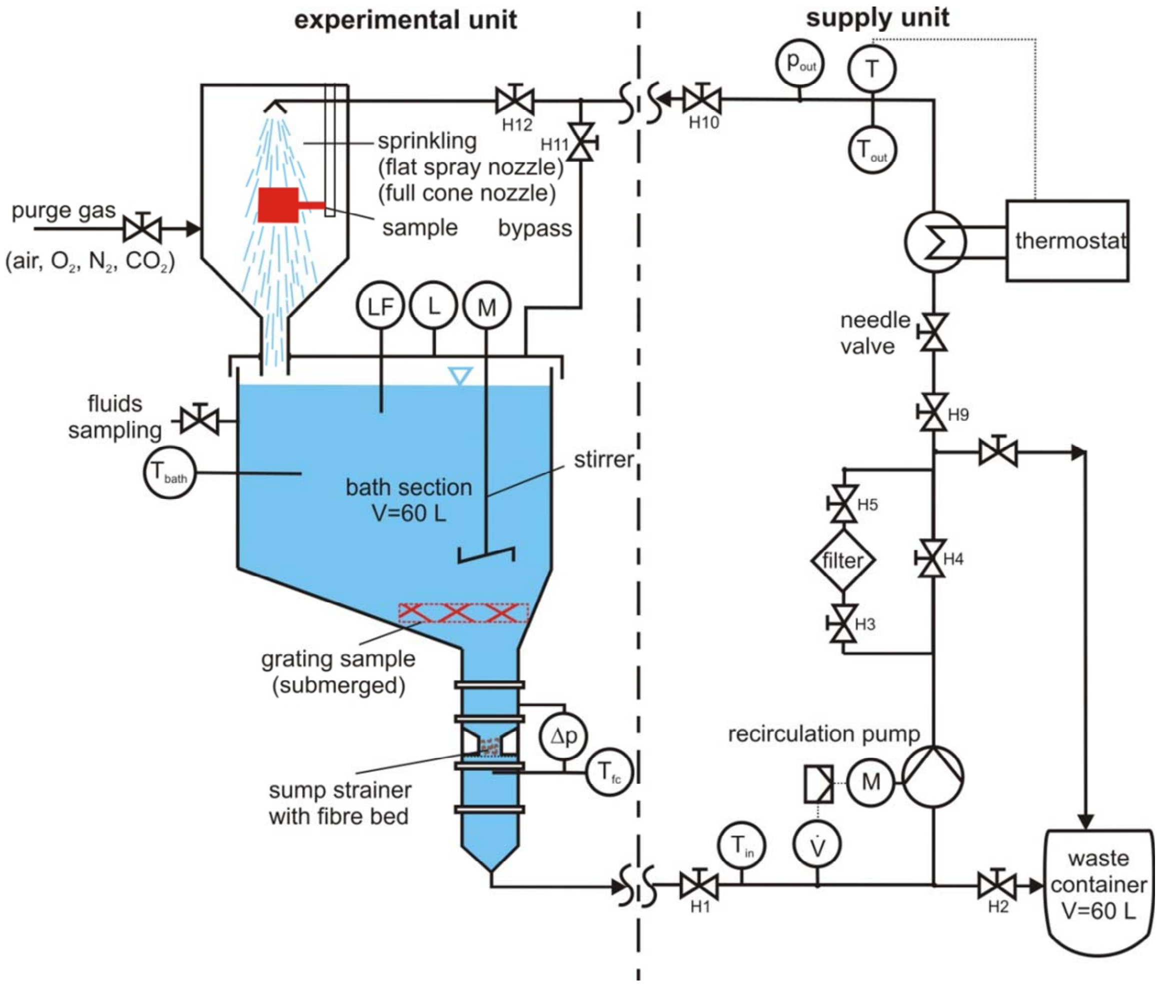
Mass of fiber bed (offline)

Corrosion particle components (offline)

Characterization of corrosion sample surface and corrosion product deposits using REM/EDX (offline)

Tests performed: So far, approximately 50 long-term tests (up to 2 weeks) have been performed in the "KorrVA" test facility with different focus:

- Head loss evaluation on sump strainer using rock wool insulation material (mineral wool MD2 (Saint-Gobain ISOVER Inc.) used in German PWR plants); long term, up to 48 h;
- Influence of hydrodynamics (leakage flow impact) on corrosion processes, water chemistry and head loss across fiber beds;
- Influence of water chemistry (pH value, boric acid concentration, LiOH concentration) on corrosion processes, water chemistry and head loss across fiber beds;
- Influence of corrosion sample area on corrosion processes, water chemistry and head loss across fiber beds using different corrosion samples (hot-dip galvanized plates 3 x 3 cm, press-welded grating treads 10 x 10 cm and 30 x 30 cm).



KorrVA Test Facility Schematic

Title:	Investigation of Chemical Effects on Head Loss after Loss of Coolant Accident with F-HELO (FNC HEad LOss Test Loop)
Author:	Young Wook Chung
Company:	FNC Technology Co. Ltd., Korea Hydro & Nuclear Power Co., Ltd.
Document ID:	S08NX03-F-TR-004
Date:	December, 2010
Document Length:	32 pages
Nature of the Study:	Experimental
Phenomenon Studied:	Head loss induced non-chemical debris and chemical products on strainers screen surface

Abstract: Because of the conservatism of WCAP-16530-NP and WCAP-16785-NP, a new experimental methodology was developed for evaluation of chemical effects on sump screen performance by FNC Tech. Since LOCA-generated debris materials will dissolve or corrode when exposed to the reactor coolant and spray solutions and cause various chemical reactions within the post-LOCA environment, it is very difficult to predict the effects of precipitated material on head loss. A new experimental methodology to predict the kind and amount of chemical precipitates generated has been developed to evaluate chemical effects on containment sump performance testing. The test method consists of two different tests - chemical precipitate generation tests and head loss tests - for evaluation of the chemical effect. The first test was developed to estimate the quality and quantity of chemical precipitates, and the head loss test is then performed to evaluate chemical effects according to the results of the first test. The second test for the evaluation of chemical effects in head loss on ECCS sump strainer was conducted.

Test Setup: The facility consists of a head loss test section and a recirculation loop. The test screen was located in the test section and the debris bed could be formed on the screen. The differential pressure meter and thermocouples were instrumented in the test section to measure the head loss across the test screen and temperature. A centrifugal pump and two heaters were instrumented for recirculation and heating of the recirculation loop, and the flow was controlled by a pump inverter and butterfly valve in the recirculation loop.

According to the chemical precipitation generation database, the materials introduced into the test section were determined on a plant-specific basis. By comparison with the test results without chemical precipitates, the chemical effects on head loss on the recirculation sump screen could be evaluated.

Findings: As a result of the chemical precipitation tests, the conservatism and applicability of the WCAP-16530-NP methodology were verified. After the non-chemical debris bed was formed in test section, the chemical precipitants were introduced. The amount of chemical precipitates was obtained from the predicted amount using the WCAP-16530-NP methodology. The first test was conducted to characterize the chemical effect on head loss in the case of a Westinghouse three-loop plant. Just after the introduction of chemicals, the head loss increased rapidly and stabilized at around 0.4 KPa. The measured chemical effects in this case were about 0.1 KPa (33 %). Although this value was quite high, it was evaluated that the total head loss was in the range of margin.

Along with the results of the test for a Westinghouse three-loop plant, head loss tests for the other types of nuclear power plants were performed. Chemical effects were observed at each test and significant chemical effects were found, while the total head loss could be restrained within the acceptable range of margin.

Title:	Investigation of Chemical Precipitates during LOCA Recirculation Mode with F-WACH (FNC WAter CHemistry test reactor)
Author:	Young Wook Chung
Company:	FNC Technology Co., Ltd., Korea Hydro & Nuclear Power Co., Ltd.
Document ID:	S08NX03-F-TR-004
Date:	December, 2010
Document Length:	32 pages
Nature of the Study:	Experimental
Phenomenon Studied:	Chemical precipitates produced by non-chemical debris and spray solutions

Abstract: Because of the conservatism of WCAP-16530-NP and WCAP-16785-NP, a new experimental methodology was developed for evaluation of chemical effects on sump screen performance by FNC Tech. Since LOCA-generated debris materials will dissolve or corrode when exposed to the reactor coolant and spray solutions and cause various chemical reactions within the post-LOCA environment, it is very difficult to predict the effects of precipitated material on head loss. A new experimental methodology to predict the kind and amount of chemical precipitates generated was developed to evaluate chemical effects on containment sump performance testing. The test method consists of two different tests – chemical precipitate generation tests and head loss tests for evaluation of the chemical effects. The first test was developed to estimate the quality and quantity of chemical precipitates formed.

Test Setup: To generate plant-specific chemical precipitation under the post-LOCA environment, the actual chemical condition of the recirculation sump during post-LOCA should be simulated in the experimental reactor. This facility consists of reactor, agitator, and reactor cooling coil in the reactor head. An auxiliary recirculation loop for measuring pH and electrical conductivity, chemical reagent introduction module, and pressurization module which enable the pressure in the reactor to be kept higher than the saturation vapor pressure were installed. To protect the pH and electrical conductivity sensors and to prevent thermal shock, a heat condenser and pre-heater were instrumented in auxiliary recirculation loop.

The plant-specific containment materials introduced in the reactor to simulate the post-LOCA condition were glass fibers, concrete blocks, aluminum specimens, and chemical reagents – boric acid, spray additives or buffering chemicals (sodium hydroxide, TSP, etc.). The inner temperature of the reactor was controlled by a heater and cooling coil to simulate the plant-specific temperature profile of the recirculation sump.

Findings: Based on the test matrix, several durations of chemical reaction were used in the tests, with a maximum duration of 30 days, required for recirculation mode of the ECCS. Test durations of 1, 3, 5, 10, 20, and 30 days were used. After each test was terminated, the reactor was opened to collect the chemical precipitate generated in the reactor for the time duration. The tests were performed for the three types of nuclear power plants operating in Korea. Qualitative and quantitative analyses were performed on the collected precipitates and a precipitation generation database was established according to the each analysis result.

The 30-days test results for the three types of nuclear power plants showed that the amounts of target products (bohemite, albite, and calcium phosphate) generated in the reactor were very small. Considering the errors, including the error in measuring the reagent introduced and the analytical error in the ICP analysis, the amounts generated were smaller than the predicted amounts using the WCAP-16530-NP and WCAP-16785-NP methodology within the margin of error.

Title:	Evaluation of Chemical Effects Phenomena Identification and Ranking Table Results
Author:	B. Lin et al.
Company:	US NRC
Document ID:	Technical Report (ADAMS Accession No ML102280592)
Date:	March 2011
Document Length:	97 pages
Nature of Study:	Evaluation
Phenomena Studied	Chemical effects PIRT

Abstract: The objective of this report was to document the US NRC staff's evaluation of the implications of the 41 outstanding chemical effects phenomena (see NUREG/CR-6988 and NUREG-1918) and the technical justification supporting the disposition of these phenomena.

Findings: This report documents the staff's evaluation of the implications of the outstanding chemical effects phenomena and the technical justifications supporting the disposition of these phenomena. The staff used the existing knowledge and the additional research sponsored by the industry and the NRC to determine the significance and implications associated with each issue. Sections 1 through 7 in this report summarize the results of this evaluation. The staff's evaluation of the outstanding issues concluded that the implications of these issues are not generically significant or are appropriately addressed within the guidance associated with assessing chemical effects on ECCS performance in response to GL 2004-02.

Title:	Emergency Core Cooling System Sump Chemical Effects on Strainer Head Loss
Authors:	M.K. Edwards, L. Qiu, D.A. Guzonas
Company	Atomic Energy of Canada Limited
Document ID:	Proceedings of Nuclear Plant Chemistry 2010 (Int. Conf. on Water Chemistry of Nuclear Reactor Systems), 2010 October 3-8, Quebec City (ISBN# 978-1-926773-00-1)
Date:	2010 October
Document Length:	14 pages
Nature of Study:	Conference paper, experimental and modeling
Phenomena Studied:	Chemical reactions and effects on head loss

Abstract: The paper outlines the AECL approach to resolving the issue of chemical effects on ECCS strainer head loss, which includes modeling, bench top testing and reduced-scale testing; the latter conducted using a temperature-controlled variable-flow closed-loop test rig that includes a test section equipped with a differential pressure transmitter. Models of corrosion product release and the types of precipitates expected in post-LOCA sumps are discussed. The paper discusses reduced-scale test results and presents a possible method for chemical effects head loss modeling.

Findings: The paper compared the calcium, aluminum and silicon release models presented in WCAP-16530 that became the US industry standard with a semi-empirical equation developed by AECL using a similar data set and a first principles understanding of the overall release process. Although the predictions of the two models can differ under some input conditions, it was concluded that both are within the scatter of the data. Both models reasonably predict the aluminum concentration data reported for Tests 1 and 5 of the ICET tests.

The aluminum release data developed for PWRS in borated solutions could not be applied to CANDU plants because aluminum release rates in borated solutions are significantly higher than those reported for non-borated solutions. AECL performed detailed aluminum release testing under representative CANDU post-LOCA conditions. The 4- to 90-day tests examined the effects of pH, temperature, CO_2, hydrazine, cal-sil, TSP and alloy type on aluminum release rates from corroding coupons. The model developed was mainly a function of pH, temperature and time:

$$RR_{Al} = A \times f(T) \times \exp\left(B \cdot pH\right) \times t^{-0.5}$$

The parabolic time dependence is a common feature of long-term corrosion tests, resulting from the formation of an oxide film.

The paper discusses the importance of kinetic factors in determining the nature of the precipitating species, especially with respect to precipitation of silicate and aluminosilicate species. It notes that in the reduced-scale testing method described in WCAP-16530, precipitates are formed in concentrated solutions exterior to the test loop, thus ignoring the effects of time, concentration, competing anions and debris bed surfaces on the particle size and distribution of the resulting precipitates. It is unlikely that precipitates formed in this way are representative of precipitates that would form in a post-LOCA environment. The AECL test method involves direct addition of precipitants (soluble chemical precursors such as $NaAlO_2$, which hydrolyses to produce $Al(OH)_4^-(aq)$ within the injected solution) expected to form precipitates under the conditions in the test loop). The concentrations of precipitants during chemical additions only momentarily exceed the sump concentrations predicted from the release equations during injections. This leads to solutions far less supersaturated than those produced using the WCAP method, leading to precipitates that are believed to be more representative.

In bench-top tests conducted by AECL for Dominion Generation, low-grade concrete was found to dissolve readily below pH 8, but in the presence of TSP dissolution was almost completely inhibited. This may have been the result of the formation of a protective calcium phosphate surface film on the concrete. In reduced-scale chemical-effects tests for Dominion Generation, additions of calcium chloride had a

negligible effect on strainer head loss, calling into question the importance of calcium in the analysis of chemical effects on strainer performance. SEM analysis of debris bed fibers in tests where calcium was added showed indications of a Ca-Al-P precipitate, and calcium concentration was observed to decrease in a one-to-one molar ratio with aluminum additions. Thermodynamically, $CaAlH(PO_4)_2$ may form under certain conditions, but has been reported to be unstable with respect to hydrolysis. Calcium precipitated in the absence of significant dissolved aluminum once the concentration exceeded about 24 mg/L Ca; this concentration exceeds the solubility of $CaHPO_4 \cdot 2H_2O$ by a factor of 4 and $Ca_5(PO_4)_3OH$ by a factor of 30 billion, it is not clear which compound precipitated. This precipitation was not observed to increase head loss.

Additions of sodium aluminate ($NaAlO_2$) solutions increased the pressure drop across strainers covered with thin beds of fibrous insulation. Additions did not result in homogeneous precipitation, as samples taken downstream of the addition point did not contain precipitates or significant turbidity, but aluminum concentrations seldom exceeded the aluminum analysis method detection limit (0.4 mg/L) suggesting rather quick and complete precipitation of aluminum. SEM examination of debris beds showed primarily uniform distribution of precipitates, consistent with heterogeneous precipitation on insulation fibers. Heterogeneous precipitation was also observed in the ICET testing. It is expected that precipitation within the debris bed results in tightening or clogging of pores in the debris bed, resulting in head loss increases. Frequently, head loss peaked after additions, then stabilized at a lower value. Plotting peak head loss versus the amount of aluminum precipitated per unit area of strainer and using the available pump suction head margin allowed the maximum allowable strainer aluminum load to be calculated.

A model of the effect of chemical precipitates on head loss was developed. The debris bed was modeled as an array of pores through which most of the fluid passes. As precipitates form within the debris bed, the pores get clogged, increasing pressure drop across the strainer. In such a model, the fluid velocity through remaining pores increases as precipitants are added and precipitates form until turbulent conditions exist within those pores, at which point further increases in head loss are not expected since fluid shear would prevent precipitates from adsorbing or else cause them to spall. This may help to explain the head loss plateau observed in many tests, where the addition of more aluminum did not result in significant head loss increases.

Title:	Chemical Effects on Sump Screen Clogging under Japanese Plant Conditions
Author:	M. Fukasawa
Company:	Japan Nuclear Energy Safety Organization (JNES)
Document ID:	JNES-SS-0703, JNES-SS-0804, 09原熱報-0003, 10原熱報-0006, JNES-SS-1004
Date:	May 2007, May 2008, July 2009, October 2010, February 2011, respectively
Document Length:	45, 137, 246, 169, 68 pages, respectively [all in Japanese]
Nature of the Study:	Experimental / Analytical
Phenomenon Studied:	Chemical effects

Abstract: Chemical effects on head loss at a sump screen were investigated by performing integrated tests (ICAN) and separate effect tests using synthesized colloids for Japanese plant conditions. The ICAN test was analyzed based on the measurements of the colloid test and an evaluation method proposed.

<u>ICAN Test</u>: The ICAN test loop is equipped with a tank, two cylinders to evaluate head loss and a spray system. (Figure 1) Material coupons were installed in the tank to simulate the chemical environment of the sump water for over 30 days after a LOCA. In each cylinder, a 3 mm punching mesh screen is settled. □15 cm screen and 10 cm screen were covered with 30 g and 13.4 g of rock wool debris, respectively. Rock wool debris was prepared by shredding rock wool insulator by a shredder and a food processor in water.

Test conditions were determined based on actual Japanese plant data. In the tank, rock wool insulators and metal coupons (aluminum, carbon steel, copper, galvanized steels, zinc coated steels) were added. Table 1 shows the conditions of typical test cases. The water volume of the test was 1 m^3. The test water contained 2800 ppm B boric acid and 0.4 ppm Li lithium hydroxide initially. The metal coupons and rock wool insulators were added 4 hours before spray. In some tests, 100 ppm HCl hydrochloric acid was added to the test solution 10 minutes before the spray. Sodium hydroxide (NaOH) or hydrazine (N_2H_4) solution as pH buffer was sprayed for 4 hours. The test was performed for more than 720 hours at 60 °C, generally.

<u>Colloid Test</u>: The test loop used in the colloid test consists of a head loss measuring device, a water tank, a pump, flow control valves and measuring instruments. The screen is a disk of 15 cm in diameter with punched holes of 3 mm in diameter. In the colloid test, rock wool debris was deposited on the screen and then colloid solution was added stepwise in the test loop to measure the head loss in terms of amount of colloid.

<u>Analysis</u>: The ICAN tests were analyzed based on the measurements of the colloid test and an evaluation method proposed. The proposed method estimates the amount of surrogate precipitate by summing up each chemical effect of the specified precipitates, which is the same as the WCAP-16530 but included the effects of iron and zinc hydroxides.

Findings: For the ICAN and colloid tests, following conclusions are obtained for chemical effects under the typical Japanese plant condition:

- Hydrochloric acid severely corrodes rock wool debris and suppresses head loss increase;
- Corrosion of carbon steel can increase the head loss significantly;
- In NaOH-buffered solution, the head loss increase is larger than in N_2H_4-buffered solution;
- Enlarging the sump screen to decrease the approach velocity is very effective in preventing unacceptable head loss increase (Figures 2, 3);
- Head loss becomes larger when particles deposit on the fiber debris than the head loss when the debris deposits after the particles or premixed debris and particles deposit on the screen;

- Head losses in terms of amount of colloids are obtained for the colloids of aluminum, iron, copper and zinc hydroxides and for $CaSiO_3$ particles. It is found that the head loss leaps after a certain amount of colloid is deposited on the debris.

For the analysis, following conclusions are obtained:

- A method is proposed to include the chemical effect of iron and zinc into the WCAP method. In the method, the dissolution rate of carbon steel is analyzed with StreamAnalyzer, additional precipitates of iron and zinc hydroxide are assumed and conversion factors to estimate the amount of the surrogate precipitate are estimated based on the colloid test;
- The ICAN test was analyzed based on the proposed method and the measured head losses in terms of amount of colloids. The analysis of the ICAN test that includes only one corrosive material shows the appropriateness of the assumed precipitates, which are iron and zinc hydroxides;
- The analysis of the ICAN test that includes a number of corrosive materials shows the evaluation method estimated by summing up each chemical effect of the specified precipitates including AlOOH, $NaAlSi_3O_8$, FeOOH and $Zn(OH)_2$ was holistically conservative for typical Japanese plant conditions;
- The conservativeness of the evaluation method is mainly caused by the assumption that all the Si dissolved from the rock wool insulation is assumed to precipitate.

Table 1 Test conditions (quoted from 10原熱報-0006)

Test	Sprayed pH buffer		Metals (m^2/m^3)					Insulator (m^3/m^3)
			Aluminum	Copper	Carbon Steel	Galvanized Steel	Carbo Zinc 11	Rock Wool
ICAN-7	NaOH: 8348g pH10	Submerged	$3.3x10^{-4}$	3.4	1.4	0	0.2	0.121
		Unsubmerged	$6.2x10^{-3}$	10	25	0	0	0.016
ICAN-9		Submerged	$3.3x10^{-4}$	3.4	0.2	1.4	0.2	$4.9x10^{-3}$
		Unsubmerged	$6.2x10^{-3}$	10	0.4	25	0	$3.3x10^{-3}$
ICAN-8	N2H4·H2O: 993.5g NaOH: 182g pH 7.2	Submerged	$3.3x10^{-4}$	3.4	0.2	1.4	0.2	$4.9x10^{-3}$
		Unsubmerged	$6.2x10^{-3}$	10	0.4	25	0	$3.3x10^{-3}$
ICAN-10		Submerged	$3.3x10^{-4}$	3.4	0.2	1.4	0.2	$4.9x10^{-3}$
		Unsubmerged	$6.2x10^{-3}$	10	0.4	25	0	$3.3x10^{-3}$
ICAN-13		Submerged	0.2	3.4	0.2	1.4	0.2	$4.9x10^{-3}$
		Unsubmerged	0.8	10	0.4	25	0	$3.3x10^{-3}$

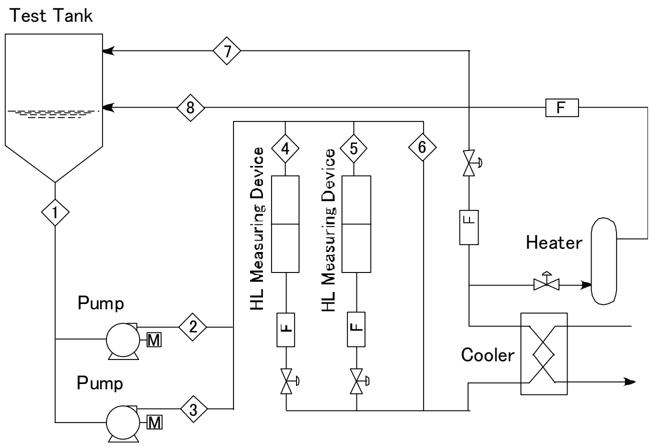


Figure 1: Flow diagram of a test loop (from JNES-SS-1004)

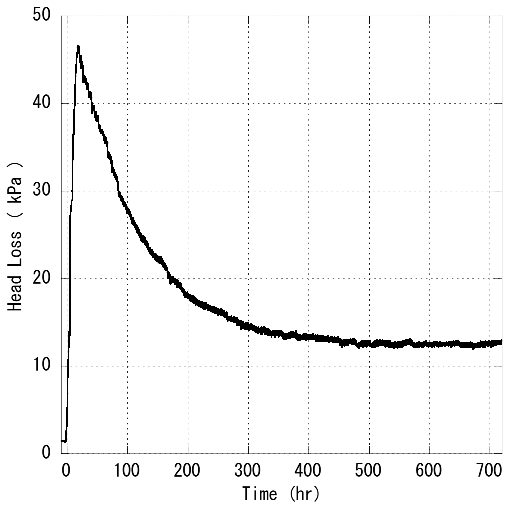


Figure 2: Head loss change in ICAN-10 test with approach velocity of 2 cm/s (from JNES-SS-1004)

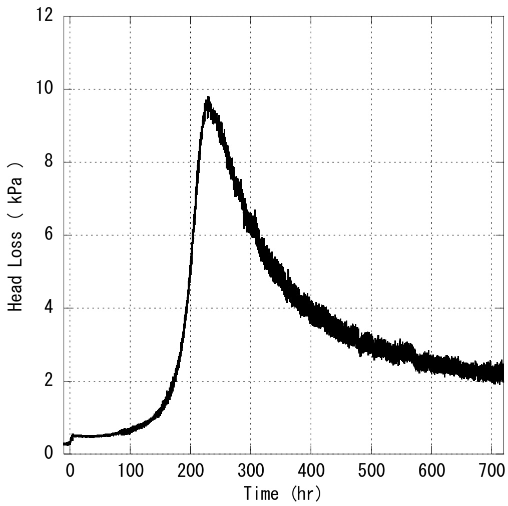


Figure 3: Head loss change in ICAN-10 test with approach velocity of 0.3 cm/s (from JNES-SS-1004)

Title: The Effects of Temperature on Head Loss with Chemical Debris
Author: N. Minami, T. Enomoto et al.
Company: Japanese PWRs (Hokkaido, Kansai, Shikoku, Kyushu and Japan Atomic Power Company), and Mitsubishi Heavy Industries
Document ID: -
Date: March 2011
Document Length: -
Nature of the Study: Experimental
Phenomenon Studied: Head loss tests

Abstract: The Japanese PWRs conducted head loss tests with chemical debris corresponding to the conditions of each plant. The tests were conducted at room temperature, then the head loss at the actual temperature under the LOCA condition was converted using the kinematic viscosity ratio of water. The effect of temperature on head loss with chemical debris, however, has not been validated, and so its effect should be assessed.

The objective of the test program was to collect head loss data at the specified temperatures and approach velocities for each test that can be used to establish the correlation of the kinematic viscosity ratio of water with and without chemical debris. The tests collected and recorded differential pressure, temperature, and flow rates while building a bed of a specific type and quantity of debris across the screen with WCAP chemicals (AlOOH).

Test setup: The head loss tests were performed at the Alion Science & Technology Hydraulics Laboratory. A schematic view of the test apparatus is shown in Figure 1. To ensure that chemical effects were controlled in the tests, reverse osmosis (RO) water was used. The test apparatus was equipped with temperature control equipment which allowed the test fluid to be maintained at the specified temperature for the duration of the test. Flow was circulated through the loop via either a high or low flow pump, depending on the required flow rate. The test screen was perforated plates that supported the debris bed and imparted minimal clean screen head loss. Clean screen head loss data collected during the tests showed that a difference in hole size diameter did not affect the measured head loss.

The tests were used to collect steady state head loss data for debris beds at a range of temperatures and flow rates, with and without chemicals in the test fluid. The tests used debris beds composed of rock wool and/or calcium silicate, and WCAP aluminum oxyhydroxide (AlOOH) was added to the test fluid.

For the first two tests, B-1 and B-2, after a rock wool and calcium silicate debris bed was built, a flow sweep was performed before and after adding aluminum oxyhydroxide. Debris beds were formed at the highest approach velocity of the Japanese strainers (~9 m/h). After the debris bed had been formed, the approach velocity was lowered to three distinct values (7, 5, 3 m/h) to measure the head loss across the test screen at these lower approach velocities. The approach velocity was then raised to each approach velocity (5, 7, 9 m/h).

For tests B-3 through B-5, after a rock wool and calcium silicate debris bed was built (9 m/h), a temperature sweep was conducted before and after adding aluminum oxyhydroxide. As a reference, aluminum oxyhydroxide was not added in test B-3. First, the temperature was controlled at 20 ºC. After the head loss was measured, the temperature was raised to each temperature (40 ºC, 50 ºC), and was then lowered to distinct temperatures (40 ºC, 20 ºC).

The test was inspected for head loss stability after 5 pool turnovers, and the difference in head loss over the course of 1 h was found to be less than 1% of the head loss value. This stabilization criterion was used after each debris addition. The criterion was also used when the flow rate or temperature was changed.

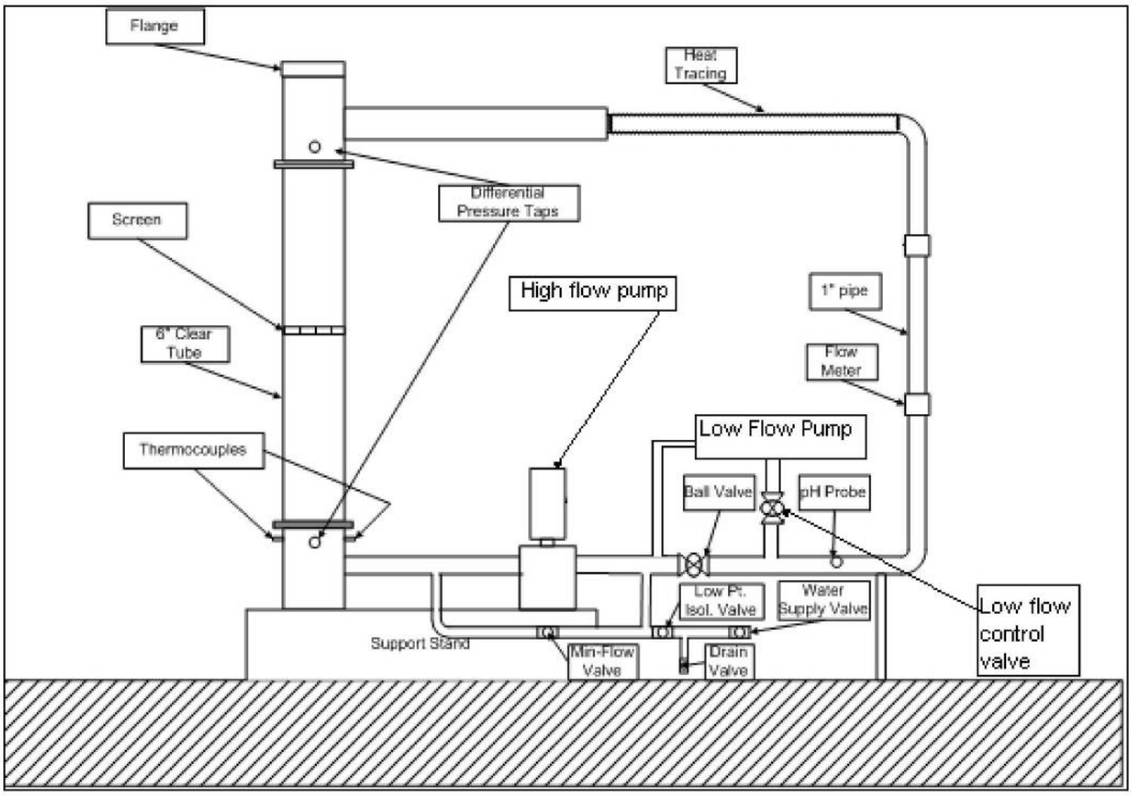


Figure 1: Schematic view of the test apparatus

Table 1: Test Parameters

Test No.	Rock Wool (g)	Calcium Silicate (g)	AlOOH (g)	Temperature (ºC)	Approach Velocity (m/h)
B-1	27.4	13.7	6	20	9-7-5-3 (decrease) then 5-7-9 (increase)
B-2	27.4	13.7	6	40	
B-3	27.4	0	3	20-40-50 (increase) then 40-20 (decrease)	9.0
B-4	27.4	13.7	3		9.0
B-5	27.4	13.7	2		9.0

Findings: In this study, a series of tests was performed to evaluate the effect of temperature on pressure drop with chemical debris. As a result, the following conclusions were obtained.

From the results of tests B-1 and B-2, the approach velocity and head loss showed a linear relationship. Therefore, it is appropriate to use "kinematic viscosity" for compensating temperature.

From the results of tests B-3 through B-5, both the head loss – temperature ratio and kinematic viscosity – temperature ratio indicated a similar tendency, although the former ratio was higher than the latter in some cases of increasing water temperature (at 50 ºC) because of the instability of the debris bed (residual

deformation against compression and solid fraction caused by debris re-penetration).

On the other hand, visual confirmation showed that the water clarity after the head loss had evened out was almost the same as that before injection of debris, indicating that the liquid was not a colloidal solution.

These results indicate that it is reasonable to use the kinematic viscosity of “water” with chemical debris for compensating the head loss.

COATING DEBRIS GENERATION & TRANSPORT

Title:	Degradation and Failure Characteristics of NPP Containment Protective Coating Systems
Author:	M. Dupont et al.
Company:	Westinghouse Savannah River Company for the U. S. NRC
Document ID:	4 separate reports (WSRC-TR-2000-0079, TR-2000-0340, 2001-067, 2001-0163)
Date:	March 2000 through March 2001
Document Length:	approx 425 pages total
Nature of Study:	Experimental
Phenomena Studied	Protective coating failure mechanisms

Abstract: A research program to investigate the performance and potential for failure of Service Level I coating systems used in nuclear power plant containment was conducted at Savannah River Technical Center (SRTC). The research activities are aligned to address phenomena important to cause failure as identified by the industry coatings expert panel. The period of interest for performance covers the time from application of the coating through 40 years of service, followed by a medium-to-large break LOCA scenario, which is a DBA scenario. The SRTC program consists of three major elements: Materials Properties Development, Failure Modeling Development, and DBA Performance Testing. These elements are directed at determining Service Level I coatings performance under simulated DBA conditions. The coating materials properties data (not previously available) are used in predictive coatings failure models which are then compared against coating behavior under simulated DBA conditions to obtain insights into failed coating materials characteristics and degree of failure (i.e. amount of coatings debris). The resulting data and insights are used in NRC's GSI-191, "PWR Sump Blockage" research program. The effects of aging on coating materials properties and performance are addressed by applying an aging treatment (irradiation to 10e9 RAD, per ASTM D4082-95) to test specimens.

Findings: The SRTC coatings program findings provided in these reports illustrate the investigative approach and significant findings obtained for several coatings systems, epoxy-polyamide primer and topcoat applied to a steel substrate, epoxy-phenolic over epoxy concrete surfacer, and epoxy-phenolic over inorganic zinc primer.

The experimental approach is a combination of measurement of critical coating materials properties at conditions representative of a post-LOCA period, the development of a predictive coating system failure model, subjecting such coating systems to DBA conditions, comparing model and test results to judge predictive capability, documenting the degree of failure and characterization of failed coating debris which will be integrated into the PWR sump blockage research program (GSI-191).

The research results reported in these reports arrive at the following conclusions:

1. Properly applied "qualified" coatings systems can be expected to exhibit adequate adhesion strength to a steel or concrete substrate following exposure to simulated DBA conditions.
2. Artificial aging (related to gamma radiation exposure as defined in ASTM Standard D-4082-95) exhibited some near surface degradation of the epoxy polymer materials. This degradation appears to the consequence of coating oxidation resulting from irradiation and temperature effects and would be expected to vary with oxygen availability and permeability in a particular coating system.
3. Although a properly applied epoxy coating system exhibited only blistering without detachment when subjected to a simulated LOCA, it is projected that this coating system (if there were coating flaws which had entrapped moisture) could fail during the rapid containment cool down introduced by activation of containment spray systems.

Title:	Hydraulic Transport of Coating Debris
Author:	T. Fu and A. Fullerton
Company:	U S Naval Surface Warfare Center, Carderock Division for the U.S. NRC
Document ID:	NUREG/CR-6916
Date:	December 2006
Document Length:	93 pages
Nature of Study:	Experimental
Phenomena Studied	Coating chip transport

Abstract: This study included experiments to characterize the hydraulic transport of coating chips generated from five coating systems that are considered to be broadly representative of coatings used in PWR power plants. The coating chip transport tests included (1) time-to-sink tests, (2) terminal settling velocity tests, (3) tumbling velocity tests, and (4) suspension transport tests. The parameters examined during the testing were chip properties (e.g., size, shape, density, thickness, presoaking, thermal-curing) and fluid velocity.

Findings: Failed coatings debris is one potential source for debris transported to the ECCS sump screens. This document describes a limited number of tests conducted to study the transportability of coatings debris (chips) in ambient temperature water, at specific conditions of uniform flow. It is intended that the transport parameters observed in these tests could be used as the basis for the evaluation of coating chip transport under plant specific conditions. The transport characteristics of coatings particulates were not examined in these experiments as fine particulate are assumed to transport. Five coating systems, typical of coatings applied to equipment and structures located in the contaminant buildings of PWR plants, were tested. The effects of chip size, shape, density, thickness, stream velocity, water saturation, and thermal curing on transportability were examined through two types of tests – quiescent settling and transport within uniform flow. The quiescent settling tests were conducted in a 0.3 m wide by 0.3 m long by 1.2 m deep (one ft wide by one ft long by four ft deep) acrylic tank. The goals of the quiescent water tests were to determine: (1) the time necessary for coating chips dropped onto the water surface to break the surface and begin to sink (time-to-sink tests), and (2) to determine the terminal settling velocity of submerged coating chips (terminal velocity tests). The transport tests were conducted in a 0.91 m wide by 0.91 m deep by 9.1 m long (three ft wide by three ft deep by thirty ft long) acrylic flume suspended in a large circulating water channel. The goal of the transport tests was to characterize the behavior of coating chips in moving water. The tests consisted of a tumbling-velocity test to study the behavior of coating chips placed on the flume floor and a steady-state velocity test to study the behavior of coatings debris released into the moving stream below the water surface. A statistically meaningful number of data tests were conducted for each coating type, chip size and chip shape in each test category in order to more accurately quantify observations. The quiescent tests demonstrated that, when dropped onto the water surface, coating chips with a density close to that of water tended to remain on the surface indefinitely and heavier chips tended to sink almost immediately. The tumbling velocity tests demonstrated that all but the lightest chips and curled chips remained in their initial position at stream velocities in excess of 0.09 m/s (0.3 ft/s). The steady-state velocity test demonstrated that, at a uniform water velocity of 0.06 m/s (0.2 ft/s), all but the lightest chips settled to the bottom before reaching the end of the flume.

Title:	Design Basis Accident Testing of Coating Samples from Unit 1 Comanche Peak SES
Author:	J. Cavallo and J. DeBarba
Company:	Keeler and Long PPG
Document ID:	Report 06-0413
Date:	April 13, 2006
Document Length:	252 pages
Nature of Study:	DBA autoclave tests
Phenomena Studied	Aged protective coatings resistance to DBA environment

Abstract: DBA autoclave tests were conducted on coating chip samples from Comanche Peak Unit 1 containment building. Samples were placed in (2) 9 inch diameter trays made of stainless steel sheeting with 1/32 inch diameter holes. The top tray located in the vapor phase of the test was attached to the upper portion of the autoclave stand and was designed without a lid so as to avoid covering the samples. The bottom tray was designed with a lid to contain the samples and was attached to the lower autoclave stand or immersion zone.

Findings: The total weight loss of sample chips after DBA testing would be considered transportable debris.

The 3.766 g of coating debris generated during the DBA test appears to have been collected on the 10 µm filters in the recirculation loop of the autoclave.

The coating debris collected on the 10 µm #2 filter in the recirculation loop of the autoclave is grayish/grayish-white in color, indicating that it is comprised of zinc and zinc oxide particles released from the back side of the original coating pieces during DBA testing.

Based on 50X microscopic observation of the coating debris collected on the 10 µm #2 filter in the recirculation loop of the autoclave, the debris appears to be primarily >10 µm to <100 µm in diameter, further indicating that it is comprised of zinc and zinc oxide particles released from the back side of the original coating pieces during DBA testing.

There was no observation of any transported particles of phenolic topcoat on the 10 µm filter in the recirculation loop of the autoclave, indicating that the phenolic topcoat sample pieces generated relatively large (>1/32 in. diameter), non-transportable debris during the DBA testing.

Further examination and evaluation of the filter using scanning electron microscopy energy dispersive x-ray spectroscopy (SEM-EDS) with microphotography up to 5000X is in process. This will serve to confirm visual observation above.

The chip size characterization of the debris located at the bottom of the autoclave was photographed prior to infrared spectroscopy and can be viewed in the picture section of this report. Although it was not measured for exact size, the 50X microscopic observation of the coating debris collected on the recirculation loop filter indicated smallest size >10 µm. It can be correlated that the smallest size in the bottom of the autoclave would also be >10 µm. The largest measurement of any single chip in the bottom of the autoclave was <127 µm.

Title:	Adhesion Testing of Nuclear Coating Service Level 1 Coatings
Author:	J. Cavallo
Company:	Corrosion Control Consultants and Labs, Inc. for Electric Power Research Institute
Document ID:	EPRI Report 1014883
Date:	August 2007
Document Length:	114 pages
Nature of Study:	Adhesion tests
Phenomena Studied	Protective coatings

Abstract: EPRI and the Nuclear Utilities Coating Council (NUCC) initiated a program in 2005 to evaluate coating failures and the potential influence of aging. This phase of the program collected coating adhesion data for coating systems to provide a baseline correlation to original qualification and to provide confirmatory support for ASTM coating inspection methods that rely upon visual inspection as an initial step. Coating adhesion test data were collected in containment building at four commercial nuclear power facilities.

Findings: Review of the adhesion test data confirms that aged, visually intact, DBA-qualified coatings (from various manufacturers) that exhibit no visual anomalies (that is, no flaking, peeling, chipping, blistering, etc.) continue to exhibit system pull-off adhesion at or in excess of the originally specified (ANSI N5.12 and ASTM D5144) minimum value of 200 psi.

DOWNSTREAM EFFECTS

Title:	Screen Penetration Test Report
Author:	C.B. Dale and B.C. Letellier
Company:	Los Alamos National Laboratory for the U. S. NRC
Document ID:	NUREG/CR-6885
Date:	October 2005
Document Length:	50 pages
Nature of Study:	Experimental
Phenomena Studied	Suction strainer debris penetration

Abstract: This report addresses the propensity of different types of insulation debris (fibrous, particulate, and RMI) to penetrate PWR sump screens. The variables under consideration include the size of screen openings; the size, shape, and type of debris; the flow velocity upstream of the screen; and the manner in which the debris reaches the screen (on the floor or in the flow). The test matrix consists of 44 tests using combinations of representative screen-opening sizes of 1/4 in., 1/8 in., and 1/16 in. and debris sizes and shapes. Insulation debris consisting of NUKON fiberglass, calcium silicate, and stainless-steel RMI was tested individually within a linear hydraulic flume. Approach velocities ranged from 0.2 to 1.0 ft/s. These velocities are representative of containment pool approach velocities at the sump screen for current (pre-2007) PWR designs.

Findings: Debris screen penetration depends to some extent on all of the test variables examined: screen size; debris size, shape, and type; flow velocity; and method of introduction (on the floor versus in the flow). The debris type determines the relative importance of the remaining test variables. Under certain conditions, results indicate the potential for significant debris screen penetration. It was observed that a significant amount of particulate calcium silicate insulation (up to 70% in some cases) can pass through a screen opening of any size. Higher flow velocities cause large calcium silicate clumps to break up, allowing more calcium silicate to be transported to and pass through the sump screen. A significant amount of fibrous NUKON™ debris (up to 90% in some cases) arriving at the screen in finely separated fibers can pass through the screens. However, if the NUKON™ debris arrives at the screen in larger, agglomerated pieces, only a small amount (<5%) may pass through the screens. Last, when RMI debris was introduced on the floor, the RMI tended to remain stationary on the floor and not transport to the screen. The result was that <22% of the RMI introduced on the floor passed through the screen for all tests. However, a significant percentage (up to 75%) of the RMI passed through the screen when the RMI was introduced directly into the flow immediately before the test screen.

The results presented are applicable to the determination of the effect of the debris that passes through the sump screen on downstream components, such as high-pressure safety injection system pumps and throttle valves. These effects are being investigated in ongoing research at the University of New Mexico, using debris sizes and shapes that can penetrate the screen, as demonstrated by this testing.

Title:	Effects of Insulation Debris on Throttle-Valve Flow Performance
Author:	C.B. Dale et al.
Company:	Los Alamos National Laboratory for the U.S. NRC
Document ID:	NUREG/CR-6902
Date:	March 2006
Document Length:	197 pages
Nature of Study:	Experimental
Phenomena Studied	Suction strainer debris affects downstream

Abstract: This document describes a series of tests conducted to assess the potential for LOCA–generated debris to be trapped in the throttle valve downstream of the sump screen. Trapping debris in the valve has important consequences for ECCS operation because it may result in unacceptably high pressure losses in the system and degrade ECCS performance. Tests have been performed using a range of debris loadings and compositions of insulation introduced either as a single batch or as a set of successive batches. The tests used a surrogate throttle valve designed to simulate a range of representative valve configurations in use within United States PWRs.

Findings: These tests addressed the downstream effects of the debris that was able to penetrate the sump screen on the potential blockage of the high-pressure safety-injection throttle valves.

The insulation debris that was tested included calcium silicate insulation, NUKON fiberglass insulation, and RMI; however, many other types of insulation exist in plants. The range of debris sizes was based on the results of the screen penetration tests (NUREG/CR-6885). Debris blockage in the valve was gauged using the valve-loss-coefficient *K*, which was calculated using measured data for the pressure drop across the valve, the flow rate through the valve, and the temperature of the water. As the effective flow area of the valve decreased because of blockage, the loss coefficient increased. The overall approach was first to establish baseline loss coefficients for each valve configuration of interest and then to compare loss coefficients for various debris flow conditions with the data to get an indication of the extent of blockage caused by the debris. In addition, baseline loss coefficients were determined for selected known blockages (blockage-area fractions simulated using shims) to determine the relationship between *K* and the blocked-area fraction, as well as the blockage detection threshold of the system (~5%–8%). Loss coefficients for debris flow conditions then were compared with those for shim blockage data to obtain estimates of the blockage-area fractions. Data from tests with single batches of unmixed debris showed that, in general, higher debris loadings and larger debris sizes (relative to the throttle-valve opening) resulted in higher observed increases in *K*. The *K* increases were higher for RMI than for NUKON for equivalent mass loadings. However, NUKON is judged to be more likely than RMI or calcium silicate to cause throttle valve blockage because of the propensity for NUKON to transport and penetrate the sump screen.

Tests using calcium silicate-RMI mixtures were the only two-component combinations that exhibited clear increases in *K* when compared with results from analogous single-debris calcium silicate and RMI tests. The results of tests performed using NUKON-RMI or calcium silicate-NUKON mixtures did not differ significantly from results for analogous separate tests, with one possible exception. One mixture test performed using unsieved calcium silicate with NUKON showed an appreciable increase in valve blockage compared with single-debris NUKON tests. However, it is unclear if this result is attributed to clumping within the unsieved calcium silicate or to retention by NUKON fibers within the valve.

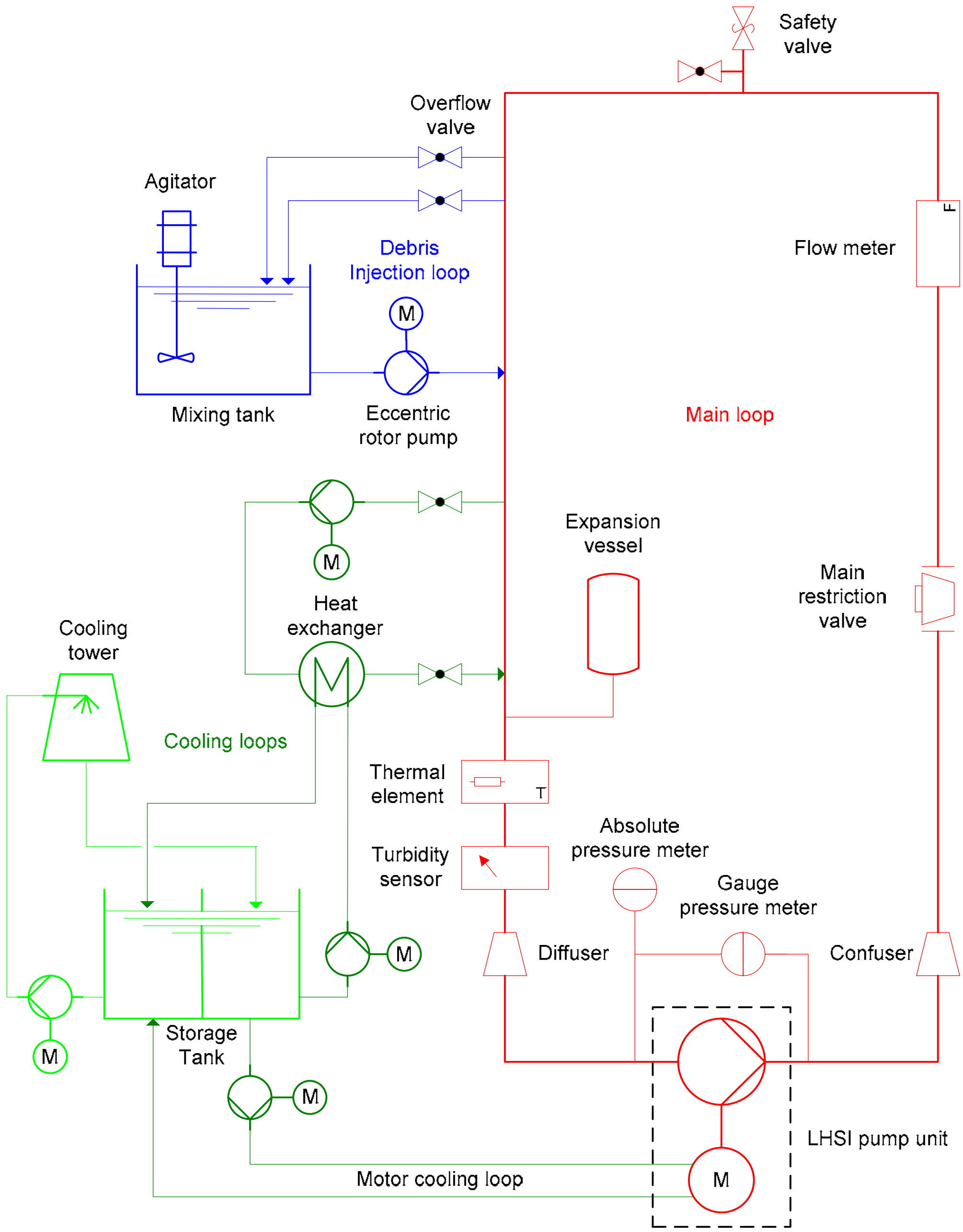
Title:	Test Facility Regarding Pump Behavior Handling Water with Solid Content
Authors:	I. Ganzmann et al.
Company:	AREVA NP GmbH
Document ID:	Various
Date:	From 2008 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Behavior of pumps (pressure head, vibrational behavior) handling water with solid content

Abstract: In 2008 AREVA NP Technical Center extended its Thermal Hydraulic Platform by a pump qualification test facility. The facility is designed to investigate the behavior of a pump handling water with solid content (debris). The test facility is designed to prevent particles settling as much as possible. An additional circuit equipped with a waste water pump provides the debris (e.g. fibers and particles) mixture. The mixture can be added to the facility during operation of the pump to be tested, the debris concentration is adjustable. Long term tests can be performed for several weeks.

Test Facility Capabilities:

Scaling:	Full scale
Test section:	Tubing DN150 Austenitic Material
Operating pressure:	40 bar max.
Operating temperature:	80 °C max.
Mass flow:	190 kg/s max.
Debris preparation:	Fibers heated at 300 °C for 24 h, mechanically or high pressure water jet fragmented; particulates (e.g. paint, concrete, Microtherm) sieved to different size classes
Measured variables:	Flow rate (pump) online Water temperature online Pressure head online System pressure online Turbidity online Vibration on pump and motor body (actual 12 sensors) Water solid content offline after sampling Water Ion concentration offline after sampling

Tests performed:
Tests have been performed for an EPR™ LHSI pump in 2008/2009 with a maximum debris concentration of 1500 ppm at a water temperature of 40 °C. Test of hydraulic pump performance based on DIN EN ISO 9906 has been performed in addition.



Schematic of the Pump Test Facility

Title:	Experiments on the Integral Test Facility “VIKTORIA”
Authors:	V. Soltesz (VUEZ (Slovakia)), J.- M. Mattei (IRSN (France)),
Companies:	VUEZ (Slovakia) and IRSN (France)
Document ID:	Various
Date:	From 2012 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Pressure loss on sump strainers; back flushing; downstream effects; chemical effects

Abstract: The "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN) has conducted a large program of research on the sump plugging issue between October 1999 and November 2000. This led to a methodology and technical specifications for an experimental program, which was carried out until 2003. Studies were carried out for different sizes of primary breaks: large, intermediate and small LOCA. The subjects giving rise to important questions were collected and it was decided to do a corresponding full-scale experimental program in order to answer the questions raised from the preliminary study. The following points are currently under experimental investigation:

- IVANA loop (VUEZ / SLOVAKIA): study of grinding of fibrous debris on the grating system (mechanical action of falling water);
- VITRA loop (EREC / RUSSIA): study of horizontal transfer speed of debris;
- MANON loop (VUEZ / SLOVAKIA): study of pressure drop and air and debris ingestion at the sump filters;
- ELISA loop (VUEZ / SLOVAKIA): establishment of different correlations.

Moreover, topics to be assessed have been identified to carry out a new research program using the VIKTORIA loop. The questions remaining open are related to gas phase creation, chemical effects, downstream effects and possible deposition of precipitates in different parts of the safety systems and the main coolant system (heat exchangers, core fuel assemblies, etc.). In 2010, IRSN and VUEZ decided to build the VIKTORIA loop with representative, universal and relevant characteristics that shall be able to model layout of different NPPs such as EPR, CPR1000, AP1000, VVER and existing PWR designs particularly focused to chemical effects and downstream effects.

The VIKTORIA loop, inaugurated the 2011 December 14, is designed to perform 30 day integral chemical effects experiments. The main assumptions used for the new loop test facility are to study:

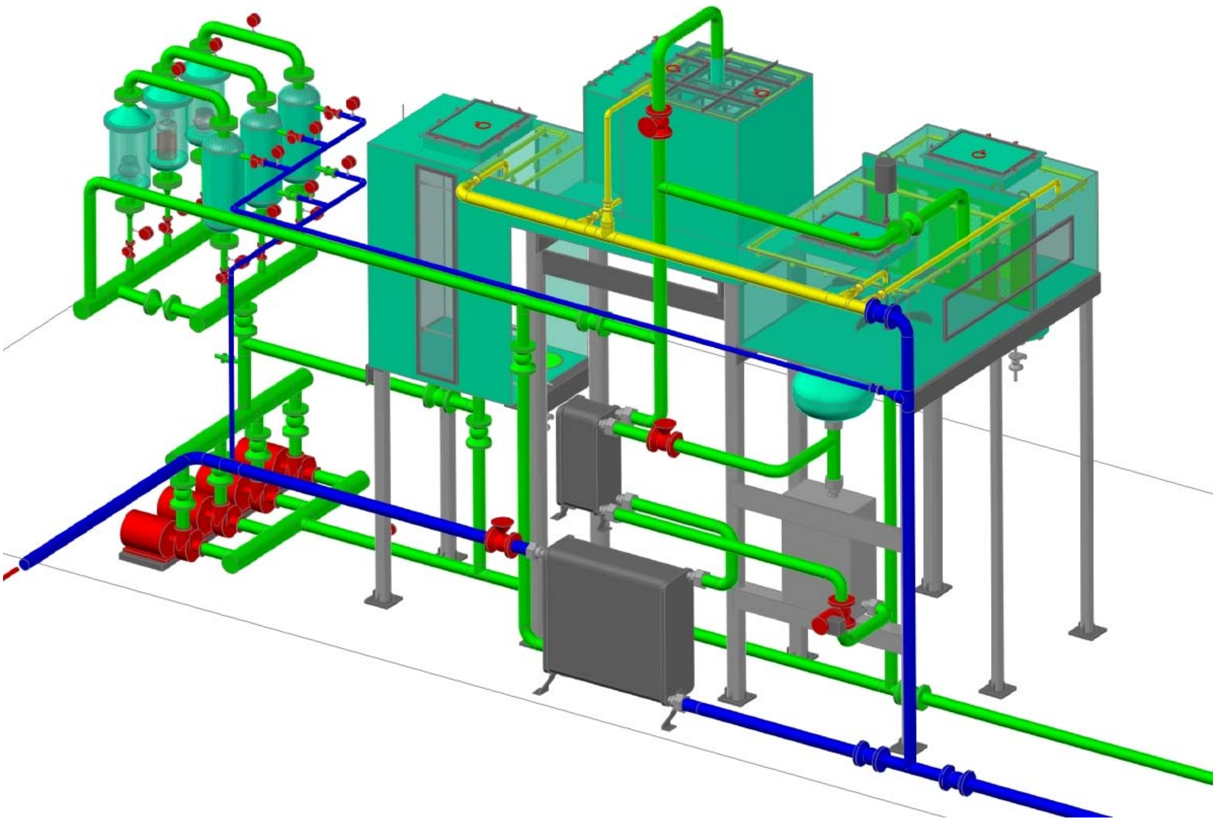
- Head loss of the filter;
- Chemical effects and influence on head loss and on downstream effects;
- Gas effects due to temperature and chemical process;
- Downstream effects.

Test Facility Capabilities: The VIKTORIA hydraulic test facility consists of 5 main interconnected segments:

1. Debris preparation tank – a tank where the debris that would be transported to the strainer is introduced and homogenously mixed;
2. Submerged material tank – a tank for placing coupons and samples of representative chemical reactive materials that would be submerged in the post-LOCA pool;
3. Spray system tank – a tank for placing coupons and samples of representative chemical reactive materials that would be exposed to containment spray;
4. Strainer tank – a tank for placing a full scale segment of a strainer. The debris preparation tank is connected to the strainer tank by a flume to prototypically simulate the debris transport to the strainer;

5.Downstream modules – a series of parallel chambers that can be used to place fuel assemblies, valves, heat exchangers, or other components downstream of the strainer.

Volume:	5 m^3
Operating Temperature:	90 °C max.
Mass flow:	175 gpm (40 m^3/h) max.
Strainer design:	All kinds of strainer designs applicable
Fuel element Section:	FA (fuel assembly) section to handle one or more FAs downstream sump strainer; flow direction in FA up- or downstream, pressure loss measurement on FA components
Debris preparation:	Fibers heated at 300 °C for 24 h, mechanically or high pressure water jet fragmented according to NEI guide “ZOI Fibrous Debris Preparation: Processing, Storage and Handling”; particulates sieved to different size classes
Measured Variables:	Flow rate (strainer and equipment as FA, heat exchanger, etc.) online
	Water temperature online
	Water pH online
	Water Turbidity online
	Pressure loss strainer online
	Pressure loss FA components online



Schematic of the Test Facility VIKTORIA

Title:	Model Experiments with VVER-440 Fuel Element and TH (ECCS)-Sump Filter with Improved Filtering Surface
Author :	L. Jani
Company:	Lappeenranta University of Technology, Nuclear Safety
Document ID:	SUPA 1/2008
Date:	19.12.2008
Document Length:	93 + 22 pages (in Finnish)
Nature of the Study:	Model test report
Phenomenon Studied:	Fibrous debris filter penetration and accumulation to the VVER-440 fuel element

Abstract: The ECCS of Loviisa NPP has been equipped with dedicated filters to prevent insulation debris and other impurities of the sump water from entering the process during the accident. However, during some phases of ECCS operation it is inevitable that small amounts of fibers penetrate the filters. The phenomenon has been studied experimentally.

The conditions and parameters of the core cooling modelling during recirculation phase depend on the size and location of the break. The parameter selection for the test model was based on the process analyses with the APROS simulation tool.

The performance of the VVER-440 strainer arrangement with different filters was studied experimentally at Lappeenranta University of Technology. The test set-up consisted of a heated water tank for mixing the boric acid to the water, a tank for mixing insulation material and a sedimentation tank for strainer with filter element. Additional devices were a fine filter element for catching the fibers passing the strainer filter, pumps for recirculation of the water and a full scale VVER-440 fuel element model.

The experiments were carried out in two phases. In the first phase the main objective was to define the amount of the fibers passing through the strainer filter element and the pressure loss over the fiber bed attached on the outer surface of the filter. Both the original filter and an enhanced filter structure were used in these tests. The pressure loss over the new filtering surface was also verified for licensing purposes so that the NPSH-requirements for the ECCS pumping system are met (tests LIS1 and LIS2). In the second phase of the tests the amount of fibers carried to the fuel element in the test arrangement was also studied. In these tests the surface area of the strainer filter was scaled according to the coolant flow through one fuel element in the VVER-440 reactor.

The insulation material, mineral wool, was tempered with heating it for several hours in the temperature of 350 °C or more. This procedure removed the chemicals used as binding agent in the mineral wool. After the heat treatment the mineral wool was crushed with high pressure water jet through a steel wire net.

In the tests the processes in a real NPP were simulated with the accuracy needed for finding out the behavior of the strainer system. This included mixing of the material and releasing the mixture containing water, mineral wool and boric acid to the sedimentation tank. After each test the amount of fibers was weighted after collecting them by washing and drying the samples.

Findings: The Phase 1 studies were conducted to support the Phase 2 fuel element studies. The aim was to study effects of selected parameters on fiber penetration. Among the chosen parameters were sedimentation time, fiber concentration, and nominal mass flow. Phase 2 was started with 25 min T_{sed}, 1.1 kg/m^3 concentration and a nominal flow of 0.61 kg/s. It was also decided that after first test, the following cases can be determined based on the results of the first experiment.

The pressure loss over the improved filtering surface (#0.7 mm wire mesh covering the old 2 mm perforated plate) was measured to verify that the NPSH-requirements for the pumping system are met (LIS2 test). The pressure loss was found to be well below the target.

The results of the fiber penetrations are in the following tables.

Table 1: Phase 1 Test Parameters.

Test	Filter (hole/area) [∅2 / #0.7, 0.08 / 0.44 m^2]	Time to Sedimentation [min]	Fiber concentration [$kg/m^3_{vettä}$]	Mass Flow [kg/s]	Temperature [°C]
SED1	∅2, 0.08	25	1.1	0.61	50
SED2	#0.7, 0.08	25	1.1	0.61	50
SED3	∅2, 0.08	25	1.1	0.30	50
SED4	#0.7, 0.08	25	2.2	0.61	50
SED7	#0.7, 0.08	50	1.1	0.61	50
FILL1	∅2, 0.08	25[1]	1.1	0.61	50
VER1	∅2, 0.08	25	1.1	0.61	50
MIN1	∅2, 0.08	0	1.1	0.61	50
LIS1	∅2, 0.44	25	6.4 kg	3.3	50
LIS2	#0.7, 0.44	25	6.4 kg	3.3	50

[1] Starting time for the recirculation

Table 2: Phase 1 Test Results.

Test	Penetrating mass [g]	Max. dP [mbar]	dP Aftern Cleaning [mbar]
SED1	8.7	18	Not measured
SED2	1.2	16	3
SED3	2.4	7	2
SED4	1.7	38	10
SED7	1.4	14	5
FILL1	3.8	16	7
VER1	11.3	20	5
MIN1	0.8	16	Not measured
LIS1	31.2	41	18
LIS2	9.0	33	16

Phase 2 tests were conducted using a similar test procedure as the Phase 1 tests. The test parameters for the first fuel element test were selected according to the results from Phase 1 tests. It was also determined that after the first fuel element tests, the situation can be reconsidered if results allow this.

Since the first test showed no or very little penetration with scaled filter surface, the following adjustments were made. The filter surface was increased to allow more open surface for the initial penetration phase, and at the same time, more fiber load to the fuel element. These changes are variations of the possible flow patterns for the filter in the containment and also for the fuel inside the core assembly.

Table 3: Phase 2 Test Parameters.

Test	Filter [∅2 / #0.7, 0.08 / 0.44 m^2]	Time to sedimentation [min]	Concentrati on [$kg/m^3_{vettä}$]	Flow thorough fuel element [kg/s]	Flow in Filter circuit [kg/s]	Temperatur [°C]
NIPPU1	#0.7, 0.08	25	1.1	4.3	0.61	50
NIPPU2	#0.7, 0.44	25	1.4	2.2	3.3	50
NIPPU2-2	#0.7, 0.44	25	1.4	2.2	3.3	50

The results for the fuel element tests show that the fibrous debris can accumulate on the fuel spacers and

develop additional pressure loss. However, even for the conservative cases, the pressure loss is well below the threshold where the cooling of the fuel element can be compromised. The coolability of the fuel element was determined with an APROS simulation model where the additional pressure loss caused by the fiber load was included in the core model according to the test results.

Table 4: Summary for Phase 2 Test Results.

Test	Fiber mass accumulated to fuel element [g]	dP over filter element [mbar]	dP after cleaning blow [mbar]	Max. dP over fuel element [kPa]
NIPPU1	<1	21	4	<1
NIPPU2	5.0	11	8	13
NIPPU2-2	3.2	12	8	9

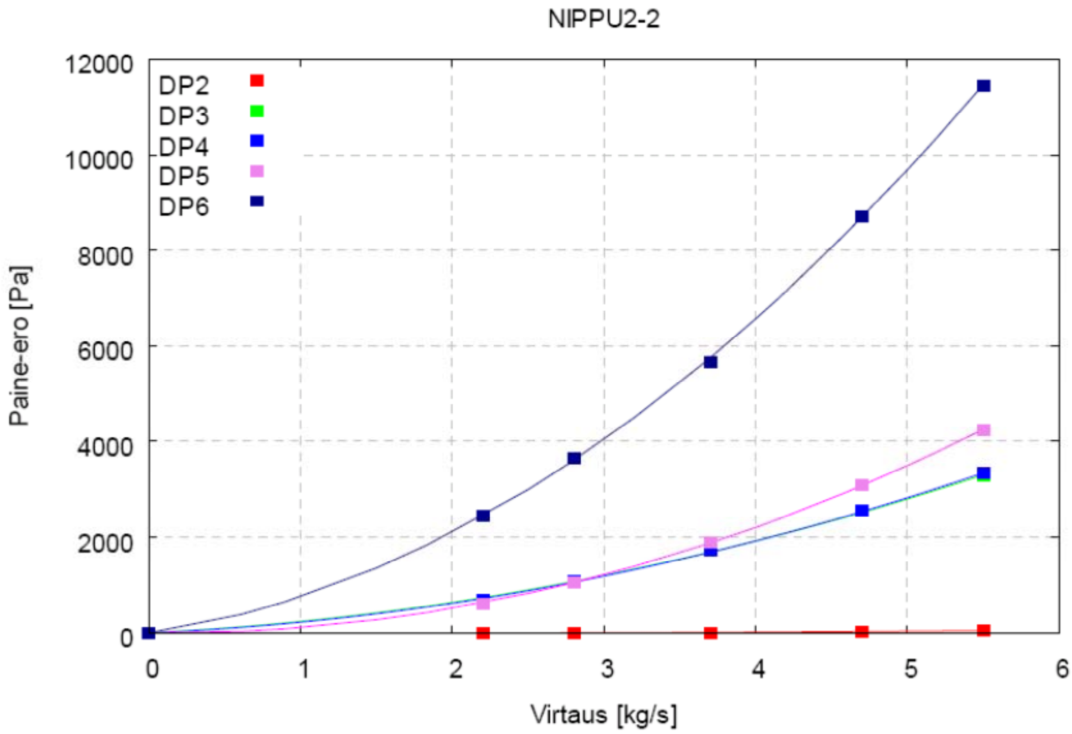


Figure 1: dP Measurements over the Fuel Element before Cleaning the Filter with Air Blow

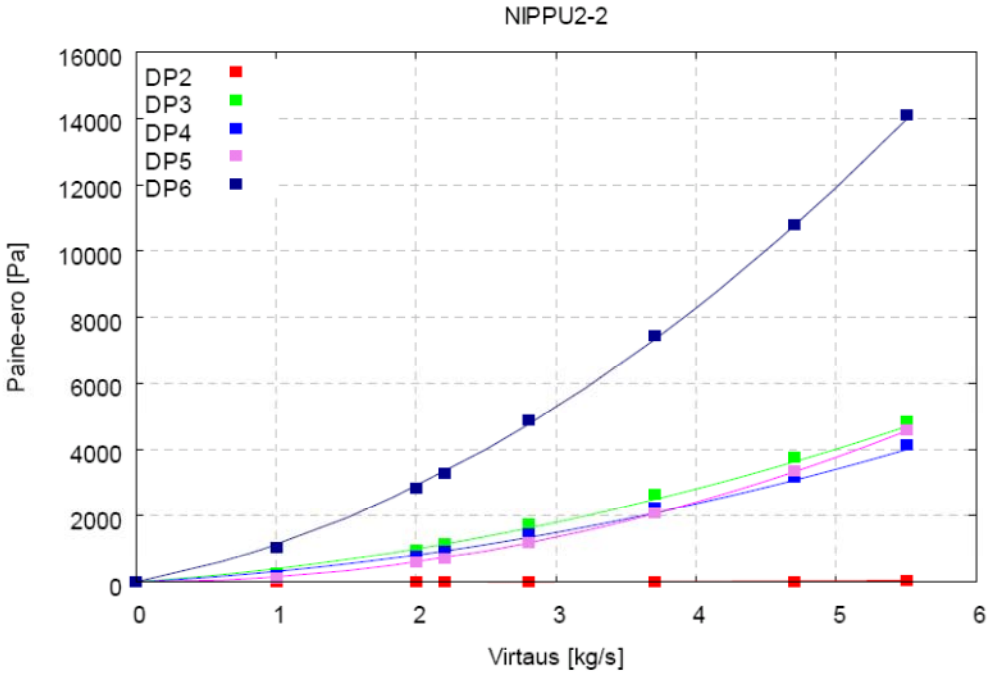


Figure 2: dP Measurements over the Fuel Element after Cleaning the Filter with Air Blow

Application to the Present Study: This test program was conducted to study the blocking effect of the fibrous debris in VVER-440 hexagonal fuel element. The fuel bundles were housed inside a hexagonal tube, which restricts the crossflows from element to element, allowing mixing only inside one hexagonal tube. The mechanism and resulting dP loss caused by blocking of the spacers can be considered as universal, but the importance of the blocking in the VVER-440 closed core is plant-type specific.

Mode of Debris Generation: Debris was generated with a cold water jet, 100 - 120 bar working pressure, by forcing the insulation material thorough a wire screen (#5 mm) to help destroy all the material to slurry. For every experiment, the required amount of new insulation material was crushed.

Debris Type: Mineral wool, base material diameter ~ 5 µm.

Debris Size: The material was destructed to a very homogenous slurry. The base material diameter is about 5 µm, and the mean length from a sample from the slurry was about 0.7 mm. Distribution of the sample as well as the mean length of the fibres was analysed with Lorentzen and Wettre Fibertester, and combined results are presented from the raw datafiles. With smaller hole, the resulting mean length for penetrating fibres is smaller, but not significantly. Longer fibers from the raw sample can be seen disappearing with both filters, except in LIS2_2 sample, which is very small (0.2 g, vs. 15 g in sample LIS1_2) taken after first blowdown.

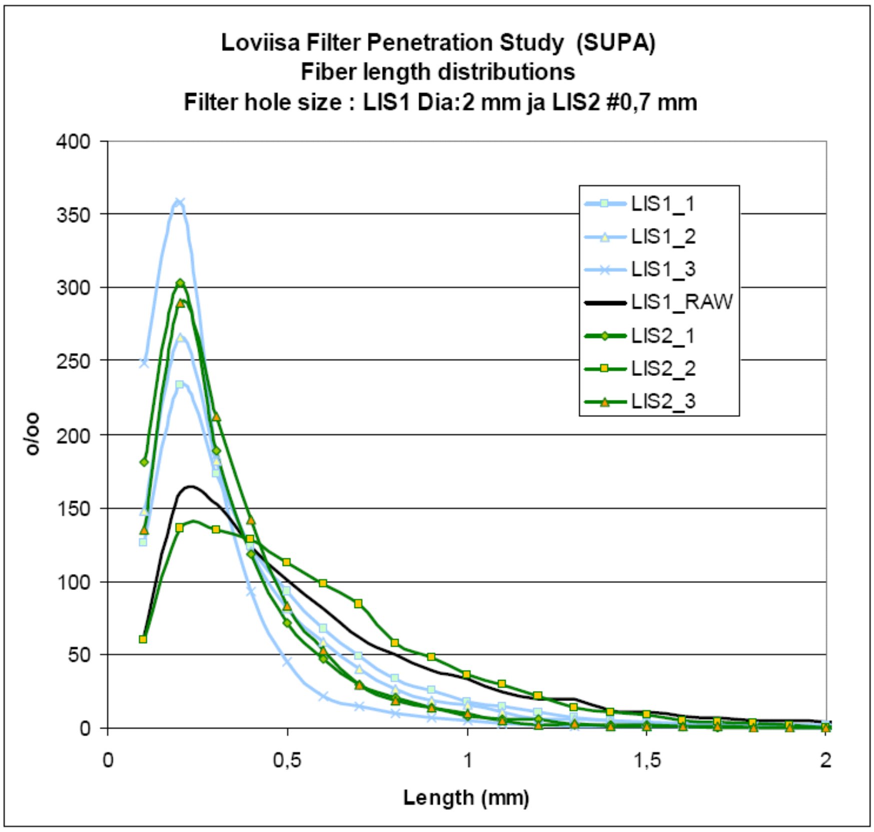


Figure 3: Fiber Length Distribution for Tests LIS1 and LIS2, with Sample 1 always from the Initial Penetration Phase

Suppression Pool Data: The volume of the facility was about 780 L in the first phase of the experiment. The pool water level was 0.8 m, the same as in the plant during ECCS operation. Turbulence inside the pool was suppressed since no sedimentation effect was studied. At the end of the experiment, the sedimented layer was mixed to the pool water and collected to the filter surface so that the effect of injected insulation debris mass to the pressure loss could be evaluated.

In the second phase the water volume was about 830 L, including the fuel element and downcomer model and excluding the fine filter loop. Downcomer module was a scaled volume at the inlet of the fuel element to simulate the pressure vessel bottom volume where the flow direction will turn upwards to pass thorough the core.

The water level for the filter was the same 0.8 m, and the test procedures were the same as previously.

Head Loss Data: Head loss was measured across the ECCS filter element. Since the amount of filters is not the same as the amount of fuel elements, the flow area in the filter was scaled so that the flow velocity at the filtering surface and inside the fuel element was the same as in plant during accident conditions with nominal ECCS flow. The debris load was scaled similarly.

During the experiment, flow rate was varied to examine the behaviour of the debris bed with different flows.

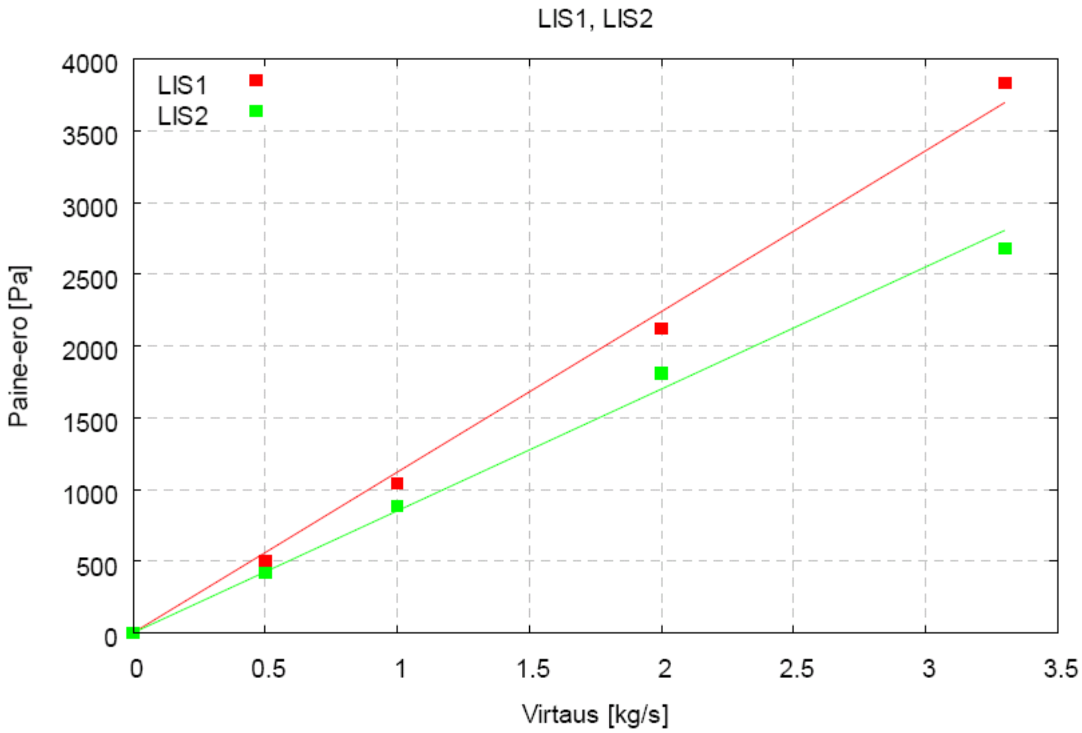


Figure 4: Pressure Loss over Filter Element against Flowrate (licensing experiments)

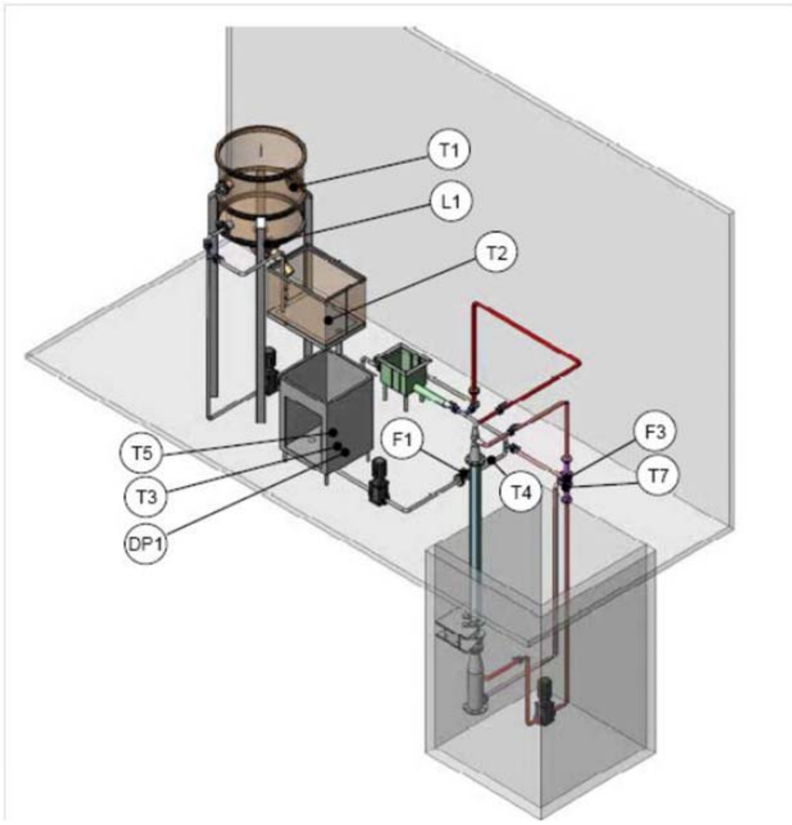
Table 5: Phase 1 Measurements and Facility Geometry

Code	Measurement	Equipment	Range	Accuracy
DP1	dP across the filter element	dP transmitter Yogogawa EJA 110	-20 000– 20 000 Pa	±380 Pa
F1	Flow in the filter circuit	Magnetic flow meter Fischer & Porter 10DX3111	0–600 l/min	±0.10 kg/s
F2	Air - blow flowrate	Vortex-flow meter Yokogawa Yewflo YF101-AAUD6D-S363	0–360 l/min	±0.68 g/s
L1	Level in boron tank	Transmitter for dP Foxboro IDP10-T22C01M-B1	0– 100 000 Pa	±0.10 m
P1	Pressure in air-blow	Pressure anturi Wika Tronic 891.14.500	0–10 bar	±0.09 bar
T1	Temperature in boron tank	Termoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T2	Temperature in mixing tank	Termoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T3	Temperature in filter tank	Termoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T4	Temperature for Flow measurement	Termoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T5	Temperature for Filter element	Termoelement K-tyyppi, NiCrNi, ∅1.5	0–250 °C	±2.5 °C
T6	Temperature of air flow	Termoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C

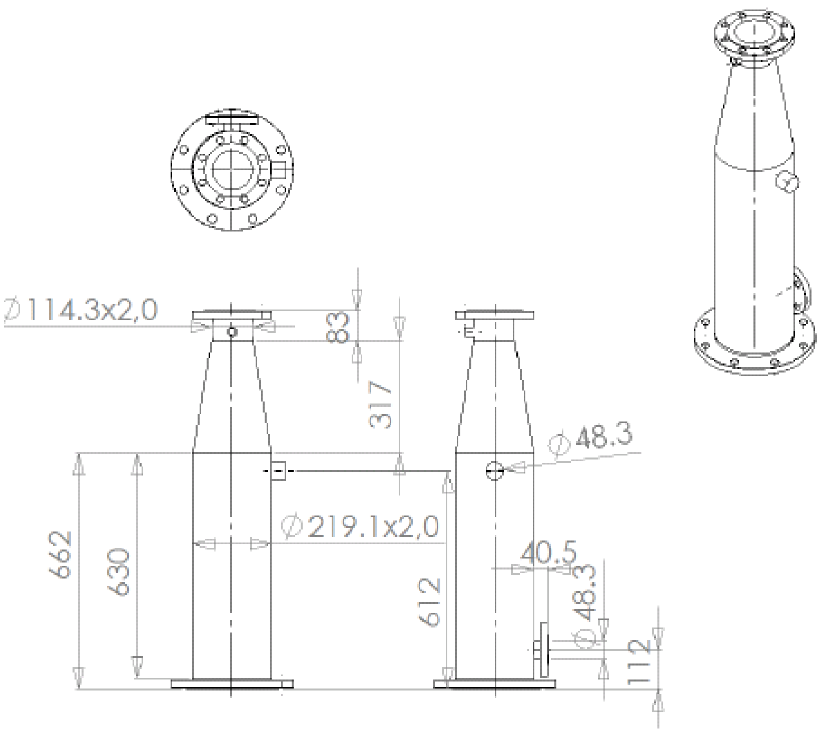
Table 6: Phase 2 Measurements and Facility Geometry

Code	Measurement	Equipment	Range	Accuracy
DP1	dP across the filter element	dP Transmitter Yogogawa EJA 110	-20 000–20 000 Pa	±380 Pa
DP2	dP across	dP Transmitter Foxboro IDP10-T22C01M-B1	-40 000–40 000 Pa	±750 Pa
DP3	dP thimbles 6 - 10	dP Transmitter Foxboro IDP10-T22C01M-B1	-40 000–40 000 Pa	±770 Pa
DP4	dP over thimbles 2 - 5	dP Transmitter Foxboro IDP10-T22C01M-B1	-40 000–40 000 Pa	±760 Pa
DP5	dP thimble 1	dP Transmitter Foxboro IDP10-T22C01M-B1	-40 000–40 000 Pa	±760 Pa
DP6	dP across over Fuel element	dP Transmitter Foxboro IDP10-T22C01M-B1	-100 000–100 000 Pa	±1900 Pa
F1	Filter element circuit Flow	Magnetic flow measurement Fischer & Porter 10DX3111	0–600 l/min	±0.10 kg/s
F2	Air Flow	Vortex-flow measurement Yokogawa Yewflo YF101-AAUD6D-S363	0–360 l/min	±0.68 g/s
F3	Fuel element circuit Flow	Magnetic flow measurement Krohne Altometer DN25-T-V4A[2]	-348–348 l/min	±0.11 kg/s
F3	Fuel element circuit Flow	Magnetic flow measurement Fischer & Porter 10DX3111[3]	0–500 l/min	±0.08 kg/s
L1	Boron tank Level	dP Transmitter Foxboro IDP10-T22C01M-B1	0–100 000 Pa	±0.10 m
P1	Air Pressure	Pressure measurement Wika Tronic 891.14.500	0–10 bar	±0.09 bar
T1	Boron tank Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T2	Mixing pool Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T3	Pool Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T4	Flow F1 Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T5	dP over filter Temperature	Thermoelement K-tyyppi, NiCrNi, ∅1.5	0–250 °C	±2.5 °C
T6	Air Flow Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C
T7	Flow F3 Temperature	Thermoelement K-tyyppi, NiCrNi, ∅3.0	0–250 °C	±2.5 °C

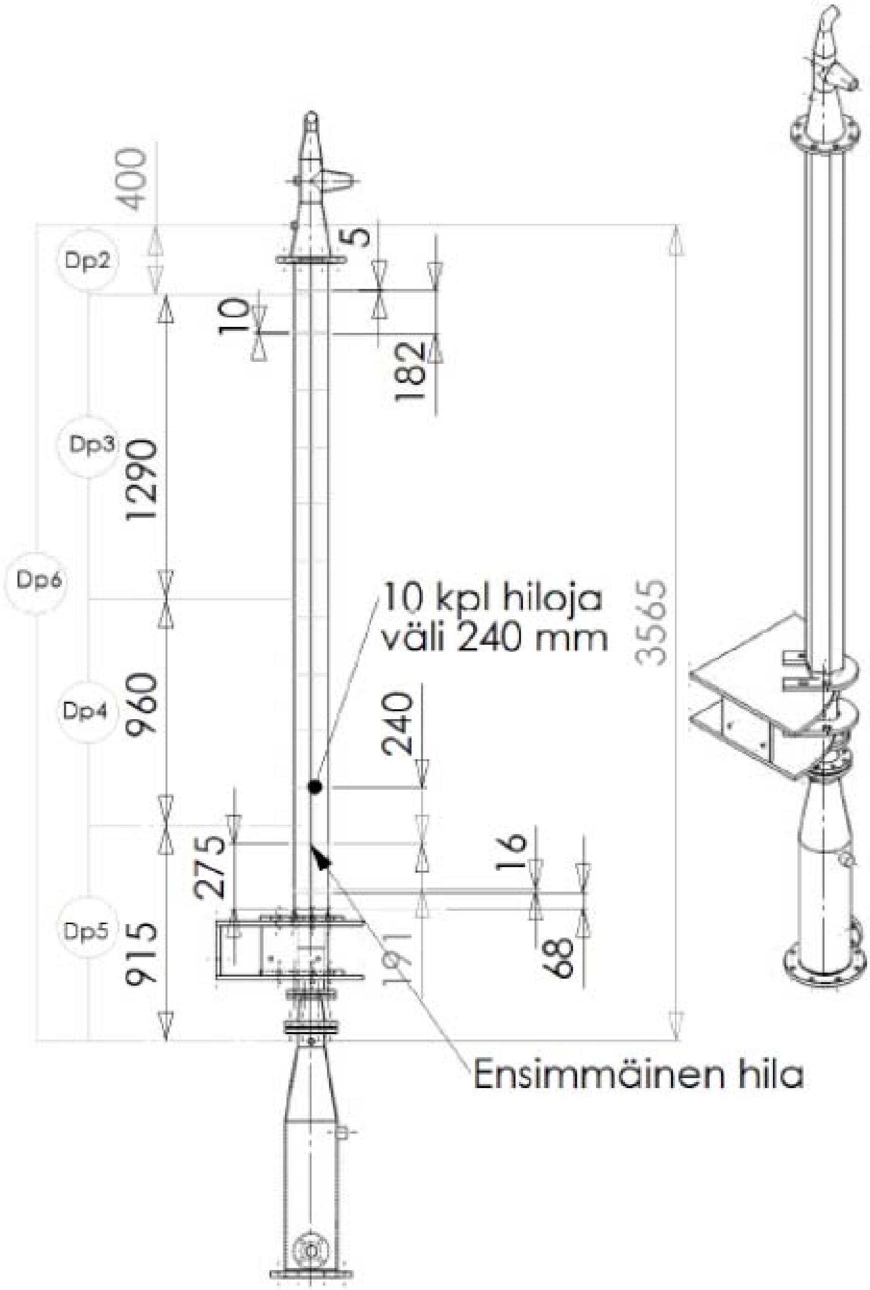
[2] In tests NIPPU1 ja NIPPU2
[3] In test NIPPU2-2



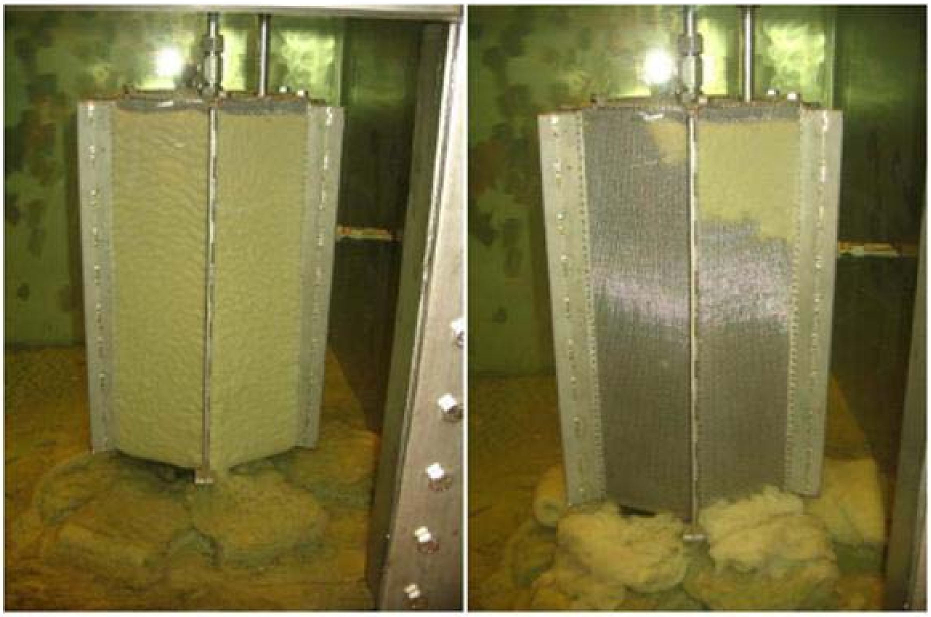
Picture 1: The Test Facility for Phases 1 and 2



Picture 2: Downcomer Modelling Volume



Picture 3: Phase 2 Measuring Instruments for Fuel Element Pressure Loss



Picture 4: The Filter before (left) and after Stopping the Flow at Time 216 min.

Picture 5: The Dismantled Fuel Element and Collected Debris in Spacer Lower Part after the NIPPU2-2 Experiment.

Title:	Test Facility Regarding Valve Behavior Handling Water with Solid Content
Authors:	I. Ganzmann et al.
Company:	AREVA NP GmbH
Document ID:	Various
Date:	From 2010 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Behavior of valves (opening/closing time and forces, leak tightness) handling water with solid content

Abstract: In 2010 AREVA NP Technical Center extended its Thermal Hydraulic Platform by a valve qualification test facility. The facility is designed to investigate the behavior of a valve handling water with solid content (debris). The test facility is designed to prevent particles settling as much as possible. The debris mixture can be added to the facility during operation of the valve to be tested, the debris concentration is adjustable. Long term tests can be performed for several weeks.

Test Facility Capabilities:

Scaling:	Full scale
Test section:	Tubing DN150 Austenitic Material
Operating pressure:	16 bar max.
Operating temperature:	80 °C max.
Mass flow:	280 kg/s max.
Debris preparation:	Fibers heated at 300 °C for 24 h, mechanically or high pressure water jet fragmented; particulates (e.g. paint, concrete, Microtherm) sieved to different size classes
Measured variables:	Flow rate (pump) online Water temperature online Pressure difference across valve online System pressure online Water solid content offline after sampling Water ion concentration offline after sampling

Title: Tests for Chemical Precipitate Deposition on Fuel Cladding
Author: M. Fukasawa, H. Utsuno
Company: Japan Nuclear Energy Safety Organization (JNES)
Document ID: 10原熱報-0006, JNES-RE-2012-0001
Date: October 2010, August 2012, respectively
Document Length: 169, 8 (pp. 25-32) pages, respectively (in Japanese)
Nature of the Study: Experimental
Phenomenon Studied: Downstream effects

Abstract: Deposition of chemical precipitates on the fuel cladding using an electrically heated rod was investigated with the integrated chemical effect test facility, which was additionally equipped with a loop simulating boiling at a fuel pin in the core. A test shows chemical precipitates deposited on the cladding and the deposit was found to be mainly calcium compounds.

Test Condition: Deposition of chemical precipitates on the fuel cladding was investigated with the ICAN test facility, which had been used for chemical effects studies on sump screen clogging. The ICAN test loop is equipped with a tank and two cylinders to measure head loss to simulate chemical environment of the sump water and the head loss at the screen for 30 days. The ICAN facility was newly equipped with a loop which has an electrically heated fuel pin model to make boiling of the solution from the tank. The cladding of the fuel pin model is made of Zircaloy-4 and is 500 mm long and 10.7 mm of diameter. A 300 mm heater long was installed inside of the cladding. The heater had a maximum power of 2 kW and could boil the solution from the tank at a velocity of a few mm/s, which simulates ECCS water from the sump during long term core cooling after a LOCA.

Tests were conducted under the chemical condition simulating a plant using NaOH as the pH buffer.

Findings: The following conclusions were obtained.

1. Table 1 shows the basic data on the chemical precipitates. The deposits were analyzed to be Ca compounds ($CaCO_3$) originating from insulation and their thermal conductivity was evaluated;

2. Chemical precipitates deposited on the cladding and the surface temperature increased by a few tens of a degree centigrade;

3. A deposition model in which the deposition rate was equal to the steaming rate multiplied by the chemical product concentration of the solution did not simulate the test results;

4. Figure 2 shows the pH dependencies of deposition of chemical precipitates. The deposition of chemical precipitates on the fuel cladding did not occur under conditions where the sump pH solution was less than 9. Therefore, it was recommended to keep the pH of the sump solution less than 9 in a plant using NaOH as the pH buffer.

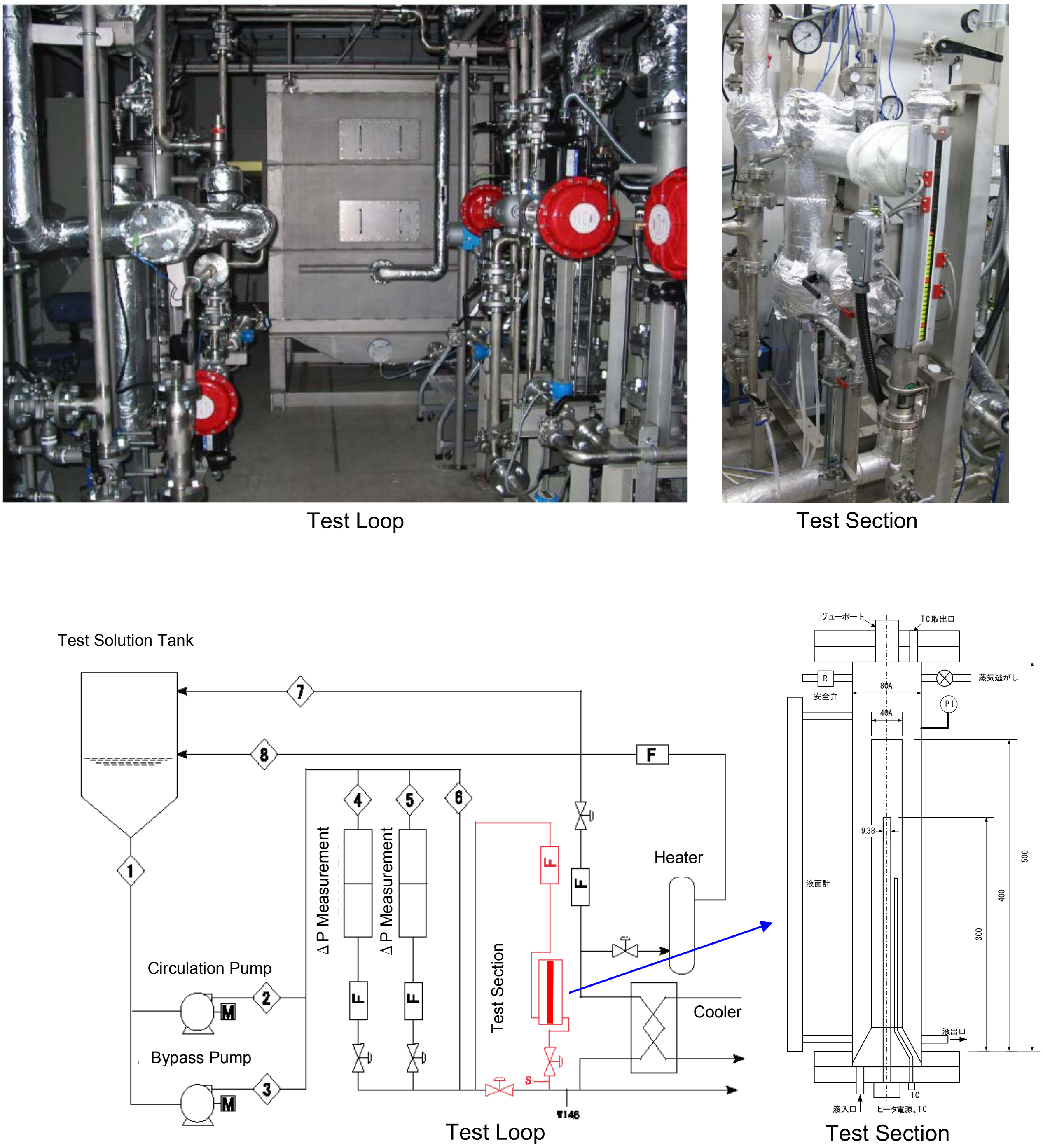


Fig. 1: Test Facility for Chemical Precipitate Deposition on Fuel Cladding (from 10原熱報-0006 and JNES-RE-2012-0001).

Table 1: Basic Data on Chemical Precipitates (from JNES-RE-2012-0001)

Test No.		Unit	ICAN-D1	ICAN-D2	ICAN-D3	ICAN-D4
Simulated PWR Condenser			DC	DC	IC	DC
Insulation			RW	RW	RW	RW+ $CaSiO_3$
Iodine Remover			NaOH	N_2H_4	$Na_2B_4O_7$	NaOH
pH			10.3	7.0	8.2	10.3
Chemical Precipitates			$CaCO_3$	ND	ND	$CaCO_3$
Thermal Conductivity		W/(mK)	1.6	-	-	2.6
Deposited Thickness on Fuel Cladding	Max.	mm	0.87	-	-	1.96
	Ave.	mm	0.55	-	-	1.11

DC: Dry Condenser, IC: Ice Condenser, RW: Rock Wool, ND: Not Detected

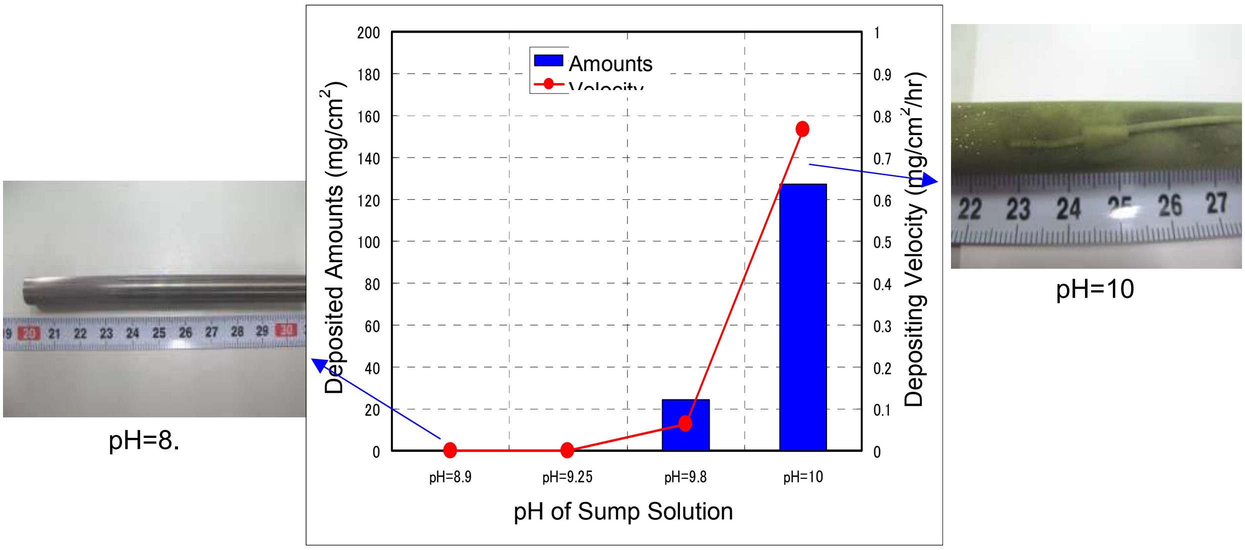


Fig. 2: pH Dependencies of Deposition of Chemical Precipitates (from JNES-RE-2012-0001)

Title:	Tests for Downstream Flow Clogging due to Debris Accumulation
Author:	M. Fukasawa, H. Utsuno
Company:	Japan Nuclear Energy Safety Organization (JNES)
Document ID:	10原熱報-0006, JNES-RE-2012-0001
Date:	October 2010, August 2012, respectively
Document Length:	169, 8 (pp. 25-32) pages, respectively [in Japanese]
Nature of the Study:	Experimental
Phenomenon Studied:	Downstream effects

Abstract: Characteristics of fiber debris passing through the sump screen were investigated.

In the downstream pressure drop test, 100% debris passing through the sump screen and transportation was assumed for conservatism, the relation of pressure loss and approaching flow velocity during flow clogging condition was investigated.

Test Condition: Figure 1 shows the test facility. The test facility consists of a test solution tank, circulation pump, debris supply section, flow controller and the pressure loss measurement section. Supplied debris were rock wool as a fiber debris and FeOOH with a diameter of 0.1-0.2 μm as particulate debris.

At first, the characteristics of fiber debris passing through the sump screen were investigated. Next, the relation between accumulated debris amounts and approaching flow velocity under the condition with a constant pressure was investigated. Then, 100% debris passing through the sump screen and transportation was assumed for conservatism in the downstream pressure drop test and the relation of pressure loss and approaching flow velocity during flow clogging condition was investigated.

Findings: The following conclusions were made:

1. Figure 2 shows fiber debris amounts that passed through the sump screen. The fiber debris amounts that passed through the sump screen were a few percent of the amount supplied, and increased with the diameter of the sump screen or approach flow velocity.
2. Figure 3 shows the distribution of fiber debris size that passed through the sump screen. Major fiber debris of size less than 20 μm passed through the sump screen with a mesh diameter 1.5 mm, similar to the one used in the actual plant.
3. Figure 4 shows the relation between accumulated fiber debris amounts and the sump screen and approaching flow velocity. Approach flow velocity decreased with an increase of the accumulated fiber debris amount to the sump screen.
4. The flow clogging condition was obtained under the test condition that assumed 100% debris passing through the sump screen to be conservative, where particle debris accumulated on a fiber debris layer when the pressure loss is less than 30 kPa and particle debris detached from a fiber debris layer when the pressure loss is more than 35 kPa. Figure 5 shows the relation between pressure loss and approaching flow velocity during the flow clogging condition.

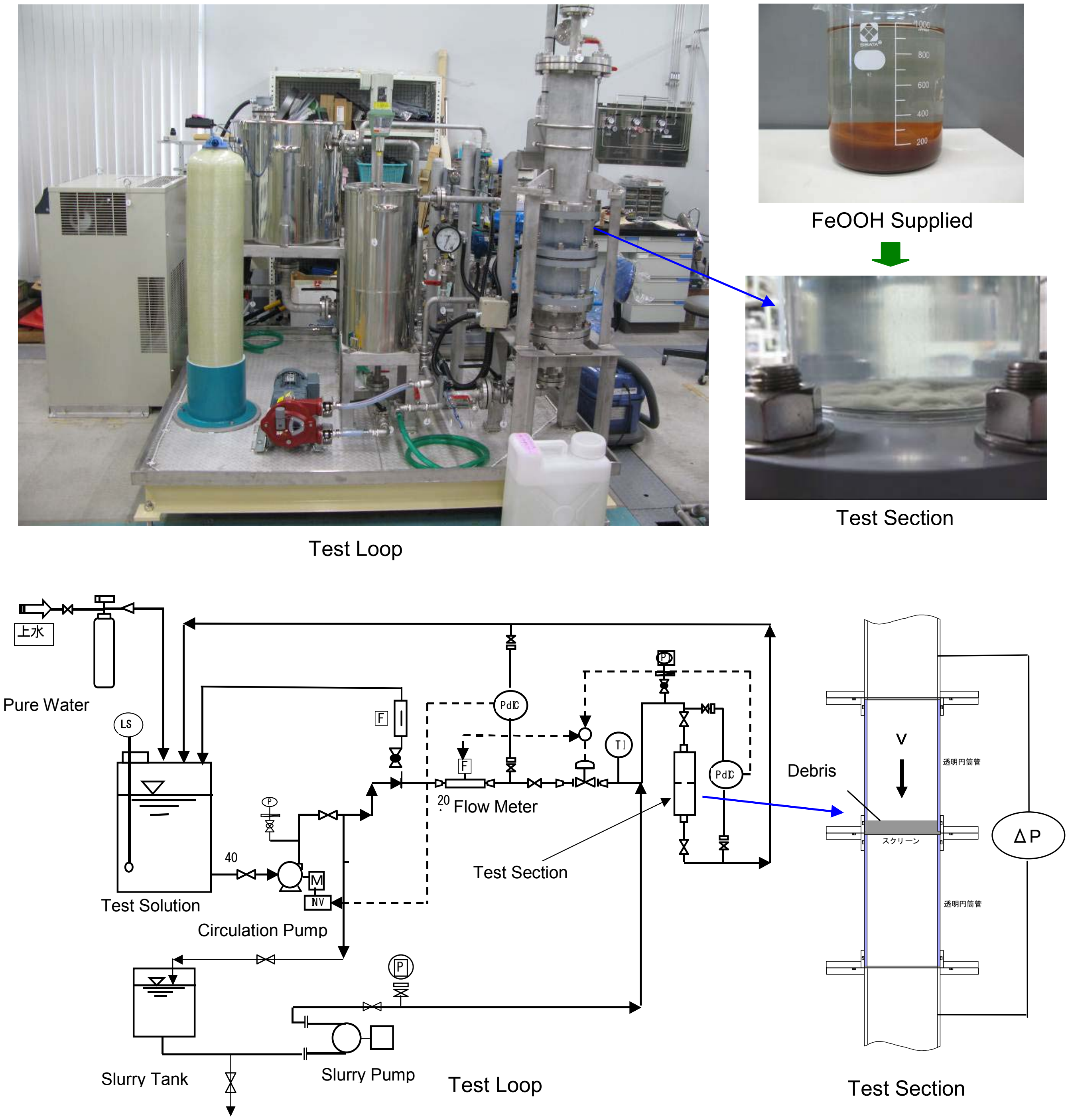


Figure 1: Test Facility for Downstream Flow Clogging due to Debris Accumulation (from 10原熱報-0006 and JNES-RE-2012-0001)

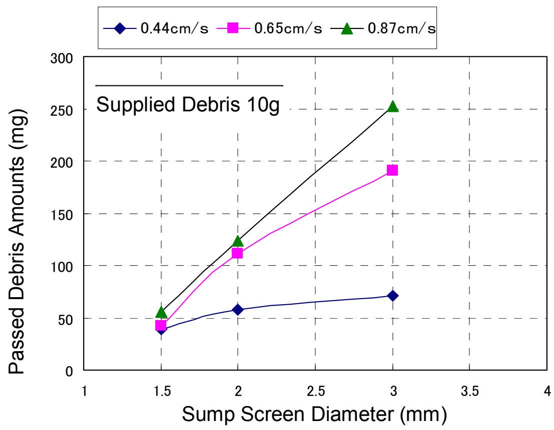


Figure 2: Fiber debris amounts passed through sump screen (from JNES-RE-2012-0001)

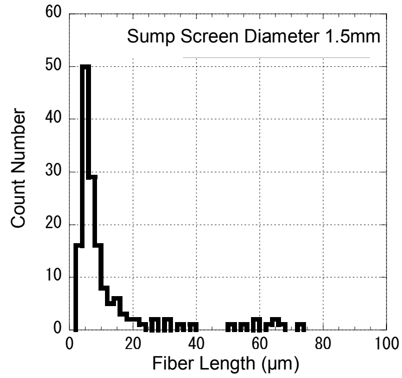


Figure 3: Distribution of fiber debris size passed through sump screen (from JNES-RE-2012-0001)

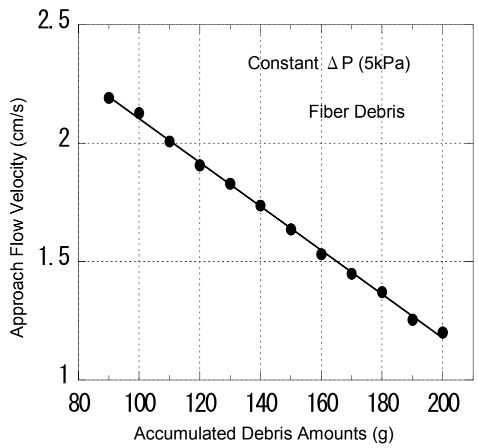


Figure 4: Relation between accumulated fiber debris amounts and approach flow velocity (from JNES-RE-2012-0001)

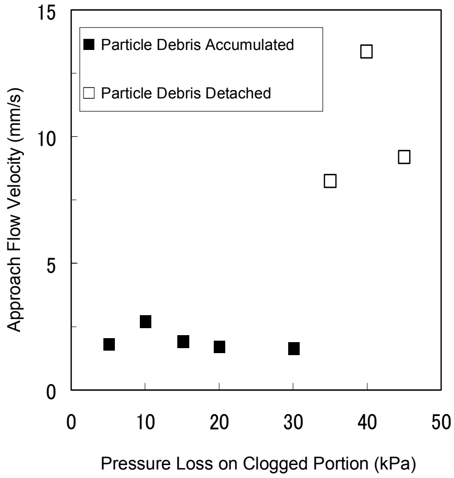


Figure 5: Relation of pressure loss and approach flow velocity during flow clogging (from JNES-RE-2012-0001)

Title: Analysis on Core Inlet Clogging during LOCA in PWR
Author: H. Utsuno, H. Asaka, K. Fujioka
Company: Japan Nuclear Energy Safety Organization (JNES)
Document ID: 10原熱報-0008, JNES-RE-2012-0001
Date: March 2011, August 2012, respectively
Document Length: 72, 8 (pp. 25-32) pages, respectively [in Japanese]
Nature of the Study: Analytical
Phenomenon Studied: Downstream effects

Abstract: To confirm long term core coolability in the case of core inlet clogging due to debris passed through the sump screen, an analysis with the thermal-hydraulic code TRACE has been conducted. The analysis with the thermal-hydraulic code TRACE has shown the long term core cooling condition in case of the core inlet clogging during a LOCA in PWR plants.

Analytical Condition: To confirm long term core coolability in case of core inlet clogging due to accumulation of debris passed through the sump screen, an analysis with the thermal-hydraulic code TRACE has been conducted. It was assumed that the core inlet was 99% clogged with an additional pressure loss coefficient K, and chemical precipitates were deposited on all fuel rod cladding just after ECCS recirculation operation started during a cold-leg or hot-leg break LOCA in a PWR. The additional pressure loss coefficient K was treated as a parameter.

Figure 1 shows the three-loop PWR plant TRACE analytical model, in which the reactor vessel is divided into 18 vertical levels, 5 radial rings and 6 azimuthal sectors with cylindrical coordinates.

The criterion for long term core coolability applied is that the peak cladding temperature (PCT) is less than 700 K.

Findings: The following conclusions were obtained.

1. Figure 2 shows the analytical result for PCT in case of core inlet clogging during a cold-leg break LOCA, which is the representative event for the long term core cooling in a PWR plant. Long term core cooling (PCT<700 K) is maintained even if the core inlet was 99% clogged with an additional pressure loss coefficient of less than 20 (K≦20).
2. Figure 3 shows the long term core cooling condition. Pressure drop is evaluated for the flow pass clogged 99% with an additional pressure loss coefficient of 20 (K=20). The long term core cooling condition was obtained as eq. (1) in terms of approach flow velocity and pressure loss on the clogged core inlet during a LOCA in PWR plants.

$$\Delta P \leq 0.1V^2 \qquad (1)$$

where

ΔP :pressure loss on the clogged core inlet (kPa)

V : approach flow velocity (mm/s).

Recommendation based on Experimental and Analytical Study: The long term core cooling condition in terms of approach flow velocity and pressure loss on the clogged core inlet during LOCA in a PWR was obtained by analysis with TRACE.

Although the probability of core inlet clogging becomes lower after taking the characteristics of the rate and the size of debris passing through the sump screen into consideration, if 100% debris passes through the sump screen and transportation is assumed the core inlet may be clogged due to debris accumulation and the long term core cooling condition on the clogged core inlet may not be satisfied.

Therefore, in order to confirm whether the long term core cooling condition is satisfied or not it is recommended to conduct experiments simulating the once-through process with debris passing through the sump screen, transportation and core inlet clogging due to accumulation of debris which passed through the sump screen.

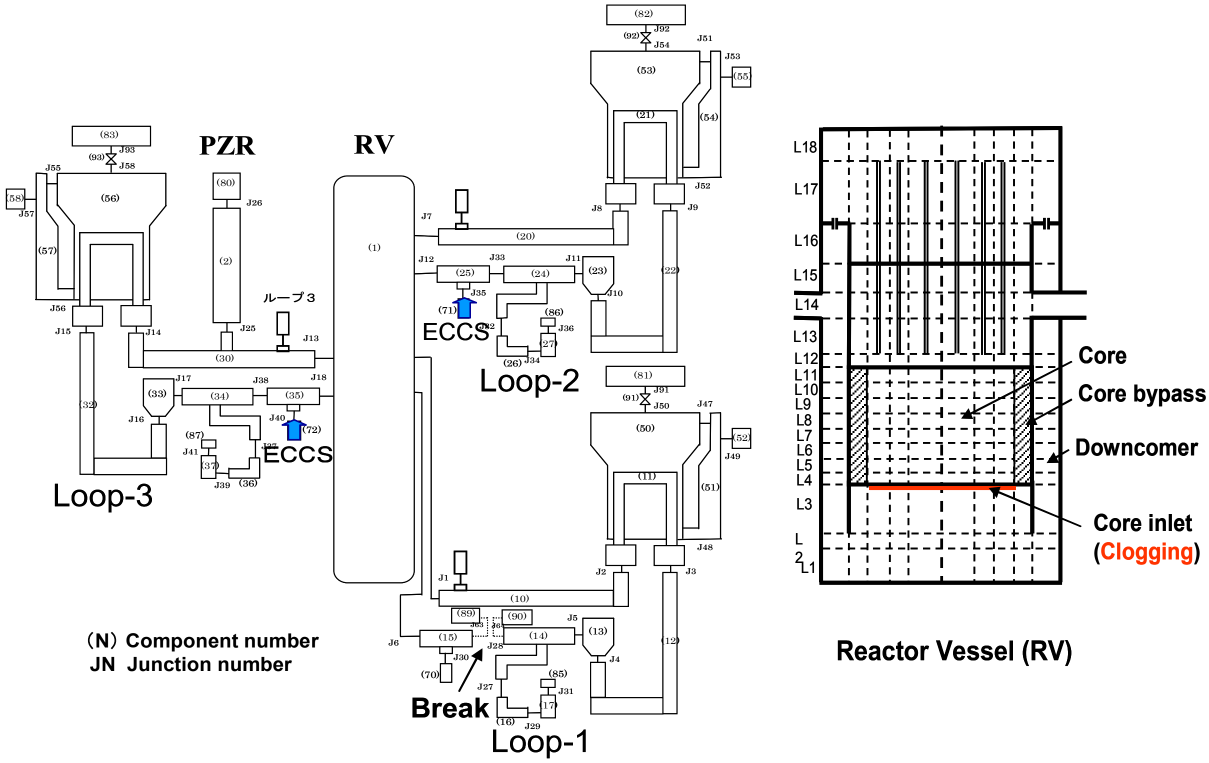


Figure 1: Three-loop PWR plant TRACE Analytical Model (from 10原熱報-0008)

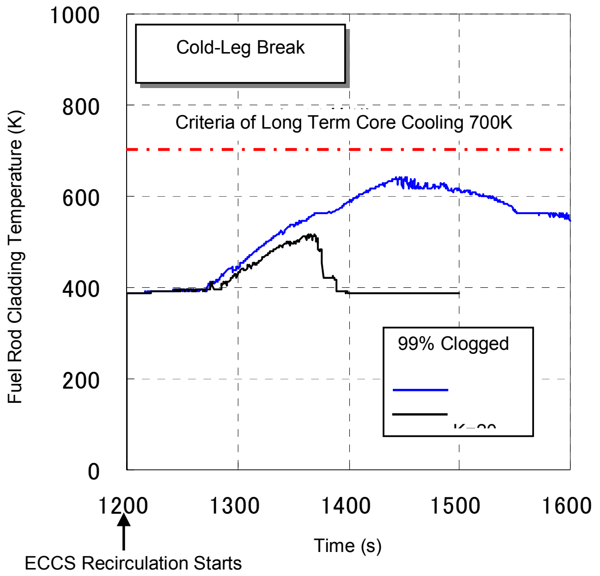


Figure 2: Analytical result for PCT in case of core inlet clogging during a cold-leg break LOCA in a PWR (from JNES-RE-2012-0001)

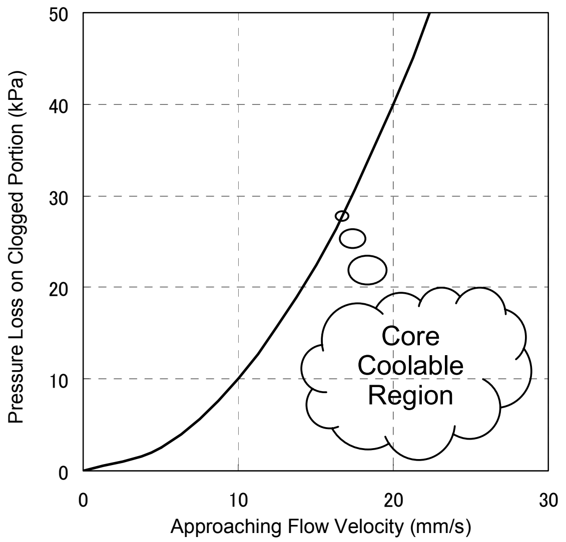


Figure 3: Long term core cooling condition on the clogged core inlet during a LOCA in a PWR (from JNES-RE-2012-0001)

RISK ASSESSMENT OF DEBRIS BLOCKAGE

Title:	GSI-191: The Impact of Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency
Author:	J. L. Darby et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	NUREG/CR-6771
Date:	August 2002
Document Length:	115 pages
Nature of Study:	Evaluation
Phenomena Studied	PWR Core Damage Frequency

Abstract: This report documents a risk significance study that supported a parametric evaluation of operating U.S. PWR plants to assess whether or not ECCS recirculation sump failure is a plausible concern. This evaluation was part of the NRC GSI-191 study tasked to determine if the transport and accumulation of debris in a containment following a LOCA will impede the operation of the ECCS in operating PWRs.

Findings: The parametric evaluation identified a range of conditions in which PWR ECCS could fail in the recirculation mode of operation. These conditions stem from the destruction and transport of piping insulation materials, containment surface coatings (paint), and particulate matter (e.g., dirt) by the steam/water jet emerging from a postulated break in reactor coolant piping. The likelihood that sufficient quantities could transport and accumulate on the recirculation sump screen to severely impede recirculation flow is plant specific and a review of PWR plant design features indicated adverse conditions exist in several plants.

The specific goal of the risk significance study was to estimate the amount by which the core damage frequency (CDF) would increase if failure of PWR ECCS recirculation cooling due to debris accumulation on the sump screen were accounted for in a manner that reflects the results of recent experimental and analytical work. Further, the estimate was made in a manner that reflected the total population of U.S. PWR plants. Results suggest the conditional probability of recirculation sump failure (given a demand for recirculation cooling) is sufficiently high at many U.S. plants to cause an increase in the total CDF of an order of magnitude or more.

Title:	The Impact of Recovery from Debris-Induced Loss of ECCS Recirculation on PWR Core Damage Frequency
Author:	K. T. Kern and W. R. Thomas
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	Technical Report LA-UR-02-7562 (ADAMS ML030610174)
Date:	February 2003
Document Length:	50 pages
Nature of Study:	Evaluation
Phenomena Studied	Core damage frequency

Abstract: This letter provides an extension of the findings given in NUREG/CR-6771, GSI-191: *The Impact of Debris-Induced Loss of Emergency Core Cooling System (ECCS) Recirculation on Pressurized Water Reactor (PWR) Core Damage Frequency*. Specifically, given here is an analysis of the recovery from the events discussed in NUREG/CR-6771 and the impact of recovery on core damage frequency. Recovery options were described in NUREG/CR-6771 but not analyzed. The recovery options from debris-induced loss of NPSH are (1) continued cooling with ECCS recirculation and (2) alignment of an alternative source of borated cooling water. Continued ECCS recirculation could be achieved by the pumps if they provide sufficient flow despite loss of NPSH or by operator actions to restore NPSH. Cooling with alternative sources of borated water involves realigning the pumps to injection mode and refilling the refueling water storage tank (RWST).

Findings: NUREG/CR-6771 showed that debris effects resulted in a CDF for LOCA events that was almost 140 times the CDF without considering debris when traditional initiating event frequencies are used. (Note: corrections to the NUREG/CR-6771 results are reflected here.) Allowing for leak before break, the CDF with debris was 45 times the CDF without debris. The analysis discussed here shows that, considering the effects of debris and allowing for recovery, the CDF resulting from LOCA events for PWRs is on average 19 times higher than the CDF when debris effects are not considered. Allowing for leak before break initiating frequencies, the CDF with debris and recovery is twice the CDF without considering debris.

These results indicate that the potential for increased CDF due to LOCA events because of sump blockage is significant enough to warrant detailed plant-specific analysis of recovery options, leading to actions to mitigate the increase in CDF.

Title:	Fiber Bed Behaviour in Two-phase Flow Test Facility “ISOTRAN“
Authors:	C. Schuster, A. Hurtado
Contact:	christoph.schuster@tu-dresden.de
Company:	Technische Universität Dresden
Date:	From 2009 to 2011
Nature of study:	Original geometry experiments to investigate the behavior of fiber beds below BWR rod bundle spacers during the transition to two-phase flow
Phenomenon studied:	Formation of fiber beds below spacers; appearance of steam bubble inside and below fiber bed; disaggregation and destruction of fiber bed due to steam bubble dynamics

Abstract: Within a research project founded by the company Vattenfall Europe Nuclear Energy GmbH, the test facility ISOTRAN has been designed to investigate the behavior of insulation material fiber beds in a BWR rod bundle. During emergency core cooling with sump water, fibers can form a layer (fiber bed) in rod bundles below the spacers. After the formation of a fiber bed the recirculating fluid was heated with the heater rods up to saturation temperature. The formation of steam bubbles inside the fiber bed which is soaked with liquid water causes primarily a disaggregation and subsequent the destruction of the fiber bed. Therefore the flow path through the rod bundle was re-established due the onset of two-phase flow. In addition to the measurement of heater power, temperature, flow rate and differential pressure the visual observation (video film) provides an informative basis about the process.

The test facility ISOTRAN consists of a closed loop with an overall height of 2.8 m (Figure 1). The scheme of the facility (Figure 2) shows the channel with the heater rod bundle and 3 spacers as the main component. The radial geometry of the rod bundle was adopted from BWR fuel elements including the use of original spacers (Figure 3 and 4). The water recirculates in the loop and can be heated by the heater rods up to a fully developed two-phase flow. The condenser deals as a heat sink. The loop is connected to the atmosphere. The insulation material fibers were stirred in a small flask and after that filled into the loop at high fluid velocities. After the formation of the fiber bed below the lowermost spacer the velocity was reduced and the heater power was increased to produce steam in the rod bundle. The most significant statements can be derived from high resolution video films which are showing the spacer and the fiber bed (Figure 5).

Test facility capabilities: Number of heater rods: 25

Diameter of heater rods: 10.0 mm

Grid step: 12.4 mm

Power per rod: 1 kW

Length of heater rod/heated: 1565 mm/1000 mm

Maximum velocity in rod bundle: 25 cm/s

Tests performed: 11 experiments with 5 g insulation material MDK-2

4 experiments with 10 g insulation material MDK-2

1 experiments with 15 g insulation material MDK-2

Fiber preparation: Crushing by hand and stirring in water

Measured variables: Fluid velocity in rod bundle

Heater power

Differential pressure over all spacers

Fluid temperature at channel inlet, 12 mm and 4 mm below lowermost spacer, inside spacer, channel outlet

Surface temperature at central rod, 12 mm and 4 mm below lowermost spacer and inside spacer

Video films

Literature:

C. Schuster; H. Ohlmeyer; G. Laczko; M. Ignaczak; A. Hurtado: Untersuchung des Transports von Isoliermaterial durch SWR-Abstandshalter beim Übergang zur Zweiphasenströmung; Annual Meeting on Nuclear Technology 2011, Berlin, 17-19 May 2011, proceedings

Figure. 1: Test facility ISOTRAN

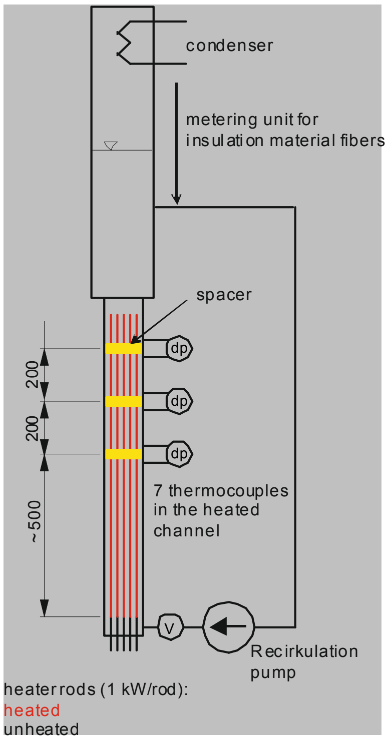


Figure 2: Schematic of ISOTRAN

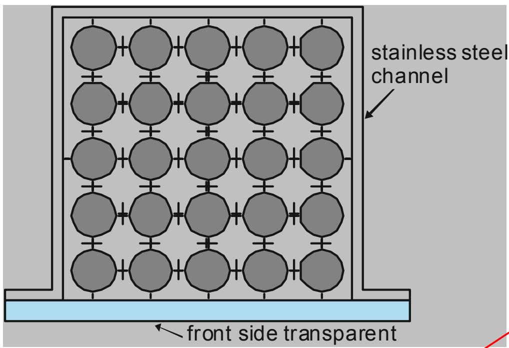


Figure 3: Cross section of the rod bundle

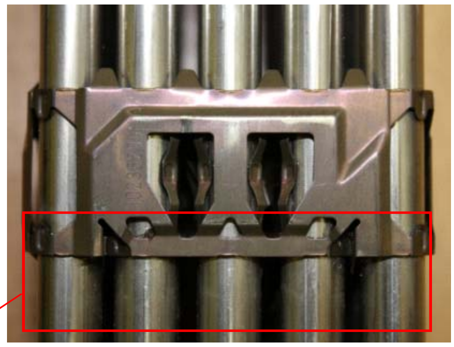


Figure 4: Rod bundle with original BWR spacer

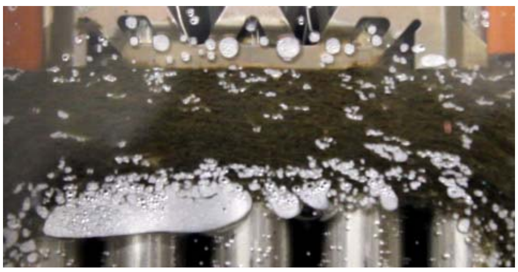


Figure 5: Fiber bed with steam bubbles

Title:	Acrylic Glass Test Facilities “Column”, “Tank” and “Ring channel”
Authors:	S. Renger et al.
Company:	University of Applied Sciences Zittau/Görlitz (IPM)
Document ID:	Various
Document length:	
Date:	From 2003 onwards
Nature of study:	Experimental
Phenomenon studied:	Transport behavior of mineral wool, plunging jet

Abstract: Within a common research project funded by the Federal Ministry of Economics and Technology (BMWi) the test facilities “Ring channel”, “Column”, and“Tank” have been designed to investigate different transport phenomena with the aim to extract an experimental data base for the development as well as the verification and validation of CFD-models to simulate the transport of insulation material fragments.

The acrylic glass test facilities are connected with a water supply system, waste water disposal and auxiliary components (ball valves, pumps, heaters). It is possible to feed the facilities with potable or deionized water or a mixture of both. Degassing of water can be realized by electric heaters in the storage water tank. The three acrylic rigs work under atmospheric pressure conditions. The temperatures can vary between 20 °C and 80 °C.

The “Column” (Figure 1) represents a straight sedimentation line of 3 m for the development of different digital image processing algorithms and the investigation of the settling behavior and parameters like the sphere equivalent diameter of the insulation material fragments.

The “Tank” (Figure 2) is applied for the experimental analysis of water jet effects on air entrainment in a water seal, the flow field in a water seal, corrosion of zinc plated grates and re-suspension of insulation material.

The “Ring Channel” (Figure 3) was developed for the observation of insulation material transport in horizontal flows and different flow phenomena. The “Ring Channel” was designed as an oval acrylic glass flow channel. The channel consists of two straight sections with a length of 5 m, separated into single segments with a length of 1 m, and two semi-circular segments.

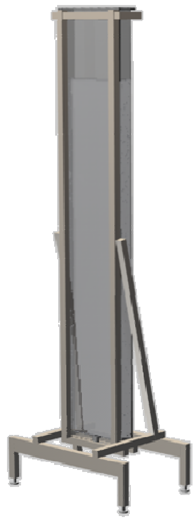


Figure 1: Test facility "Column"

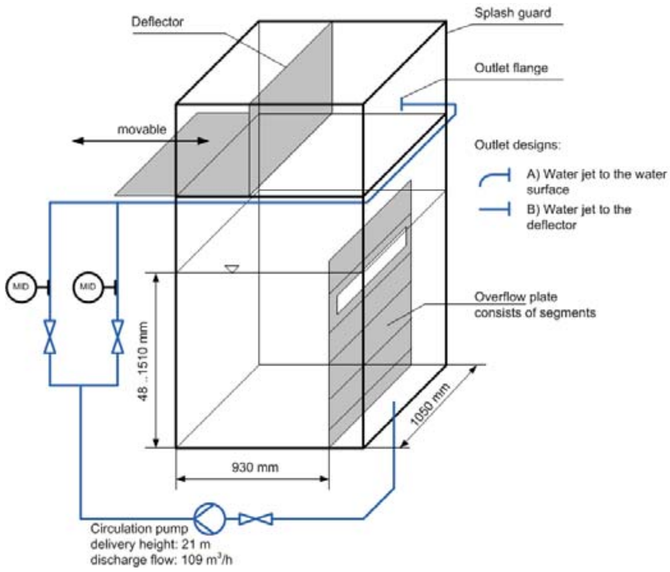


Figure 2: Test facility "Tank"

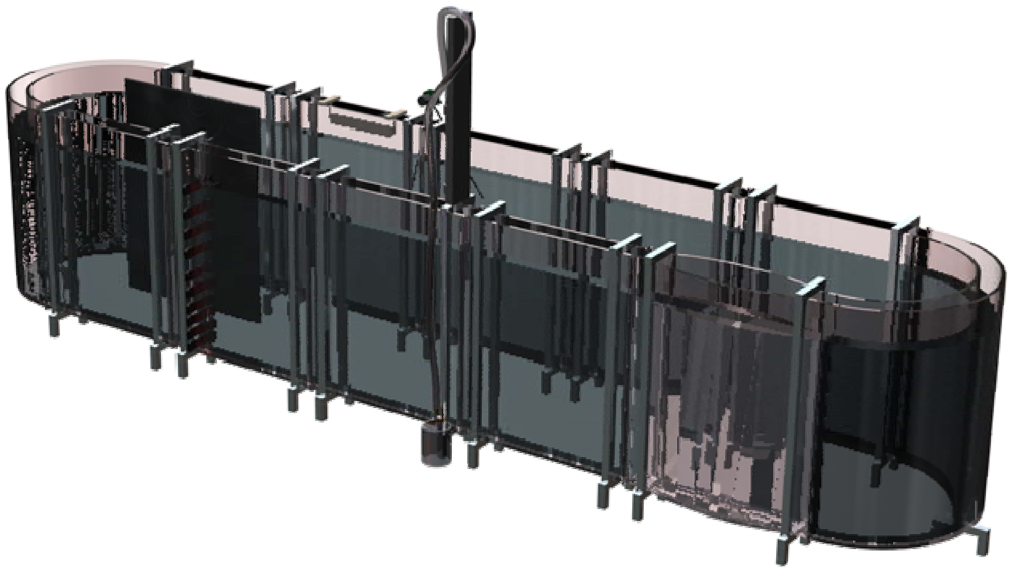


Figure 3: Test facility "Ring Channel"

Test setup: The behavior of gravitating insulation particles in aqueous solution and sedimentation processes were observed at the test facility "Column" in 1/2D-geometry without enforced water flow using an image processing system. Therefore sinking experiments were carried out with single particle fragments as well as with particle mixtures. Experiments performed at the test facility "Tank" included investigations of waterfall effects on a two phase mixture of insulation particles and water according turbulences in a 3D-flow field. Different types of water fall jets were taken into account. Experimental results at the "Ring Channel" were generated with constant cross section area along the whole channel length as well as with barriers and varied cross section areas (e.g. stairs). The vertical and horizontal profiles of the water basis flow were determined in the segments. After the determination of the basis

water flow, experiments with particle fragments were realized.

Findings: The realized experiments led to a large data base, concerning e.g., particle size distribution of the fragmented insulation material, sinking velocities, and parameters of the air entrained by a plunging jet. Statistical analysis allowed a classification of flow relevant parameters in clusters which depend on typical optical parameters, geometrical dimensions and on shape factors of different particle sizes. The analysis also allows the formulation of general rules concerning the behavior of insulation particles under various ancillary conditions.

Debris type: Mineral wool (MD2-2004, MDK).

Mode of debris generation: Rockwool fibers tempered at 225 °C, steam jet fragmented.

Debris size: Small clusters to single fibers.

Title:	Integral Test Facility “Zittauer Strömungswanne” (Zittau Flow Tray)
Authors:	S. Renger et al.
Company:	University of Applied Sciences Zittau/Görlitz (IPM)
Document ID:	Various
Date:	From 2006 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Vertical debris transport; horizontal debris transport; debris sedimentation; head loss on sump strainers; back flushing; downstream effects (FA deposition); chemical effects; long term effects, back-flushing

Abstract: Next to the investigations of separate effect phenomena (acrylic glass test facilities “Ring channel”, “Column” and “Tank”) the IPM inaugurated the integral test facility “Zittauer Strömungswanne” (Figure 1, Figure 2) in 2006 to investigate processes following a LOCA in the reactor sump and downstream the sump strainers as well as the influence of corrosion of hot-dip galvanized containment internals on cooling water. The geometry and dimensions of a simplified sump model were scaled on the basis of a generic PWR according to German PWR conditions. Upstream generic PWR sump data in front of the sump strainer were selected on the following basis:

- Original dimension of the generic reactor sump height up to 3.0 m;
- Original flow path length for the time required to transport the debris from the break location to the sump strainer up to 5.5 m;
- Simplified rectangular flow cross section in the upstream region without obstacles
- Volume dependent scaling of sump strainer surface area (superficial velocity), pump volume flow;
- Stable temperature (up to 70 °C) and chemical resistant materials like stainless steel and acrylic glass.

Important parameters that have been considered were:

- Insulation material transport and sedimentation behavior;
- Pressure loss caused by insulation material agglomeration on the sump strainer;
- Influence of strainer area and mesh size on the pressure loss;
- Pressure loss caused by debris bypassing the sump strainer (downstream effect);
- Influence of erosion and corrosion processes on the pressure loss behavior;
- Influence of erosion and corrosion products on downstream effects after back flushing

Test Facility Capabilities:

Scaling vertical:	1:1 (sump height, strainer height, 1:10 for leak height: falling spray is simulated by a spray nozzle)
Scaling horizontal:	1:25 to 1:75 (volumetric, depending on NPP sump design)
Test flume:	Height 3 m; width 1 m; length 6 m; volume 18 m³
	Austenitic Material
Operating temperature:	70 °C max.
Volume flow:	180 m³/h max.
Strainer design:	2x2 and 3x3 mm mesh size, different area to volume fractions

Fuel assembly section:	Downstream of sump strainer: shortened single FA-dummy (head, bottom, 3 spacers), or 2x2 shortened FA-dummy-cluster (head, bottom, 2 spacers); flow directions in FA-dummy up- or downstream, pressure loss measurement on FA-dummy components
Debris preparation:	Artificial ageing and expulsion of bonding oils by tempering at 225 °C over a period of 24 h (MD2, MDK is produced without bonding oils), Fragmentation (HP-cold high pressure) or SF-steam fragmentation in a separate fragmentation rig), Drying and weighing of the dry insulation mass per suspension, Re-suspension into deionized water.
Measured variables:	Flow rate (strainer and FA) (online) Water temperature (online) Water turbidity in FA (online) Head loss strainer (online) Head loss FA components (online) Dry masses of debris input Dry masses of debris (distribution after experiment) Mass of chemical inputs (e.g. boric acid) Mass of corrosion components (before and after experiment) Water solid content offline after sampling Water ion concentration offline after sampling Water pH offline after sampling Water conductivity Flow profile in the tray

Tests Performed:

The tests were performed to investigate the upstream and downstream effects as well as the long term / chemical behavior.

- Upstream phenomena:
  - Transportation and sedimentation of fibers and mass distributions
  - Agglomeration at sump strainer
  - Head loss at sump strainer
- Downstream phenomena:
  - Penetration mass through sump strainers
  - Deposit mass of fibers in the FA-dummy(s)
  - Head loss at debris screen and spacers
- Corrosion behavior
  - Head losses
  - Long-time results

- o Chemical and microscopic analyses

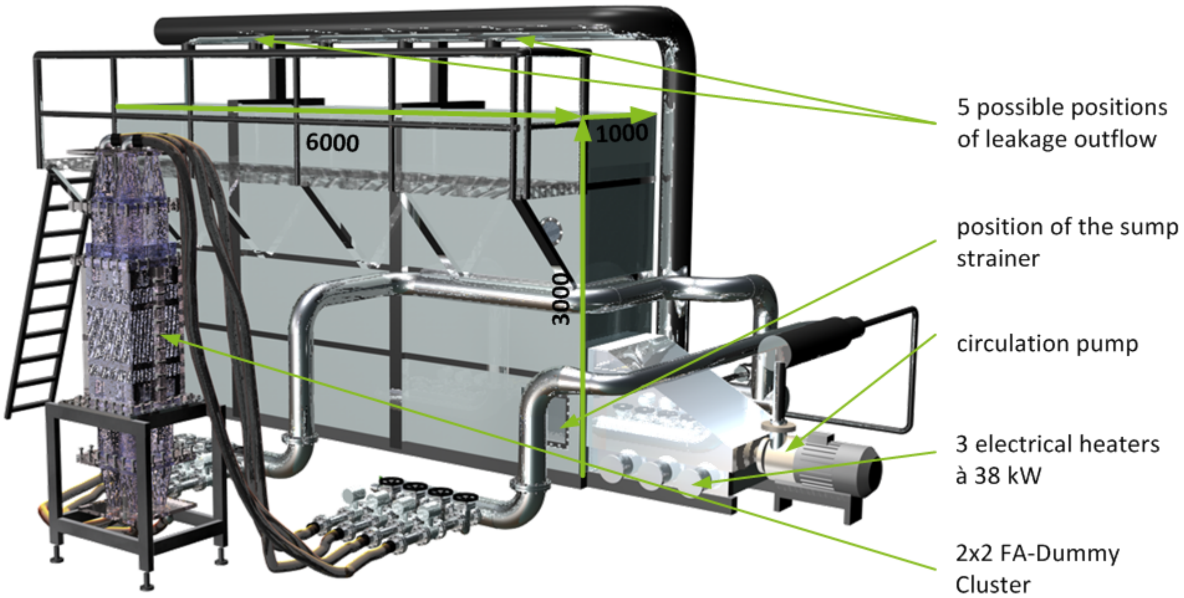


Figure 1: Zittau Flow Tray Test Facility 3-D view

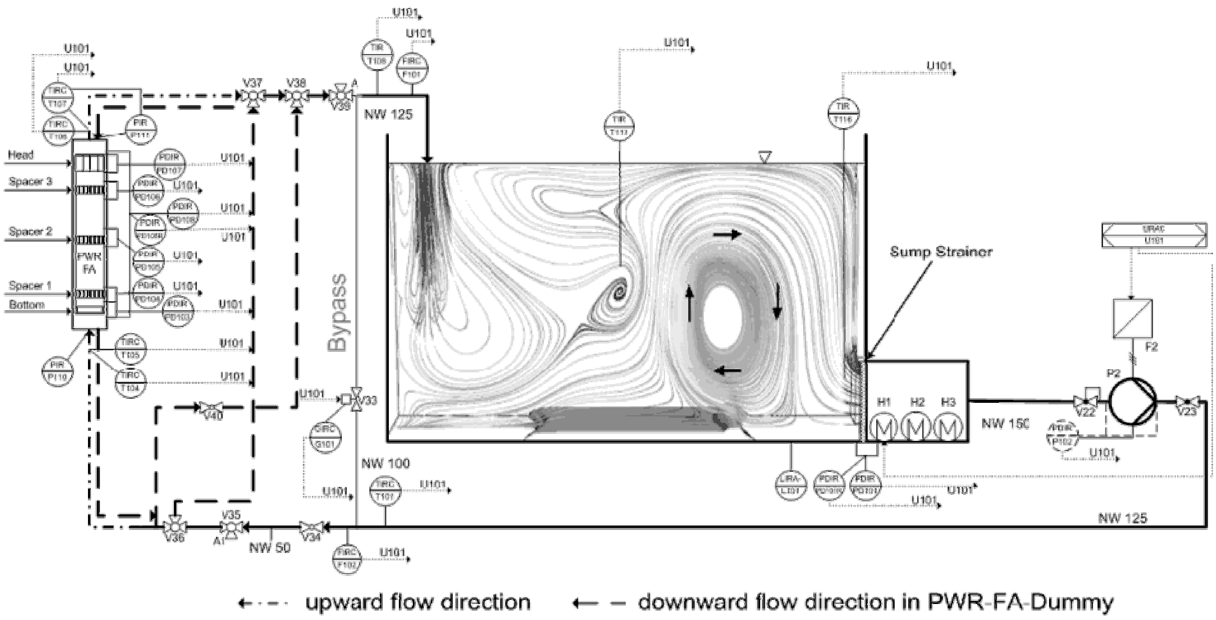


Figure 2: Test Facility Set Up with Flow Profile and Single FA Dummy

Title:	Fragmentation Rig
Authors:	S. Renger et al.
Company:	University of Applied Sciences Zittau/Görlitz (IPM)
Document ID:	Various
Date:	From 2003 onwards
Document Length:	
Nature of Study:	Experimental
Phenomenon Studied:	Fragmentation of insulation materials under Loss of Coolant Accident (LOCA) conditions

Abstract: Aims are the simulation of LOCA-induced jets and the fragmentation of different mineral wool insulation materials under real accidental conditions. Blast experiments were realized at the pressurizer test facility which is connected with the "Fragmentation" rig (Figure 1, Figure 2). The "Fragmentation" rig consists of a primary vessel (simulating dry well), a condensation pipe and a secondary vessel (simulating wet well). The insulation material specimens (targets) were installed in the primary fragmentation vessel. The pressurizer test facility provided saturated steam up to 11 MPa (PWR, BWR-LOCA) and saturated or sub-cooled water up to 11 MPa (PWR, BWR-LOCA). Blow downs were realized with a quick opening ball valve which was activated by a pneumatic system. As a result of these experiments fragmented insulation materials were produced. The debris of each experiment was stored in aqueous solution in order to apply it in various separate effect acrylic glass test facilities.

The primary vessel has an inspection window in the area of the outlet of the pipe for the capturing of the expansion of the free jet by a high speed camera. These images allow an analysis of the characteristics of the free jet by digital image processing and the influence of different pipe outlet properties (Figure 3).

Test Facility Capabilities:

Stainless steel container with a volume of 5.8 m³ (dry well)

Condensation pipe (OD 219.1 mm)

Stainless steel container with a volume of 3.9 m³ (wet well: 1.8 m³ water, 2.1 m³ air)

Glass window in primary vessel for process observation with a high speed camera

Connected with Pressurizer:

- Electrical heating power: 32 kW
- Pressure: up to 16 MPa
- Temperature: up to 350 °C
- Volume: 175 l
- Media: water, steam, non-condensable gases

Tests Performed: As a result of these experiments fragmented insulation materials were produced. The debris of each experiment was stored in aqueous solution in order to apply it in various separate effect acrylic glass test facilities.

Investigation of the mass of insulation material carried in the secondary vessel (carryover mass) and the structure of the free jet (Figure 2). To define characteristics of the material in the stainless steel container and the holding tank different types of experimental analyses at the test rig column were carried out:

- Settling behavior of separate particles;
- Settling of observed solid phase;
- Settling of fine fibers.

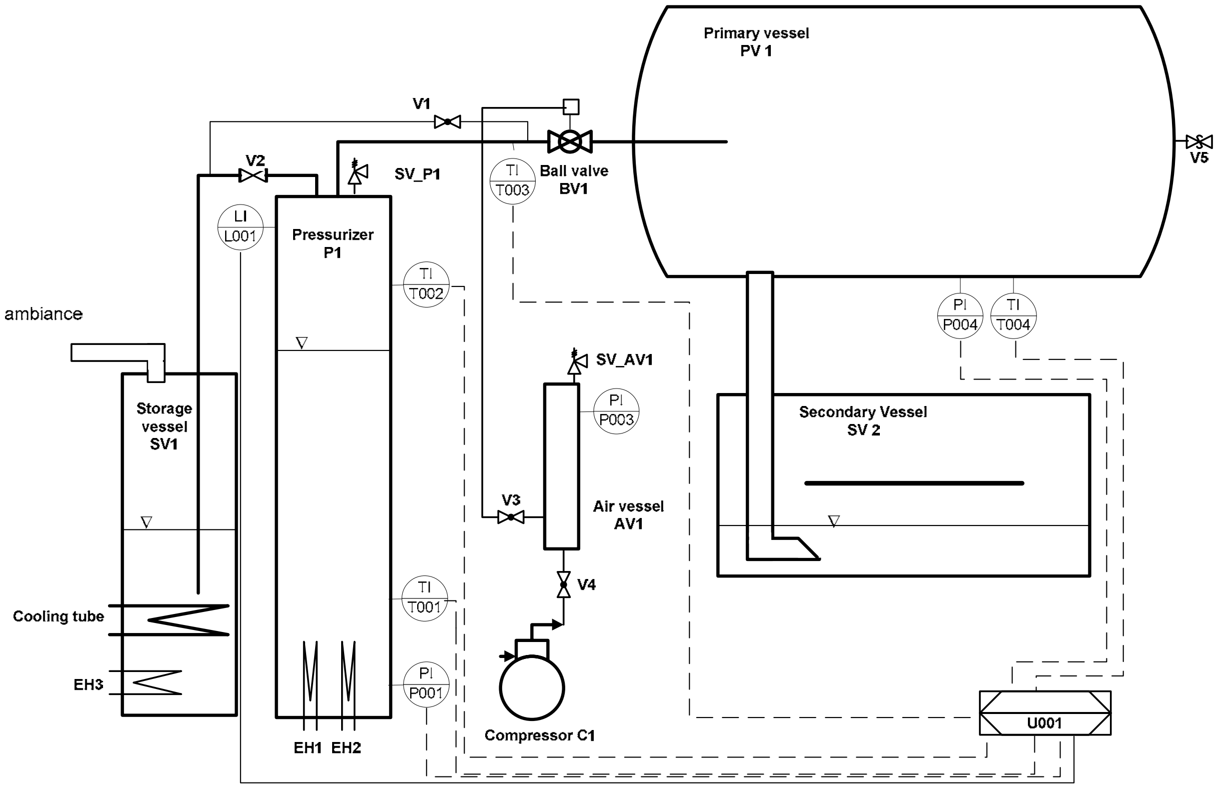


Figure 1: Scheme of the Test Rig “Fragmentation” with Pressurizer

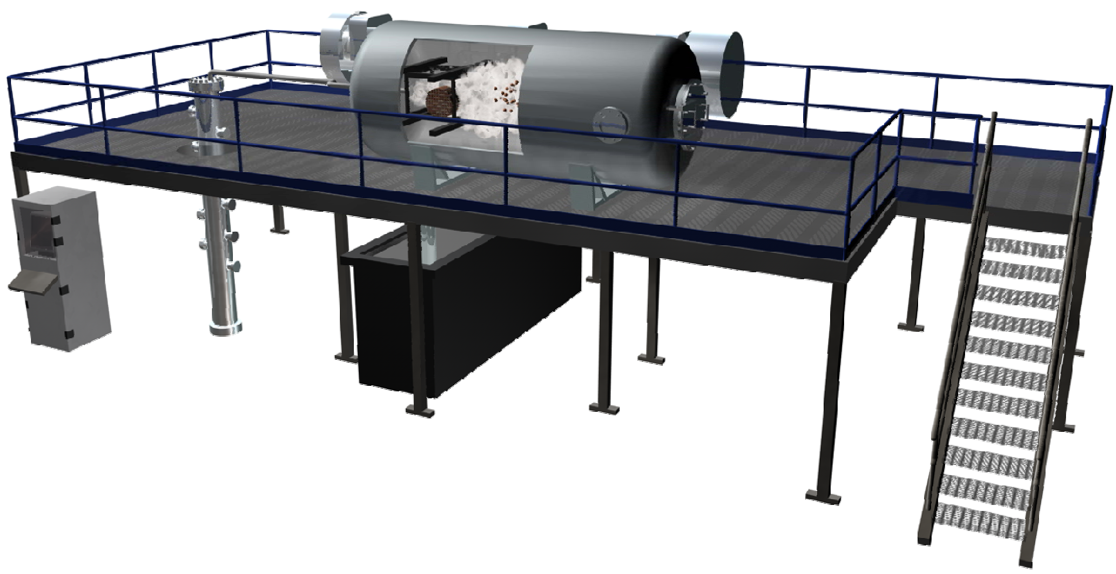


Figure 2: 3-D view of Test Rig “Fragmentation”

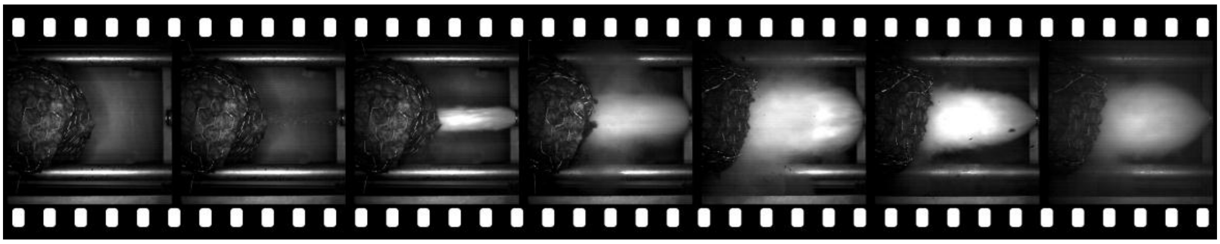


Figure 3: Images of Free Jet and the Insulation Material Target Captured with a High Speed Camera

Title:	Integral Test Facility “Zittauer Ringleitung II” (Zittau Ring Line II)
Authors:	T. Gocht et al.
Company:	University of Applied Sciences Zittau/Görlitz Institute of Process Technology, Process Automation and Measuring Technology
Document ID:	Various
Date:	From 2004 onwards
Nature of Study:	Experimental
Phenomenon Studied:	Debris transport, sedimentation, agglomeration; penetration of insulation material; implementation of horizontal and vertical retention devices; differential pressure at retention devices (perforated sheets and grids with various mesh sizes); deposition of fibers at components of fuel assemblies for BWR and PWR; chemical effects; long term effects relating to chemical effects and differential pressure behavior of filter beds (fibers)

Abstract: Next to the investigations of separate effect phenomena (acrylic glass test facilities “Ring channel”, “Column” and “Tank”) the Institute of Process Technology, Process Automation and Measuring Technology (IPM) realized the integral test facility “Ring Line II” in 2004 to investigate processes mainly regarding deposition and penetration of fragmented insulation material at retention devices installed in the ECCS (strainers, perforated sheets and grids with various mesh sizes). Penetrated insulation material through the installed retention devices in BWR and PWR may influence the fluid flow behavior in the reactor core (deposition of fibers at the fuel assemblies). In the test facility, BWR or PWR fuel assembly (FA) dummies (real fuel elements with geometry and structure materials with shorter length and three spacers, but without fuel) can be investigated regarding the differential pressure behavior at the components of FA-dummy (FA-head, spacers, FA-feed). The experimental results were used for investigation of head loss models of the impact of insulation material. Using investigated data bases, physical models can be developed with the help of soft computing methods. In combination with the integral test facility “Zittau Flow Tray”, experiments can be performed for investigation of long term chemical effects (corrosion). The corrosion process (mainly hot dip galvanized compounds) influences the differential pressure of the filter beds with accumulated insulation material fibers.

Test facility Ring Line II allows the analysis of sedimentation and re-suspension behavior of fragmented insulation material. Furthermore, differential pressure changes caused by insulation material accumulation on horizontal and vertical retention devices in particle-water- flows may be investigated at various parameters (flow rate, temperature, mass of insulation material). The visual monitoring of deposition processes with help of image processing systems at acrylic glass segments is possible. Investigations of the penetration of insulation material through the retention devices may be performed by using a special fine filter (filter bags with mesh size at 100 µm to 5 µm).

Important Parameters:

- Differential pressure behavior caused by insulation material agglomeration on various retention devices (perforated sheets and grids with various mesh sizes);
- Influence of geometry of retention area and mesh size on the differential pressure behavior;
- Influence of erosion and corrosion processes on the differential pressure behavior;
- Influence of flow rate and temperature of the fluid on the behavior of filter beds with accumulated insulation material;
- Insulation materials from various manufacturers and different year of production
- Fragmentation of insulation materials.

Test Facility Capabilities:

- Stainless steel components (storage tanks and pipes)
- Acrylic glass flow tracks for visual monitoring of sedimentation and agglomeration processes as well as deposition of insulation material at retention devices
- Possibility for implementation of various retention devices in horizontal or vertical position with maximum diameter of 219 mm
- Implementation of FA-dummies (with shorter length)
- Investigations of fluid flow with maximum flow rate of 40 m^3/h and temperature up to 70 °C
- Instrumentation and control (programmable logic control from company MAUELL, Germany)

Debris Preparation:

- Artificial ageing and expulsion of bonding oils by tempering at 225 °C over a period of 24 h (insulation material used in German NPP: MD2)
- Use of other insulation material directly from the NPP without ageing (MD2, MDK without bonding oils)
- High pressure- or steam-fragmentation in a separate fragmentation facility ("Fragmentation Rig")
- Drying and weighing of the dry insulation mass per suspension

Measured Variables:

- Flow rate (fluid) (online)
- Water temperature (online)
- Wall temperature at the piping system (online)
- Differential pressure over retention device (online)
- Water level at the storage tank (online)
- Water solid content (offline after sampling)
- Water ion concentration (offline after sampling)
- Water pH (offline after sampling)
- Water conductivity (offline after sampling)

Tests Performed:

The tests were performed to investigate the differential pressure behavior of retention devices and of components of FA-dummies, the penetration of fragmented insulation material as well as the long term/chemical behavior of filter beds.

- Phenomena at retention devices:
  - Transportation and deposition of insulation material fibers and mass distributions
  - Head loss at retention devices
  - Influence of corrosion products on differential pressure
- Generation of data bases by investigations of the differential behavior of various insulation materials with variation of:
  - Fluid temperature
  - Flow rate
  - Mass of inserted insulation material
  - High of the filter bed
- Phenomena at FA-dummies:
  - Investigation of deposition process and mass distribution of fragmented insulation materials
  - Head loss at debris screen and spacers

- Corrosion behavior
    - o Head losses
    - o Long-time investigations
    - o Chemical and microscopic analyses

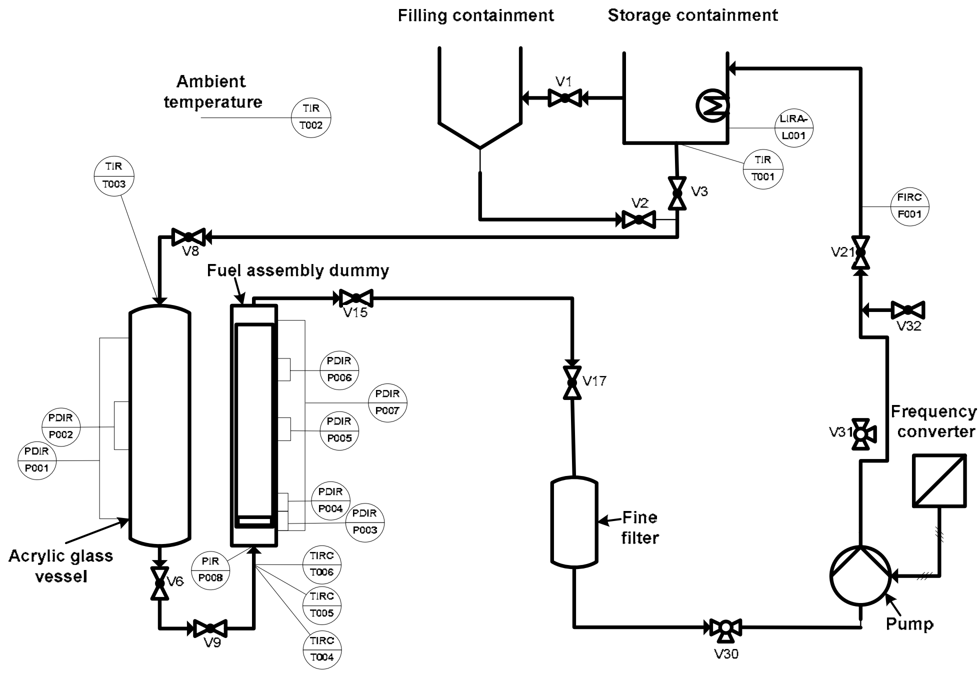


Figure 1: Schematic of the Test Facility "Ring Line II" with FA Dummy (example)

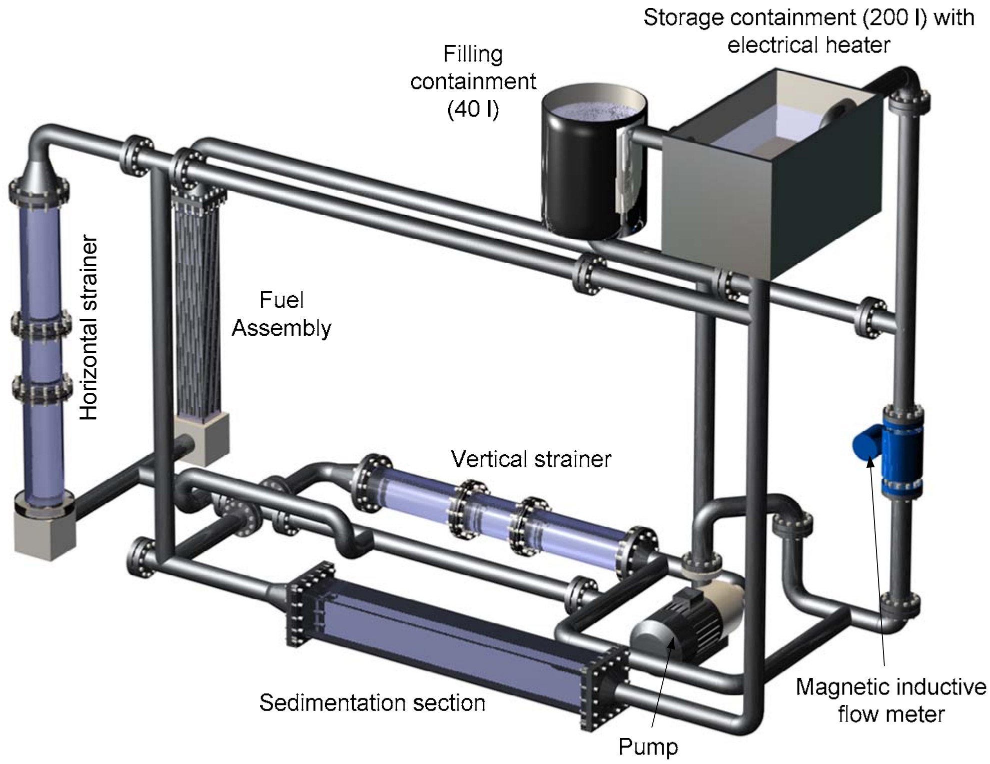


Figure 2: 3-D View of Test Facility "Ring Line II"

KNOWLEDGE BASE REPORTS

Title:	BWR ECCS Strainer Blockage Issue: Summary of Research and Resolution Actions
Author:	D. V. Rao, C.J. Shaffer, and R. Elliott
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	Technical Report LA-UR-01-1595 (ADAMS ML012970246)
Date:	March 2001
Document Length:	148 pages
Nature of Study:	Evaluation
Phenomena Studied	BWR responses to NRC Bulletin 96-03

Abstract: The research and technical review efforts that form the basis for the resolution of the BWR strainer blockage issue in NRC Bulletin 96-03 "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors" are summarized here.

Findings: The BWR industry resolved the strainer blockage issue on a plant-specific basis by installing large-capacity passive strainers in each plant utilizing strainer design guidance provided by the BWR Owners Group (BWROG). The staff reviewed the BWROG guidance and performed detailed reviews of several plants. The results of the staff's review are also summarized here.

Title:	GSI-191 Summary and Analysis of US Pressurized Water Reactor Industry Survey Responses and Responses to GL 97-04
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	Technical Report LA-UR-01-1800 (ADAMS ML020280288) (Also published as NUREG/CR-6762, Volume 2)
Date:	August 2001
Document Length:	82 pages
Nature of Study:	Evaluation
Phenomena Studied	Generic Letter 97-04 responses

Abstract: Based on the findings of the BWR ECCS strainer blockage study, review of facility Safety Analysis Reports, and several plant visits, the NRC and LANL identified a set of plant design features (e.g., sump design) and sources of debris (e.g., insulation materials and containment coatings) that were considered to strongly influence debris generation, transport, and accumulation in PWRs. One of the tasks under GSI-191 is to compile a database of insulation, containment, and ECCS sump design and operation information for the operating US PWRs. It was determined that such a database would benefit the GSI-191 study in two ways:

1. It would provide the most up-to-date information on the insulation and sump configurations at each operating PWR unit. Such information can be used in the design and conduct of research programs related to GSI-191.
2. It would provide a means by which the results of the GSI-191 study can be used to draw conclusions regarding the risk significance of this issue to the overall population of operating US PWRs. The NRC formulated a set of questions that captured the information needs and forwarded them to the licensees of the operating US PWRs. Appendix A presents the questions prepared by NRC along with an explanation to the licensees on how the information would be used in the GSI-191 study. The licensee response to these survey questions was voluntary and consisted of written responses and engineering drawings (as deemed necessary by the individual licensees). The NEI report *Results of Industry Survey on PWR Sump Design and Operations* (June 7, 1999) forwarded the industry responses to the NRC. The most recent addendum (January 14, 2000) forwarded the last set of industry responses.

Findings: This report presents a summary and analysis of the industry survey of the plant designs and features that most likely affect generation, transport, and accumulation of debris in operating US PWRs. Typically, the responses reflected the licensees' interpretation of the survey questions and the availability of information solicited by that question. In some cases, the licensee response consisted of detailed explanations and copies of the most recent engineering drawings (or data sheets). In some extreme cases, the responses consisted of references to appropriate sections of the plant Updated Final Safety Analysis Report with no further explanation provided. LANL undertook a thorough review and analysis of the industry responses

Title:	Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance
Author:	D. V. Rao et al.
Company:	Los Alamos National Laboratory for the US NRC
Document ID:	NUREG/CR-6808
Date:	February 2003
Document Length:	289 pages
Nature of Study:	Evaluation
Phenomena Studied	ECCS suction strainer performance

Abstract: This report describes the substantial base of knowledge that has been amassed as a result of the research on BWR suction-strainer and PWR sump-screen clogging issues. These issues deal with the potential insulation and other debris generated in the event of a postulated loss-of-coolant accident within the containment of a light-water reactor and subsequently transport to and accumulation on the recirculation sump screens. This debris accumulation could potentially challenge the plant's capability to provide adequate long-term cooling water to the ECCS and the containment spray system pumps. Analytical and experimental approaches are discussed, that have been used to assess the different aspects of sump and strainer blockage and to identify the strengths, limitations, important parameters and plant features, and appropriateness of the different approaches.

Findings: The report provides background information (Section 1) regarding the PWR containment sump and the BWR suction-strainer debris clogging issues. This background information includes a brief historical overview of the resolution of the BWR issue with a lead into the PWR issue, a description of the safety concern relative to PWR reactors, the criteria for evaluating sump failure, descriptions of postulated accidents, descriptions of relevant plant features that influence accident progression, and a discussion of the regulatory considerations. The purpose of a sump screen is to prevent debris that may damage or clog components downstream of the sump from entering the ECCS and reactor coolant system. Debris accumulation across a sump screen would create a pressure drop across that screen that potentially could cause insufficient flow to reach the pump inlet. The knowledge-base report is organized in the same manner that an evaluation of the potential of sump screen blockage would be performed. These steps are the identification of sources of potential debris (Section 2); the potential generation of insulation debris by the effluences from a postulated LOCA (Section 3); the potential transport of the LOCA generated debris to the containment sump (Section 4); the potential transport of debris within the sump pool to the recirculation sump screen (Section 5); the potential accumulation of the debris on the sump screen, specifically the uniformity and composition of the bed of debris (Section 6); and the potential head loss associated with the accumulated debris (Section 7). The report also summarizes the resolution options available to BWR plant licensees to resolve the BWR suction-strainer clogging issue and the advanced features of the new replacement strainers that were implemented in the BWR plants so that the strainers can accumulate the potential debris loading without the associated debris-bed head loss (Section 8). Domestic and foreign plant events relevant to the PWR sump-screen clogging issue are discussed next (Section 9). Finally, an overall summary of the knowledge base is provided in Section 10.

Title:	Test Qualification Synthesis on Industrial Test Programs Performed by the Suppliers on the Existing Plants
Authors:	L. Pradel, G. Champion
Company:	EDF
Document ID:	EMEIS060399 B
Document length:	49 pages (EDF proprietary)
Date:	December 2006
Nature of study:	Experimental

Phenomena studied: This technical note presents the results of the qualification programs implemented for the new strainers of the exiting French plants. It gives the base and rationale of the tests specification together with a detailed description of the facilities built-up for this qualification program by the sump suppliers.

Abstract: The report gives a detailed description of the criteria and sizes of the test facility together with the predictions given before the implementation of the supplier testing and the final results of these sump qualifications.

Tests program setup: As a principle the qualification program has been based on performance tests which have to be performed in order to demonstrate and reach the requirements given in the EDF technical specification. The program performed by the three suppliers lead in a set of tests whose goal was to get a complete picture of the sump behaviour whatever the accident conditions. Prior to any testing each supplier was asked to predict the pressure loss for each test to be below decoupling values.

Title:	Test Facility Presentation to Perform Test Programs on the Existing and EPR Plants
Authors:	L. Appocher
Company:	EDF
Document ID:	EDTCE080167 A
Document length:	10 pages (EDF proprietary)
Date:	April 2008
Nature of study:	Experimental
Phenomenon studied:	Test facility criteria and representativity

Abstract: The report gives a detailed description of the criteria and sizes of the test facility.

Test setup: Start-up tests have been performed in order to calibrate the different criteria used and to correlate them with existing NUREG 6224.

The tests set-up in this facility are related to the safety demonstration of our plants sump strainers. It comes in addition to the qualification tests performed by the industrial sump providers and gives visibility in some common areas related to the physical behaviour the sumps have to cope with: chemical and temperature effects, thin bed effects, downstream debris source term (DST).

The tests gave an indication that steam jet fragmented insulation had a higher pressure drop. In the dislodgement tests it was observed that the smaller the distance between the steam pipe and the blanket the smaller the particles of the debris. On the other hand, a scanning electron microscope (SEM) inspection did not indicate any structure differences between the water jet and steam jet fragmented pieces.

Title:	Test Program to Identify the Clogging Temperature Level on EDF Sump Strainers
Authors:	L. Appocher
Company:	EDF
Document ID:	EDTCE070046 A
Document length:	10 pages (EDF proprietary)
Date:	January 2007
Nature of study:	Experimental

Phenomenon Studied: Temperature effects on the sump clogging of the EDF existing plants sump strainers.

Test Objective: Following the Groupe Permanent 22 December 2004, EDF launched a test program to investigate chemical effects on the SIS and SS sump clogging. The CEMETE Department of EDF was in charge of this test program under the survey of EDF- SEPTEN.

During the second test performed at high temperature (95 °C) it was impossible to initiate a debris bed on the strainers. Therefore, the long term test (one month) was useless.

It was decided to investigate in more detail this temperature effect in order to identify at what temperature (given the sump screen geometry and surface) a clogging effect could be initiated.

Findings: The experiments clearly show that given a very low flowrate velocity representative of the real flow rate in the sumps an unstable clogging could only be observed at minimum temperature level.

Future test programs had to take account of this particularity in order to be able to perform long duration tests (one month).

Verification experiments: These tests have been repeated and carried out so as to force the formation of a debris bed on the screens at lower temperature and then increase it to be able to form a stable debris bed on the screens and finally to be able to monitor the pressure drop in the long term.

Debris data: The debris used in these experiments was fiberglass ISOVER 725 QN mixed with the adequate quantity of concrete, iron powder, silicon species, microtherm, plaster coatings and finally MECATISS fire protection materials.

All these material are transposed to EPR conditions from the quantity assessed with the debris source term (DST) used for the qualification program performed for the sump strainers of our existing plants.

Title:	SIS and SS SUMPS. Assessment of the Test Facility Results Related to SUMP CLOGGING.
Authors:	G. Champion
Company:	EDF
Document ID:	ENGSIN080332 A
Document length:	16 pages (EDF proprietary)
Date:	April 2008
Nature of study:	Experimental

Phenomenon studied: Significant water degasification provoked by temperature increase followed by an unexplained delta P.

Abstract: Along with the test program based on decoupled input data and focusing on the temperature effects an explained phenomenon lead to a set of complementary testing whose purpose was to conclude on the potential impact of chemical effects.

Test setup: This study has lead to install a debris bed on the EPR strainers in the most physical and realistic way. Starting from this initial state a decoupling value has been chosen to settle the behaviour of the screens.

Performing the related tests unexplained phenomena appeared. A high delta P apparently caused by water degasification at 50-60 °C committed us to an additional but complementary test program.

Findings: Significant water degasification during the temperature increase lead to a large delta P increase. Complementary testing will be performed with degasified water in order to correlate the presence of this degasification with the observed increase in delta P.

This degasification occurs because of the temperature and because the facility is running under atmospheric pressure unlike in a real containment.

Title:	Temperature Influence on EPR Sump Clogging
Authors:	G. Champion
Company:	EDF
Document ID:	ENGSIN090110 A
Document length:	10 pages (EDF proprietary)
Date:	May 2009
Nature of study:	Experimental

Phenomenon studied: Potential chemical effects in accidental temperature conditions

Abstract: In addition to the Areva qualification tests in cold water conditions, EDF have launched tests in EDF/CEIDRE. The target was to establish the existence of potential chemical effects, thanks to the existing material species in EPR. Nothing significant has been noticed.

Test setup: The facility is the one already used for the existing French plants. It is possible to regulate the flow rate and the temperature. A one month test was implemented with a variation of the temperature from 15 °C to 95 °C, representative conservatively of the expected variation of temperature during accident scenarios.

Findings: Water degasification has been observed during the increase of temperature. This degasification is seen from the sump view as it was an additional batch of particulates which lead to a pressure increase against the sumps. However, this phenomenon disappeared at a higher temperature when these microscopic bubbles finally left the debris bed (coalescence (fusion) process). These last processes lead to partial destruction of the debris bed.

A contradictory test done with degasified water confirmed this test artefact, the pressure loss being in complete correlation with what was expected in such conditions.

APPENDIX E - SUPPORTING COMPUTATIONAL FLUID DYNAMICS CALCULATIONS FOR EMERGENCY CORE COOLING RELIABILITY

Computational Fluid Dynamics (CFD) has advanced significantly since the design phase for most NPPs now in operation around the world. The issuance of GSI-191 "Assessment of Debris Accumulation on PWR Sump Performance" resulted in a large amount of research surrounding the evaluation of ECCS strainer performance and the transport of debris and chemicals to the strainers from other locations in the plant. CFD has started to play a significant role in the estimation of debris quantities and transport phenomena in recent years, in order to capture the important three-dimensional aspects of flow within a plant after a LOCA.

Several areas of ECC system modelling involving CFD have arisen over the past two decades, including:

- Air entrainment in sump flow due to plunging jets;
- Debris transport phenomena throughout the ECC system;
- Prediction of debris deposition on strainer surfaces;
- Pressure drop through debris beds and ECC system components;
- Prediction of air entrainment into ECC strainers due to free-surface dip.

The bulk of the publications reviewed focused on insulation, coating and latent debris transport and deposition modelling. These transient analyses are important as retroactive calculations are being done on many existing NPPs to address strainer performance and an overly conservative approach may show inadequate long-term or short-term performance of the ECC system. These studies show that using CFD to model debris transport within the ECC system after a LOCA may provide more realistic results for estimating the amount and timing of debris deposited on the ECC strainers, leading to more accurate estimations of strainer pressure drop. Several studies attempted to create one-dimensional approximations for these three-dimensional phenomena to be used in traditional nuclear computer codes with some success.

Other CFD studies have focused on additional parameters such as air entrainment, transport of non-condensable gases, chemical (boron) transport, steam condensation, Coriolis forces and free-surface dip above strainers. Each of the reported studies showed a good degree of success when CFD solutions were compared to experimental data. Additional studies related to the ECC system and post-LOCA analysis, but not directly concerning the strainers, were also reviewed and topics such as flow through valves, hydraulic resistance balancing, pump cavitation, valve/orifice cavitation, flow in autocatalytic recombiners, post-LOCA thermalhydraulics, post-LOCA moderator flow (buoyancy driven) and many others were investigated.

The following section includes a summary of abstracts from publications on CFD (and related experimental) studies related to ECC strainers. The Task Group has not reviewed the content of these documents and takes no position on their reliability.

Title:	Influence of Air Entrainment on the Liquid Flow Field caused by a Plunging Jet and Consequences for Fiber Deposition
Authors:	E. Krepper
Publication:	Nuclear Engineering and Design, Volume 241, Issue 4
Conference:	International Conference on Nuclear Energy for New Europe 2009, Bled (Slovenia), ISSN- 0029-5493
Date:	2011-04-15

Abstract: Plunging jets play an important role in nuclear reactor safety research. In the present paper the case of the strainer clogging issue is considered. Entrained air caused by a plunging jet has an influence of the liquid flow field and on the fiber transport in the sump. In the paper the amount of entrained air is given as an inlet boundary condition according to correlations in the literature and confirmed by own experiments. The influence of entrained air on the fiber deposition pattern at the bottom of a tank and on the mixing procedure for the case of temperature differences between jet and tank water are investigated by CFD calculations and compared to experiments. The presented work is part of a joint research project performed in cooperation between the University of Applied Science Zittau/Goerlitz and Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation of particle transport phenomena in coolant flow in Zittau and the development of CFD models for its simulation in Rossendorf. Whereas an overview and a description of the main concepts of this project are described, the focus of the actual paper is directed on the different aspects of a jet. The entrained air has a remarkably influence on the generation of swirls und therefore on the transport and deposition of fibers. At least qualitative conclusions concerning main effects, critical regions of fiber deposition and design improvements avoiding undesired fiber deposition can be drawn. CFD simulation of the sump flow conditions during a real accident scenario over several 1000 s however will fail caused by the large computational effort.

Title:	Generic Experiments at the Sump Model Zittauer Strömungswanne (ZSW) for the Behaviour of Mineral Wool in the Sump and the Reactor Core
Authors:	S. Alt, R. Hampel, W. Kaestner, A. Kratzsch, S. Renger, A. Seeliger, F. Zacharias, G. Cartland-Glover, A. Grahn, W. Hoffmann, E. Krepper, H. Kryk
Publication:	Kerntechnik, Volume 76, Issue 1
Date:	2011-03-15

Abstract: The investigation of insulation debris transport, sedimentation, penetration into the reactor core and head loss build up becomes important to reactor safety research for PWRs and BWRs, when considering the long-term behaviour of emergency core cooling systems during LOCAs. Research projects are being performed in cooperation between the University of Applied Sciences Zittau/Goerlitz and the Helmholtz-Zentrum Dresden-Rossendorf. The projects include experimental investigations of different processes and phenomena of insulation debris in coolant flow and the development of CFD models. Generic complex experiments serve for building up a data base for the validation of models for single effects and their coupling in CFD codes. This paper includes the description of the experimental facility for complex generic experiments (ZSW), an overview about experimental boundary conditions and results for upstream and down-stream phenomena as well as for the long-time behaviour due to corrosive processes.

Title: CFD Analyses of Fiber Transport and Fiber Deposition at Plunging Jet Conditions
Authors: E. Krepper, G. Cartland-Glover, A. Grahn, E.-P. Weiß, S. Alt, A. Kratzsch, S. Renger, W. Kastner
Publication: Kerntechnik Volume 76, No 1, ISSN- 0932-3902
Date: 2011-03

Abstract: The investigation of insulation debris generation, transport and sedimentation becomes important with regard to reactor safety research for PWRs and BWRs when considering the long-term behaviour of emergency core cooling systems during all types of LOCAs. A joint research project on such questions is being performed in cooperation between the University of Applied Sciences Zittau/Gorlitz (HSZG) and the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The project deals with the experimental investigation of particle transport phenomena in coolant flow and the development of CFD models for its description (see 10-12). While the experiments are performed at the University at Zittau/Gorlitz, the theoretical modeling efforts are concentrated in Rossendorf. In the current paper, the basic concepts for CFD modeling are described and feasibility studies are presented. The model capabilities are demonstrated via complex flow situations, where a plunging jet agitates insulation debris.

Title: Numerical Analysis of Containment Pool Flow and Transport of Insulation Debris
Authors: Tae Hyub Hong, Sang Won Lee, Hyeong Taek Kim
Publication: Proceedings of the Korean Nuclear Society Autumn Meeting, 21-22 Oct. 2010
Date: 2010-10-15

Abstract: In the event of a LOCA at a nuclear power plant, insulation debris can be released near the break. Some of this debris can be transported in the containment water pool to the vicinity of the sump and increase the pressure drop across the sump screen, at which point the ECCS can fail to re-circulate coolant to the reactor core. In the present study, a CFD analysis of the coolant flow in the containment pool is carried out and debris transportation is evaluated using the Lagrangian particle tracking method.

Title: Sensitivity Study for CFD Analysis on Debris Transport to ECCS Sump for CANDU Type Plant in Korea
Authors: Byung Il Kwon, Jong Uk Kim, Jae Seon Cho, Tea Keun Park, Sang Won Lee, Hyeong Taek Kim
Publication: Proceedings of the Korean Nuclear Society Autumn Meeting, 21-22 Oct. 2010
Date: 2010-10-15

Abstract: Once containment recirculation pumps are activated and ECC flow is supplied from the recirculation sump during LOCA, various insulations and coatings on a pipe, equipments and structures damaged by LOCA break jet as well as additional debris sources are transported to recirculation sump screen by the break flow and containment spray flow drainage. This debris may result in loss of NPSH of the recirculation pumps, and have a threat to long term cooling and containment heat removal capacity. In this case, flow patterns of containment pool are important to confirm behaviors of debris transport for predicting various flow paths to the recirculation sump screen. In this paper, models using commercial CFD software CFX are developed for containment pool simulation during recirculation mode. The specific plant used for this analysis is CANDU type plant, in Korea.

Title: Predictability of Boron Transport Phenomenon in PWR Based on PKL Experimental Program
Authors: A. Del Nevo, F. D'Auria
Publication: Transactions of the American Nuclear Society, Ed. 17, Vol. 102
Date: 2010-06-17

Abstract:

The boron issue is entirely addressed to five main associated aspects: the formation of diluted boron 'plugs' in specific zones of the primary system, the transport of deborated slugs, the mixing of the diluted plugs, the deboration and boration processes (loss or gain of boron from primary system, respectively) and the reactivity feedback due to entrance of the borated diluted plug in the core. These aspects may be investigated at system level (dilution and boron transport) and at local level (boron mixing) with thermal-hydraulic system codes (TH-SYS) and three dimensional CFD codes respectively, in parallel or subsequently to dedicated experimental test campaigns. Indeed, these experimental programs constitute the database for studying the physical phenomena and for validating the codes. The mechanism of the inherent boron dilution during small break loss of coolant accident (SBLOCA) is addressed by a set of experiments performed in PKL Integral test facility (AREVA GmbH, Germany), in the framework of the OECD/NEA/CSNI SETH and PKL projects, Refs. 2 and 3. During the SBLOCA a diluted borated water plug is formed in the loop seal after a certain period characterized by the natural circulation (NC) flow rate at core inlet almost equal to zero or non-existent. Then, the sudden restart of the circulation might cause the transport of boron diluted slug to the core inlet, following primary coolant mass inventory recovery eventually after the emergency core cooling system actuations. The capabilities of RELAP5 (see Ref. 4 to 6) and CATHARE2 (Ref. 7 and 8) to predict the boron transport phenomena were tested by means of five experiments. This constitutes an extension of the validation range for those codes.

Title:	CFD Simulation of Fiber Material Transport in a PWR Core under Loss of Coolant Conditions
Authors:	T. Hoehne, A. Grahn, S. Kliem, F.-P. Weiss
Publication:	Proceedings of Annual meeting on nuclear technology 2010, Jahrestagung Kerntechnik 2010, Berlin (Germany), Jahrestagung Kerntechnik.
Date:	2010-05-15

Abstract: The aim of the numerical simulations carried out in this study was to determine how and where mineral wool fibers transported to the core by ECC water during a LOCA are deposited across the grid spacers of the fuel elements of a German PWR. The spacer grid is modeled as a strainer which completely retains the insulation material carried by the coolant and reaching the plane of the spacers. The accumulation of the insulation material gives rise to the formation of a compressible fibrous cake whose permeability to the coolant flow is calculated in terms of the local amount of deposited material and the local value of the superficial liquid velocity. The calculations showed that the fiber material at the uppermost spacer grid plane is not evenly distributed. First, it is accumulated at the positions of the break-through channels. Later when the inner circulation in the core has stopped, the insulation material can also be distributed into other regions of the spacer plane. Further investigations are necessary to determine the accumulation of insulation material for a longer period of time. Also steam production in the core or re-suspension of the insulation material during back flow should be considered. Moreover, the geometry modeling should be improved taking into account the real structures in the upper plenum and the geometry of the ECC injection nozzle.

Title: CFD-Simulations and Experiments on Steam Condensation in Polydisperse Bubbly Flows
Authors: M. Schmidtke, E. Krepper, D. Lucas, M. Beyer,
Publication: Proceedings of annual meeting on nuclear technology 2010, Jahrestagung Kerntechnik 2010, Berlin (Germany), Jahrestagung Kerntechnik
Date: 2010-05-15

Abstract: The aim of the numerical simulations carried out in this study was to determine how and where mineral wool fibers transported to the core by ECC water during a LOCA are deposited across the grid spacers of the fuel elements of a German PWR. The spacer grid is modelled as a strainer which completely retains the insulation material carried by the coolant and reaching the plane of the spacers. The accumulation of the insulation material gives rise to the formation of a compressible fibrous cake whose permeability to the coolant flow is calculated in terms of the local amount of deposited material and the local value of the superficial liquid velocity. The calculations showed that the fiber material at the uppermost spacer grid plane is not evenly distributed. First, it is accumulated at the positions of the break-through channels. Later when the inner circulation in the core has stopped, the insulation material can also be distributed into other regions of the spacer plane. Further investigations are necessary to determine the accumulation of insulation material for a longer period of time. Also steam production in the core or re-suspension of the insulation material during back flow should be considered. Moreover, the geometry modeling should be improved taking into account the real structures in the upper plenum and the geometry of the ECC injection nozzle.

Title:	Numerical Simulation of the Insulation Material Transport to a PWR Core under Loss of Coolant Accident Conditions
Authors:	T. Hohne, A. Grahn, S. Kliem, U. Rohde, F.-P. Weiss
Publication:	Proceedings - 18th International Conference on Nuclear Engineering, ICONE18
Date:	2010-08

Abstract: In 1992, strainers on the suction side of the ECCS pumps in Barsebäck NPP Unit 2 became partially clogged with mineral wool because after a safety valve opened the steam impinged on thermally-insulated equipment and released mineral wool. This event pointed out that strainer clogging is an issue in the course of a loss-of-coolant accident. Modifications of the insulation material, the strainer area and mesh size were carried out in most of the German NPPs. Moreover, back flushing procedures to remove the mineral wool from the strainers and differential pressure measurements were implemented to assure the performance of emergency core cooling during the containment sump recirculation mode. Nevertheless, it cannot be completely ruled out, that a limited amount of small fractions of the insulation material is transported into the RPV. During a postulated cold leg LOCA with hot leg ECC injection, the fibers enter the upper plenum and can accumulate at the fuel element spacer grids, preferably at the uppermost grid level. This effect might affect the ECC flow into the core and could result in degradation of core cooling. It was the aim of the numerical simulations presented to study where and how many mineral wool fibers are deposited at the upper spacer grid. The 3D, time dependent, multi-phase flow problem was modeled applying the CFD code ANSYS CFX. The CFD calculation does not yet include steam production in the core and also does not include re-suspension of the insulation material during reverse flow. This will certainly further improve the coolability of the core. The spacer grids were modeled as a strainer, which completely retains all the insulation material reaching the uppermost spacer level. There, the accumulation of the insulation material gives rise to the formation of a compressible fibrous cake, the permeability of which to the coolant flow is calculated in terms of the local amount of deposited material and the local value of the superficial liquid velocity. Before the switch over of the ECC injection from the flooding mode to the sump mode, the coolant circulates in an inner convection loop in the core extending from the lower plenum to the upper plenum. The CFD simulations have shown that after starting the sump mode, the ECC water injected through the hot legs flows down into the core at so-called "breakthrough channels" located at the outer core region where the downward leg of the convection roll had established. The hotter, lighter coolant rises in the centre of the core. As a consequence, the insulation material is preferably deposited at the uppermost spacer grids positioned in the breakthrough zones. This means that the fibers are not uniformly deposited over the core cross section. When the inner recirculation stops later in the transient, insulation material can also be collected in other regions of the core. Nevertheless, with a total of 2.7 kg fiber material deposited at the uppermost spacer level, the pressure drop over the fiber cake is not higher than 8 kPa and all the ECC water could still enter the core.

Title: Implementation of a Pressure Drop Model for the CFD Simulation of Clogged Containment Sump Strainers
Authors: A. Grahn, E. Krepper, F.-P. Weiß, S. Alt, W. Kastner, A. Kratzsch, R. Hampel
Publication: J. Eng. Gas Turbines Power, Vol. 132, No 8, ISSN- 0742-4795
Date: 2010-08

Abstract: The present study aims at modeling the pressure drop of flows through growing cakes of compressible fibrous materials, which may form on the upstream side of containment sump strainers after a loss-of-coolant accident. The model developed is based on the coupled solution of a differential equation for the change of the pressure drop in terms of superficial liquid velocity and local porosity of the fiber cake and a material equation that accounts for the compaction pressure dependent cake porosity. Details of its implementation into a general-purpose three-dimensional computational fluid dynamics code are given. An extension to this basic model is presented, which simulates the time dependent clogging of the fiber cake due to capturing of suspended particles as they pass through the cake. The extended model relies on empirical relations, which model the change of pressure drop and removal efficiency in terms of particle deposit in the fiber cake.

Title: Some Nuclear Reactor Safety Related Aspects of Plunging Jets
Authors: E. Krepper, F.-P. Weiß, S. Alt, A. Kratzsch, S. Renger, W. Kastner
Publication: Proceedings - 18th International Conference on Nuclear Engineering, ICONE18, ISBN-9780791849323
Date: 2010-08

Abstract: Plunging jets play an important role in nuclear reactor safety research. In the present paper the case of the strainer clogging issue is considered. Entrained air caused by a plunging jet has an influence of the liquid flow field and on the fiber transport in the sump. In the paper the amount of entrained air is given as an inlet boundary condition according to correlations in the literature and confirmed by own experiments. The influence of entrained air on the fiber deposition pattern at the bottom of a tank and on the mixing procedure for the case of temperature differences between jet and tank water are investigated by CFD calculations and compared to experiments. The presented work is part of a joint research project performed in cooperation between the University of Applied Science Zittau/Gorlitz and Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation of particle transport phenomena in coolant flow in Zittau and the development of CFD models for its simulation in Rossendorf (Krepper et al. 2008).

Title: CFD Modeling of Insulation Debris Transport Phenomena in Water Flow
Authors: E. Krepper, G. Cartland-Glover, A. Grahn
Publication: Kerntechnik, Volume 74, Issue 5-6
Date: 2009-11-15

Abstract: The investigation of insulation debris generation, transport and sedimentation becomes important with regard to reactor safety research for PWRs and BWRs, when considering the long-term behaviour of emergency core cooling systems during all types of LOCAs. A joint research project on such questions is being performed in cooperation between the University of Applied Sciences Zittau/Goerlitz and the Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation of particle transport phenomena in coolant flow and the development of CFD models for its description. While the experiments are performed at the University at Zittau/Goerlitz, the theoretical modeling efforts are concentrated at Forschungszentrum Dresden-Rossendorf. In this paper the basic concepts for CFD modeling are described and feasibility studies are presented.

Title: CFD Modeling of Insulation Debris Transport Phenomena in Water Flow
Authors: E. Krepper, G. Cartland-Glover, A. Grahn
Publication: Kerntechnik, Vol. 74, No 5-6, ISSN- 0932-3902
Date: 2009-11

Abstract: The investigation of insulation debris generation, transport and sedimentation becomes important with regard to reactor safety research for PWRs and BWRs, when considering the long-term behaviour of emergency core cooling systems during all types of LOCAs. A joint research project on such questions is being performed in cooperation between the University of Applied Sciences Zittau/Gorlitz and the Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation of particle transport phenomena in coolant flow and the development of CFD models for its description. While the experiments are performed at the University at Zittau/Gorlitz, the theoretical modeling efforts tire concentrated at Forschungszentrum Dresden-Rossendorf 117 the current paper the basic concepts for CFD modeling are described and feasibility studies are presented.

Title: 3D Flow Field in Hold-up Volume Tank of Advanced Pressurized Reactor 1400
Authors: T. W. Kim, Y. S. Bang, B. G. Huh, S. W. Woo
Publication: Proceedings of 2009 Autumn Meeting of the Korean Nuclear Society, Kyungju (Korea, Republic of)
Date: 2009-10-15

Abstract:

Four phases after a LOCA are progressed step by step: blow-down, refill, reflood, and long-term cooling phase. When the long term cooling phase as the fourth step is started following the LOCA, debris occurred from fiberglass insulation, stainless steel jack, and Epoxy coating etc. may block the sump screen and disturb long-term cooling. In special, the effect of debris can be more intensified in the Advanced Pressurized Reactor 1400 (APR 1400), since the effect of debris will be happened in the blowdown phase as the first step. In other words, the sump screen in the ECCS can be affected by the debris of the blow-down phase. Therefore, predictions of flow field and debris behavior are important problems. In addition, flow path of debris of APR 1400 includes break location, containment floor, Hold-up Volume Tank (HVT), spillway, In-containment Refueling Water Storage Tank (RWST), and then, role of HVT is an intermediate collector of coolant after LOCA. In this work, flow field in the HVT is analyzed and effect of debris is estimated. Full transient three-dimensional flow field is calculated by commercial CFD code.

Title: Sump Pool Flow Simulation during Fill-up Phase of LOCA Using on CFD for OPR1000 Plant
Authors: Kyung Sik Choi, Jong Pil Park, Ji Hwan Joeng, Man Woong Kim
Publication: Proceedings of 2009 Autumn Meeting of the Korean Nuclear Society, Kyungju (Korea, Republic of)
Date: 2009-10-15

Abstract:

During a LOCA DBA, emergency core coolant supplements form a recirculation sump and cool the core and containment. After a DEGB at the hot leg near the steam generator, debris could be potentially be generated at a pipe or wall nearby the steam generator due to the jet impingement discharge flow, and be transported to the recirculation sump. Therefore debris such as insulation and paint chips could be accumulated on and clog the recirculation sump screen. If debris blocks the sump strainer, the pressure drop is increased at the screen so as to increase the pressure loss of the ECCS pump NPSH. This can potentially decrease the long-term cooling capability of the recirculation sump. Recirculation sump screen clogging accidents have happened BWRs in the USA and Sweden. Considering the importance to safety, the US NRC has issued the recirculation sump blockage as GSI-191. Moreover, the US NRC published Regulatory Guide 1.82 Rev.3 incorporating R and D findings and experiences in 2003. The NEI introduced a methodology to address this safety issue in the NEI 04-07 report. Meanwhile, the US NRC also published individually the regulatory guidelines as a SER for PWR plants. However, the current available technical information including the reports is applicable to generic PWR plants and not to specific plants. Therefore, additional research reflecting plant specific characteristics is necessary to develop the methodology and technical guides on the recirculation sump clogging issue. The objective of this study is to explore the characteristics of sump pool flow during LOCA by using CFD for the OPR1000 plant.

Title: CFD Modeling and Experiments of Insulation Debris Transport Phenomena in Water Flow
Authors: E. Krepper, G. Cartland-Glover, A. Grahn, F.-P. Weiss, S. Alt, R. Hampel, W. Kastner, A. Seeliger
Publication: Nuclear Technology Vol. 167, ISSN- 0029-5450
Date: 2009-07

Abstract:

The investigation of insulation debris generation, transport, and sedimentation becomes more important with regard to reactor safety research for pressurized water reactors and boiling water reactors when considering the long-term behavior of emergency core coolant systems during all types of LOCAs. The insulation debris released near the break during a LOCA incident consists of a mixture of disparate particle populations that varies with size, shape, consistency, and other properties. Some fractions of the released insulation debris can be transported into the reactor sump, where it may perturb/impinge on the emergency core cooling systems. Open questions of generic interest are, for example, the panicle load on strainers and corresponding pressure drop, the sedimentation of the insulation debris in a water pool, and its possible resuspension and transport in the sump water flow. A joint research project on such questions is being performed in cooperation with the University of Applied Sciences Zittau/Gorlitz. The project deals with the experimental investigation and the development of CFD models for the description of particle transport phenomena in coolant flow. While the experiments are performed at the University of Applied Sciences Zittau/Gorlitz, the theoretical work is concentrated at Forschungszentrum Dresden-Rossendorf. In the current paper the basic concepts for CFD modeling are described and feasibility studies including the conceptual design of the experiments are presented.

Title: Experimental ECCS Sump Strainer Head Loss Testing and the Incorporation of CFD Computed Source Terms for Pressurized Water Reactors
Authors: S. Cain, F. Gartland, J. Bleigh, A. Johansson, D. Schowalter
Publication: Proceedings - 17th International Conference on Nuclear Engineering, ICONE17
Date: 2009-07

Abstract:

High Energy Line Breaks (HELBs) inside nuclear reactor containment are recognized as challenges to PWR and BWR NPPs arising from the collateral damage due to insulation, fireproofing, coatings, and other miscellaneous materials which are shredded and transported during the event. These materials, as well as latent debris (dirt and dust) will be transported towards the containment floor and the recirculation sump screens by flow from both the HELB and the containment spray headers. This debris, if washed towards the recirculation pumps, could potentially impede the performance of the ECCS. To evaluate transport of material towards the sump and the potential for degradation in performance of the ECCS, CFD has been used to predict the volume of material transported to the sump screens. This predicted volume is then used in full scale laboratory tests to determine head loss across the screen under design flow rates. The laboratory sump strainer tests employed a flume facility measuring 14 m by 3 m by 1.5 m tall with a 2.5 m by 3 m by 2 m deep pit at one end, which can accommodate multiple full scale strainer modules. Head loss performance of the modules under different insulation debris loading conditions was evaluated. The internal walls of the flume were adjusted to reproduce prototypical average approach flow velocity and velocity gradients such that the transport of insulation debris to the strainer modules was accurately represented. A three-port isokinetic sampling system was integrated into the downstream piping for measuring debris bypass. This paper will cover the sump screen head loss testing methodology, and the associated integration of the computational results for the source terms.

Title: Transient Flow Field in Containment Floor Following a LOCA of APR-1400

Authors: Young Seok Bang, Gil-Soo Lee, Byung-Gil Huh, Deog-Yeon Oh, Sweng Woong Woo

Publication: Proceedings of 2009 Autumn Meeting of the Korean Nuclear Society, Kyungju (Korea, Republic of)
Date: 2008-10-15

Abstract:

Adoption of the In-containment Refueling Water Storage Tank (IRWST) in the Advanced Power Reactor (APR) -1400 effectively removed the switchover process for water source of ECCS and containment spray system following a LOCA. However, it may impose an additional challenge for the resolution of the sump clogging issue (GSI-191) because the containment flow field should be calculated in transient instead of steady since the flow paths from the break location to containment sump may be established at the early phase of the LOCA. The present study discusses an analysis model to calculate the transient flow field on containment floor to be used debris transport. The model has been developed to overcome the weaknesses in existing calculation methods, i.e., non-physical modeling and high uncertainty when using a system transient code such as RELAP5 and long computational time in CFD code.

Title: Preliminary CFD Analysis on Debris Transport to ECCS Sump in Recirculation Mode for Kori Unit 3

Authors: Su Won Lee, Kyung Jin Lee, Soon Joon Hong, Sung Bok Lee, Hyeong Taek Kim

Publication: Proceedings of the 2008 Autumn Meeting of the Korean Nuclear Society, Pyongchang (Korea, Republic of)
Date: 2008-10-15

Abstract:

Once containment recirculation pumps are activated and ECC flow is drawn from the recirculation sump during a LOCA, various insulation and coatings on piping, equipment and structures damaged by the LOCA break jet as well as additional debris sources are transported to the recirculation sump screen by the break flow and containment spray flow drainage. This debris may result in loss of NPSH of the recirculation pumps, and threaten long term cooling and containment heat removal capacity. In this case, flow patterns of containment pool are important to confirm the behavior of debris transport for predicting various flow paths to the recirculation sump screen. In this paper, preliminary models for containment pool simulation during recirculation mode using commercial CFD software, CFX, are made. The specific plant used for this analysis is Kori Unit 3, a three-loop Westinghouse plant in Korea.

Title: CFD Analysis of LOCA Blow-Down Transport for OPR-1000 Plant
Authors: Jong Pil Park, Ji Hwan Jeong, Man Woong Kim
Publication: Proceedings of the 2008 Autumn Meeting of the Korean Nuclear Society, Pyongchang (Korea, Republic of)
Date: 2008-10-15

Abstract:

In 1992, a spurious opening of a safety valve at Barsebäck-2, a Swedish BWR, resulted in clogging of two ECCS pump suction strainers leading to loss of both containment sprays within 1 hour after the accident. This issue is classified as GSI-191 in United States. The U.S. NRC published regulatory guidance on the performance PWR containment sump screens in 2002 in Regulatory Guide 1.82 Revision 3. As a response to these activities, the NEI performed evaluations for PWR sump performance. The methodology of debris transport is evaluated based on a debris transport logic chart. This chart is composed of blow-down, wash-down, pool-fill up, and recirculation transport. According to this methodology, 0.25 of small pieces transport to upper containment during LOCA blow-down transport. Also, NEI 04-07 suggest two methods of evaluation for debris transport. One is an open channel network model, the other is a CFD model. The analysis for recirculation transport is performed using CFD code. The present work aims to evaluate the fraction of debris transport during LOCA blow-down based on CFD. The reference plant is the OPR-1000 plant (Optimized Power Reactor 1000 MWe), Ulchin nuclear power plant unit 3 and 4 (UCN3 and 4). The results will give a clear figure about flow patterns during LOCA blow-down, and the fraction of debris transport to the upper containment, which is one of the major safety issues. The real geometry of OPR-1000 plant was used in the analysis. FLOW-3D version 9.2, a commercial CFD code, was used in the present work.

Title: Debris Transport Evaluation during LOCA Blow-down using CFD Methodology for OPR-1000 Plant
Authors: Jong Pil Park, Ji Hwan Jeong, Man Woong Kim
Publication: Proceedings of the 2008 Autumn Meeting of the Korean Nuclear Society, Pyongchang (Korea, Republic of)
Date: 2008-10-15

Abstract:

The ECCS provides water to cool the core of a nuclear reactor in case of a LOCA that would result, for example, from a reactor coolant system pipe break. The water supplied by the ECCS comes from the refueling water tank (RWST) and safety injection tanks. When the low level limit is reached in the RWST, the water that has accumulated in containment sump will be recirculated through the reactor core using the ECCS system. This process provides long-term cooling for the core. Accumulation of debris generated during a LOCA will result in an increase in head loss across the sump screens and if the head loss across the screen becomes too large, the pumps will no longer have adequate NPSH, which could result in cavitation and failure of the pumps to deliver the amount of water needed. In 1992, a spurious opening of a safety valve at Barsebäck-2, a Swedish BWR, resulted in clogging of two ECCS pump suction strainers leading to loss of both containment sprays within 1 hour after the accident. This issue is classified as GSI-191 in United States. The U.S. NRC published regulatory guidance on the performance of PWR containment sump screen in 2002 in Regulatory Guide 1.82 Revision 3. The present work aims to evaluate debris transport by LOCA blow down for the OPR-1000 plant based on a CFD methodology. This analysis result can be used to develop the regulatory capability to evaluate the safety related to the issue in NPPs.

Title: Numerical and Experimental Investigations for Insulation Particle Transport Phenomena in Water Flow

Authors: S. Alt, G. Cartland-Glover, A. Grahn, R. Hampel, W. Kastner, A. Kratzsch, E. Krepper, A. Seeliger, F.-P. Weiß

Publication: Annals of Nuclear Energy, Vol. 35, No 8, ISSN- 0306-4549
Date: 2008-08

Abstract:

The investigation of insulation debris generation, transport and sedimentation becomes more important with regard to reactor safety research for pressurized and boiling water reactors, when considering the long-term behaviour of emergency core coolant systems during all types of LOCA. The insulation debris released near the break during a LOCA incident consists of a mixture of a disparate particle population that varies with size, shape, consistency and other properties. Some fractions of the released insulation debris can be transported into the reactor sump, where it may perturb or impinge on the emergency core cooling systems. Open questions of generic interest are for example the particle load on strainers and corresponding pressure-drop, the sedimentation of the insulation debris in a water pool, its possible re-suspension and transport in the sump water flow. A joint research project on such questions is being performed in cooperation with the University of Applied Science Zittau/Gorlitz and the Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation and the development of CFD models for the description of particle transport phenomena in coolant flow. While the experiments are performed at the University Zittau/Gorlitz, the theoretical work is concentrated at Forschungszentrum Dresden-Rossendorf. In the present paper, the basic concepts for CFD modeling are described and experimental results are presented. Further experiments are designed and feasibility studies were performed. 2008.

Title:	Experimental Investigation and CFD Simulation of the Behaviour of Mineral Wool in the Reactor Sump
Authors:	E. Krepper, G. Cartland-Glover, A. Grahn, F.-P. Weiss, S. Alt, R. Hampel, W. Kastner, A. Seeliger
Publication:	2008 Proceedings of the 16th International Conference on Nuclear Engineering, ICONE16, ISBN- 0791848159; 9780791848159
Date:	2008-05-15

Abstract:

The investigation of insulation debris generation, transport and sedimentation becomes important with regard to reactor safety research for PWR and BWR, when considering the long-term behavior of emergency core cooling systems during all types of LOCA. The insulation debris released near the break during a LOCA incident consists of a mixture of disparate particle population that varies with size, shape, consistency and other properties. Some fractions of the released insulation debris can be transported into the reactor sump, where it may perturb/impinge on the emergency core cooling systems. Open questions of generic interest are the sedimentation of the insulation debris in a water pool, its possible re-suspension and transport in the sump water flow and the particle load on strainers and corresponding pressure drop. A joint research project on such questions is being performed in cooperation between the University of Applied Sciences Zittau/Gorlitz and the Forschungszentrum Dresden-Rossendorf. The project deals with the experimental investigation of particle transport phenomena in coolant flow and the development of CFD models for its description. While the experiments are performed at the University at Zittau/Gorlitz, the theoretical modeling efforts are concentrated at Forschungszentrum Dresden-Rossendorf. In the current paper the basic concepts for CFD modeling are described and feasibility studies including the conceptual design of the experiments are presented.

Title: Implementation of a Strainer Model for Calculating the Pressure Drop across Beds of Compressible, Fibrous Materials
Authors: A. Grahn, E. Krepper, S. Alt, W. Kastner
Publication: Nuclear Engineering and Design, Vol. 238, No 10, ISSN- 0029-5493
Date: 2008-10

Abstract:

Mineral wool insulation debris, which is generated during a LOCA has the potential to undermine the long-term recirculation capability of the ECCS in a NPP. Most importantly, ECCS pumps are faced with an increasing pressure drop while insulation debris accumulates at the pump suction strainers. The presented study aims at modeling the pressure drop of flows across growing cakes of compressible, fibrous materials and at the implementation of the model into a general-purpose three-dimensional (3D) CFD code. Computed pressure drops are compared with experimentally found values. The ability of the CFD implementation to simulate 3D flows with a non-uniformly distributed particle phase is exemplified using a step-like channel geometry with a horizontally embedded strainer plate.

Title: An Application of Computational Fluid Dynamics (CFD) Code to the Design of a Multi-stage Breakdown Orifice in Support of GSI-191 Evaluations
Authors: J.C. Adams, L.I. Ezekoye, S.M. Smith, S.R. Swantner
Publication: 2007 Proceedings of the ASME Pressure Vessels and Piping Conference - Operations, Applications and Components
Date: 2008

Abstract:
In September 2004, the NRC issued Generic Letter GL2004-02 "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors" to address Generic Safety Issue 191 (GSI-191) "Assessment of debris accumulation on PWR sump performance." GL2004-02 requested PWR licensees to perform a "downstream effects" evaluation of their ECCS and CSS. GL2004-02 also gave guidance on what analysis had to be completed in order to resolve GSI-191. These evaluations included a wear and plugging assessment of all ECCS and CSS components, including valves. During preliminary "downstream effects" analysis of a plant, it was determined that the positions of ECCS throttle valves could be such that the flow clearances through the valves would be too small to meet the criteria developed for component plugging or wear assessment. This suggested that a modification to the system needs to be made which allows the throttle valves to be more fully opened. In order to allow the throttle valves to be opened more fully, additional hydraulic resistance (i.e. pressure drop at the design flow rate) was added at another location. Several orifice designs were considered to provide the needed resistance. Since the required additional pressure drop was a substantial fraction of the total pressure drop, special design features of the orifice were necessary to preclude system instabilities due to cavitation, degassing and flow swirl. The purpose of this paper is to present a method for assessing the effectiveness of a multi-stage orifice that can be placed in the system to provide the required resistance, thus permitting the throttle valves to be used more efficiently. The paper presents the design aspects of the multi-stage breakdown orifice, CFD modeling used to select the design, and the system condition testing results.

Title: Experiments for CFD-modeling of Cooling Water and Insulation Debris Two-phase Flow Phenomena during Loss of Coolant Accidents

Authors: S. Alt, G. Cartland-Glover, A. Grahn, R. Hampel, W. Kaestner, E. Krepper, A. Seeliger

Publication: Proceedings - 12th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-12

Date: 2007-10-04

Abstract:

The knowledge of insulation debris generation and transport gains in importance regarding reactor safety research for PWR and BWR. The insulation debris released near the break consists of a mixture of very different fibers and particles concerning size, shape, consistence and other properties. Some fraction of the released insulation debris will be transported into the reactor sump where it may affect emergency core cooling. Experiments are performed to blast original samples of mineral wool insulation material by steam under original thermal-hydraulic break conditions of BWR. The gained fragments are used as initial specimen for further experiments at acrylic glass test facilities. The quasi ID-sinking behaviour of the insulation fragments are investigated in a water column by optical high speed video techniques and methods of image processing. Drag properties are derived from the measured sinking velocities of the fibers and observed geometric parameters for an adequate CFD modeling. In the test rig "Ring line-II" the influence of the insulation material on the head loss is investigated for debris loaded strainers. Correlations from the filter bed theory are adapted with experimental results and are used to model the flow resistance depending on particle load, filter bed porosity and parameters of the coolant flow. This concept also enables the simulation of a particular blocked strainer with CFD codes. During the ongoing work further results of separate effect and integral experiments and the application and validation of the CFD-models for integral test facilities and original containment sump conditions are expected.

Title: The Effect of Coriolis Force on the Formation of Dip on the Free Surface of Water Draining from a Tank
Authors: Jong Chull Jo, Dong Gu Kang, Hho Jhung Kim, Kyung Wan Roh, Young Gil Yune
Publication: Proceedings of 2007 Autumn Meeting of the Korean Nuclear Society, Pyongchang (Korea, Republic of)
Date: 2007-10-15

Abstract:

For the case of RWT connecting to the ECC line, it can be surmised that there is a possibility of ECC pump failure due to air ingression into the ECC supply line even before the RWT is drained away. Therefore, it is important to check if the operational limit of the RWT water level is set at a value higher than the critical height that causes a dip formation on the free surface of a draining liquid. In the previous work, such complex unsteady flow fields both in a simple water tank and in the RWT at the Korean standard nuclear power plant have been simulated using the CFX5.10 code which is well-known as one of the well-validated commercial CFD codes. However, for the simplicity of those calculations the Coriolis force has not been taken into account. Thus, in the present paper, the effect of Coriolis force-induced vortex flow on the dip formation of dip has been investigated for the simple water tank to confirm validity of the previous work. To do this the unsteady flow fields accompanied by vortex in the simple water tank has been simulated using the CFX5.10 code.

Title: Review on the NEI Methodology of Debris Transport Analysis in Sump Blockage Issue for APR1400
Authors: Jong Uk Kim, Jeong Ik Lee, Soon Joon Hong, Byung Chul Lee, Young Seok Bang
Publication: Proceedings of 2007 Autumn Meeting of the Korean Nuclear Society, Pyongchang (Korea, Republic of)
Date: 2007-10-15

Abstract:

Since the US NRC initially addressed post-accident sump performance under Unresolved Safety Issue USI A-43, sump blockage issue has gone through GSI-191, Regulation Guide 1.82, Rev. 3 (RG. 1.82 Rev.3), and generic Letter 2004-02 for PWRs. As a response of these US NRC activities, NEI 04-07 was issued in order to evaluate the post-accident performance of a plant recirculation sump. The baseline methodology of NEI 04-07 is composed of break selection, debris generation, latent debris, debris transport, and head loss. In analytical refinement of NEI 04-07, CFD is suggested for the evaluation of debris transport in ECC recirculation mode as guided by RG. 1.82 Rev.3. In Korea, the nuclear industry also keeps step with international activities of this safety issue, with Kori 1 plant as a pioneering edge. The Korean nuclear industry has been also pursuing development of an advanced PWR of APR1400, which incorporates several improved safety features. One of the key features related to the sump blockage issue is the adoption of IRWST (In-containment Refueling Water Storage Tank). This device, as the name implies, changes the emergency core cooling water injection pattern. This fact makes us to review the applicability of the NEI 04-07 methodology. In this paper we discuss the applicability of the NEI 04-07 methodology, and more over, a new methodology is proposed. Finally the preliminary debris transport is analyzed.

Title: Numerical Analysis of Unsteady Flow Field in the RWT for the Prediction of the Potential for Air Ingression into the ECC Supply Lines during the SBLOCA at the KSNPS

Authors: Jo Jong Chull, Oh Yu Seon

Publication: 2007 Proceedings of the ASME Pressure Vessels and Piping Conference - Fluid-Structure Interaction

Date: 2008

Abstract:

This paper addresses the three-dimensional analysis of unsteady flow in the RWT for the prediction of the potential for air ingression into the ECC pump during the SBLOCA at KSNPs (Korean Standard Nuclear Power plants). Upon the receipt of RAS (Recirculation Actuation Signal) by the occurrence of SBLOCA, the RWT outlet valve is designed to be isolated manually. At the nuclear power plants without the provision of automatic isolation operation of the valve on the downstream of the RWT line, the refueling water begins to discharge from the RWT, which may result in forming and developing the vortex flow in the RWT, under the condition of the minimum pressure of containment and minimum water level of containment recirculation sump during the phase of RAS. Due to the vortex flow, when the water level is below the critical height, a dip starts to develop, causing air ingression before the refueling water drains fully. Hence it can be surmised that there is a possibility of ECC pump failure due to air ingression into the ECC supply line even before the RWT is fully drained. Therefore, in this work, when the RAS is actuated followed by the SBLOCA occurrence, a quantitative evaluation for the maximum limiting allowable time for the manual closing of RWT outlet valve is carried out to eliminate the possibility of air ingression into the ECC pump from the RWT. To do this, the unsteady flow field in the RWT including the drain pit with the connected discharge piping in the process of SBLOCA is analyzed using a CFD code. In addition, the transient flow behavior accompanying air entrainment resulting from the dip formation due to vortex flow at the upper part of RWT is examined and the applicable limiting time of the isolation valve closing for preventing air ingression is assessed.

Title: Experimental and Analytical Investigations for Debris Transport Phenomena in Multidimensional Water Flow
Authors: S. Alt, A. Seeliger, E. Krepper, A. Grahn
Publication: Proceedings of 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH 11), Avignon (France)
Date: 2005-10-06

Abstract:

The investigations of insulation debris generation and transport gain in importance regarding the reactor safety research for PWR and BWR considering all types of LOCA as well as short and long term behaviour of emergency core coolant systems. The insulation debris released near the pipe break during LOCA consists of a mixture of very different particles concerning size, shape, consistence and other properties. Some fraction of the released insulation debris will be transported into the reactor sump where it can block hold up-devices and may affect the long term emergency core cooling. A common research project of IPM-Zittau and FZ-Rossendorf deals with the experimental investigation and the development of CFD models for the description of particle transport phenomena in reactor coolant flow. Open questions of generic interest are e.g. the sedimentation of the insulation debris in a water pool, possible resuspension, transport in the sump water flow and head loss at hold-up devices under various geometric and fluidic boundary conditions. Separate effect experiments for the investigation of particle transport phenomena in multidimensional water flow, sedimentation and resuspension processes were carried out at Plexiglas test facilities (Column, Ring Channel) using modern flow measurement and digital image processing technologies. The behaviour of gravitating insulation particles in aqueous solution (sink rates or settling velocities) and sedimentation processes were observed at the test facility 'Column'. Experiments for the determination of transport behaviour of different particle sizes in horizontal carrier flow were realised at facility 'Ring Channel'. Experimental results were generated with constant cross section area along the whole channel length as well as with varied cross section areas (e.g. barriers) and strainers. Model developments for CFD simulations of insulation material transportation, sedimentation, resuspension and the clogging and penetration at strainers are described. The model parameters and functions are checked based on the separate effect experiments. The paper includes the presentation of experimental results generated at the facilities, the theoretical concepts for modelling these phenomena with CFD-codes and the comparison between simulated and measured data.

Title: Numerical Investigations for Insulation Particle Transport Phenomena in Water Flow
Authors: E. Krepper, A. Grahn, S. Alt, W. Kaestner, A. Kratzsch, A. Seeliger
Publication: Proceedings of International Conference Nuclear Energy for New Europe 2005, Bled (Slovenia)
Date: 2005-07-01

Abstract:

The investigation of insulation debris generation, transport and sedimentation gains importance regarding the reactor safety research for PWR and BWR considering the long term behaviour of emergency core coolant systems during all types of LOCA. The insulation debris released near the break during LOCA consists of a mixture of very different particles concerning size, shape, consistence and other properties. Some fraction of the released insulation debris will be transported into the reactor sump where it may affect emergency core cooling. Open questions of generic interest are e.g. the sedimentation of the insulation debris in a water pool, possible re-suspension, transport in the sump water flow, particle load on strainers and corresponding difference pressure. A joint research project in cooperation with Institute of Process Technology, Process Automation and Measuring Technology Zittau deals with the experimental investigation and the development of CFD models for the description of particle transport phenomena in coolant flow. While experiments are performed at the IPM-Zittau, theoretical work is concentrated at Forschungszentrum Rossendorf. In the present paper the basic concepts for CFD modelling are described and first results including feasibility studies are shown. During the ongoing work further results are expected.

Title:	Characterisation of Size, Shape and Motion behaviour of Insulation Particles in Coolant Flow using Image Processing Methods
Authors:	S. Alt, R. Hampel, A. Seeliger
Publication:	Applied Computational Intelligence - Proceedings of the 6th International FLINS Conference
Date:	2004-09-01

Abstract:

The investigations for insulation particle genesis and transport gain in importance regarding the reactor safety research for PWR and BWR. All types of LOCA as well as short and long term behaviour of emergency core coolant systems were considered for analysis. The gist of these investigations is the development of 3-D-models simulating two-phase flow consisting of water and insulation particles in large geometries. The background of experimental investigations consists of the following parts. Generation of a wide data base, development and validation of CFD-models for the description of insulation particle transport phenomena in flows. These analyses will be carried out for various geometric and fluidic boundary conditions, as well as sedimentation, resuspension, agglomeration, clogging and increasing of differential pressure at hold-up devices. Three Plexiglas test facilities were built for exploration of the mentioned single phenomena. Especially modern flow measurement and digital image processing technologies were applied.

Title: Experimental Validation of CFD Analyses for Estimating the Transport Fraction of LOCA-generated Insulation Debris to ECCS Sump Screens
Authors: L. Bartlein, B. Letellier, A.K. Maji, D.V. Rao, K.W. Ross
Publication: Nuclear Technology, Vol. 146, No 3, ISSN- 0029-5450
Date: 2004-06

Abstract:

This paper presents a comparison between CFD analysis and experiments in order to help PWR plants develop a methodology for estimating the amount of insulation debris that may transport to the sump screens of an ECCS. This information is essential for the resolution of GSI-191 on the safety margins of the ECCS systems subsequent to debris accumulation and head loss at the screen. Tests were carried out on a simulated containment floor in the laboratory to determine the flow velocities in which different types of objects including insulation debris would move along the floor. CFD analyses were independently carried out to determine the flow velocities in the containment under different flow rates and break locations. It was shown that the flow regimes predicted by the CFD analyses compare well with the experimentally observed movement along the floor. Based on this observation the transport fraction of different types of insulation debris can be estimated specific to any PWR plant.

Title: A State-of-the-Art Report on Rapid Boron-dilution Transients
Authors: B.H. Cho, T.S. Kwon, C.H. Song
Publication: Korea Atomic Energy Research Institute Technical Report
Date: 2003-11-01

Abstract:

The rapid boron dilution transients that could potentially lead to reactivity problems, especially for the Korean advanced reactor APR1400, are suspected to be one of the major safety concerns and the need for multi-dimensional thermal-hydraulic verification test is increasing. This report gives information on the status of previous studies, technical issue and/or problems. Most studies of rapid boron dilution transients are to evaluate the borated slug mixing of the two flows at the reactor downcomer and at the entrance of core by test and/or analysis. Most of the test facilities have been built in a linear scale of 1:5 or 1:7. For the investigation of coolant mixing phenomena, a wide range of flow conditions are adapted for their interested specific reactor. The model is designed to maintain whole system volumetric ratio between the model and the prototype, such as at the flow mixing region of downcomer and core. Flow stagnation of some portion of the deborated water slug in the downcomer is investigated in the tests, and this kind of stagnation in space and time affect the boron mixing at the entrance of the core seriously. The characteristics depend on the geometries of the reactor of the specific plant, so each country should evaluate it by themselves. Analytical studies for boron dilution transient had been started regarding thermal mixing and continued until now by the several countries for their own purpose. Usually the analyses are performed using a 2D or 3D grid using a commercial CFD code with a finite volume method, such as FLUENT, CFX, PHOENICS etc. The behavior of the mixing of highly borated water entrained with the emergency core cooling water following a main steam-line break accident and the mixing of unborated water at the downcomer following the rapid boron dilution transient could have different characteristics in an APR1400 compared to previous standard nuclear power reactors, and related tests could be required. Accordingly, the evaluation for the specific thermal hydraulic behaviors related to the Direct Vessel Injection (DVI) of APR1400 and the experimental data for turbulence model, for example turbulent intensity, which have not been measured in previous experiments, can be considered very important for the future test program. A numerical analysis will be needed for the future test as a supplement.

Title: Condensation Pool Experiments with Non-condensable Gas and Fluent 5 Simulations
Authors: J. Laine, T. Tuomainen
Publication: Technical Report, Technical Research Centre of Finland, FINNUS the Finnish research programme on nuclear power plant safety 1999-2002
Date: 2002-11-01

Abstract:

The formation, size and distribution of non-condensable gas bubbles in the condensation pool of the Olkiluoto NPP in a conceivable LOCA was studied experimentally with a scaled down condensation pool test rig. Particularly, it was important to find out if any air bubbles flowed inside the ECCS strainer close to the pool wall and bottom. The effect of non-condensable gas on the performance of an ECCS pump was also examined. CFD calculations with the Fluent 5 code were made to support the design of the test rig and the planning of the experiments. Compressed air was blown to the test pool through blowdown pipes or, alternatively, air was injected directly into the intake pipe of the ECCS pump. The first large air bubbles forming at the blowdown pipe outlet touched the ECCS strainer. When two blowdown pipes were used simultaneously, a lot of air bubbles were detected inside the strainer during the first 30 seconds. A 3-7% volume fraction of air injected directly into the pump intake pipe was enough to make the pump head and flow collapse.

Title: TOKE Summary Report
Authors: M. Puustinen
Publication: Technical Report, Technical Research Centre of Finland, FINNUS the Finnish research programme on nuclear power plant safety 1999-2002
Date: 2002-11-01

Abstract:

The thermal-hydraulic experiments and code validation project addressed both the experimental and computational aspects of nuclear safety studies. Integral VVER related experiments dealing with a steam generator collector header rupture incident and with non-condensable gas behaviour in the primary circuit were carried out in the PArallel Channel TEst Loop. Local loading effects due to water flow and thermal stratification in a T-joint of a hot horizontal pipe and a cold vertical tube were investigated in a purpose-built test loop in co-operation with the structural integrity project. The behaviour of non-condensable gas during the first seconds of a conceivable LBLOCA blowdown to a BWR condensation pool was also studied in the separate effect tests related subproject. For this purpose, a test rig with a scaled down water pool, blowdown pipes, an ECCS strainer and a pump was designed and constructed in Lappeenranta University of Technology (LTKK). Thermal-hydraulic and CFD calculations with the codes APROS and Fluent, respectively, supported the planning and analysis of both the integral and separate effect tests.

Title: Transport Characteristics of Selected PWR LOCA Generated Debris
Authors: A. K. Maji, B. Marshall et al.
Publication: U.S. Department of Energy Report No LA-UR-00-4998
Date: 2000-10-01

Abstract:
In the unlikely event of a LOCA in a PWR, break jet impingement would dislodge thermal insulation from nearby piping, as well as other materials within the containment, such as paint chips, concrete dust, and fire barrier materials. Steam/water flows induced by the break and by the containment sprays would transport debris to the containment floor. Subsequently, debris would likely transport to and accumulate on the suction sump screens of the ECCS pumps, thereby potentially degrading ECCS performance and possibly even failing the ECCS. In 1998, the U. S. NRC initiated Generic Safety Issue-191 to evaluate the potential for the accumulation of LOCA related debris on the PWR sump screen and the consequent loss of ECCS pump NPSH. LANL, supporting the resolution of GSI-191, was tasked with developing a method for estimating debris transport in PWR containments to estimate the quantity of debris that would accumulate on the sump screen for use in plant specific evaluations. The analytical method proposed by LANL, to predict debris transport within the water that would accumulate on the containment floor, is to use CFD combined with experimental debris transport data to predict debris transport and accumulation on the screen. CFD simulations of actual plant containment designs would provide flow data for a postulated accident in that plant, e.g., three-dimensional patterns of flow velocities and flow turbulence. Small-scale experiments would determine parameters defining the debris transport characteristics for each type of debris. The containment floor transport methodology will merge debris transport characteristics with CFD results to provide a reasonable and conservative estimate of debris transport within the containment floor pool and subsequent accumulation of debris on the sump screen. The complete methodology will, of course, include a means of estimating debris generation, transport to the containment floor, transport to the sump screen, and the resulting loss of NPSH.

Title: Study on Solid-Liquid Two-Phase Flow on PWR Sump Clogging Issue
Authors: A. Ui, S. Ebata, F. Kasahara, T. Iribe, H. Kikura and M. Aritomi
Publication: J. Nucl. Sci. Technol., Vol.47, No.9, pp. 820-828
Conference:
Date: 2010-04-18

Abstract:
A solid-liquid multiphase model based on the moving particle semi-implicit (MPS) method coupled with a turbulence model was developed. The model is able to treat different sized solid particles, and results in reducing calculation time in a large scale simulation. In order to validate this model, several open channel hydraulic experiments with fibrous debris were conducted. A simulation code SANSUI implemented the model was validated by the comparison of the analytical results with the experiments. One of the experiments was dam-break and over-flow problem assuming blowdown of PWR containments. Analytical results using this model are in agreement with the experiment. Another was open channel flow with curbs which assumed washdown transport. The debris was observed to be transported with settling, re-suspending and passing across the curbs according to flow velocity. The analytical results show that this model is capable of simulating debris behavior such as settling, re-suspension and lifting curbs. This method was applied to the debris transport analysis of full scale PWR containment vessel floor after large break LOCA, and the debris transport behavior was evaluated. The result shows tendency of flooding and debris transport during initial stage of large break LOCA. The floor is filled by water in a few minute. Some debris stayed in stagnant regions where the flow velocity is low. And some are transported to inside of curbs surrounding sumps. A fraction of the number of debris that reached inside of the curbs for total number of debris was shown. The authors conclude that the method has a potential for realistic debris transport evaluation, and is useful to consider countermeasures against this safety issue.

Title: Application of Compressible Two-Fluid Model Code to Supersonic Two-Phase Jet Flow Analysis

Authors: H. Utsuno, M. Akamatsu and T. Morii (JNES), H. Okada (IAE) and A. Minato (Advancesoft Corp.)

Publication:
Conference: NURETH-13, N13P1368
Date: 2009-09-27

Abstract:
The ANSI/ANS model for assessing impingement loadings by the two-phase jet is a semi-empirical correlation based on thermodynamic assumptions and empirical observation of two-phase free jets. In this study, two-phase jet analysis was performed with a two-fluid model considering fluid compressibility. The numerical method is based on a two-fluid model within the finite-volume framework. The relationships between discontinuities of pressure, velocity and density in compressible flow along the characteristic curves are used to approximate the state variables at cell interfaces, and thereby to derive an expression of the numerical fluxes for the conservation laws. A reasonable agreement between the numerical and theoretical solutions was confirmed for the classic benchmark problems of the Sod's single-phase shock tube and the two-phase hydraulic hammer. Two-phase jet impingement tests performed by JAERI were analyzed and the pressure profile and load on the target plate were well predicted. Steam-water two-phase free jets were calculated under actual BWR/PWR thermodynamic conditions using the present numerical method. The predicted distribution of jet pressure, which is a potential damage defined as static pressure plus two-phase momentum flux, was compared with evaluations from the ANSI/ANS model, and the JAERI experimental correlation. The initial blast wave was not generated in the two-fluid model calculations. Regarding estimation of ZOI, the two-fluid model and the ANSI/ANS standard model were comparable in high jet pressure, while the latter is conservative in a low jet pressure region approaching atmospheric pressure. The JAERI correlation results in a smaller ZOI. The ANSI/ANS model gave conservative results in comparison with the computational fluid calculation.

GERMAN CFD MODEL DEVELOPMENT ON THE STRAINER CLOGGING ISSUE

The current task of a numerical simulation concerning the strainer clogging issue is the determination of the fiber material mass finally deposited in a certain geometry (the reactor sump) and of the fiber mass entrained by the water flow. Open questions of generic interest are for example the particle load on strainers and the corresponding pressure drop, the sedimentation of the insulation debris in a water pool, and its possible re-suspension and transport in the sump water flow. Since the momentum transport in the liquid flow plays an important role, the problem is clearly a 3D problem and has to be solved by applying computational fluid dynamic (CFD) methods.

APPLICATION EXAMPLES FOR PWRS

In the years 2002 – 2011 several joint research projects performed in cooperation between the University of Applied Science Zittau/Goerlitz (HZGR) and Forschungszentrum Dresden-Rossendorf (FZD, today Helmholtz-Zentrum Dresden-Rossendorf, HZDR) were directed at the experimental investigation of particle transport phenomena in coolant flow (HZGR) and the development of CFD models for its simulation (FZD) (see e.g. [E.1]).

Fragmentation tests were performed to blast blocks of insulation material with steam under the thermal hydraulic conditions to be expected during a LOCA (i.e. at pressures up to 11 MPa). The material obtained by this method was then used as raw material for further experiments.

The transport behavior of the steam-blasted material was investigated in a water column by measuring of the downward tumbling velocities of the fibers by optical high-speed video techniques. CFD simulations considering the fibers as a second Eulerian phase were adjusted to obtain the same tumbling velocities. The drag coefficients and other physical properties of the modeled fiber phase were derived from the experiments.

The fiber transport in a turbulent water flow was investigated in a horizontal flow in a narrow channel with a racetrack-type configuration with defined boundary conditions. Laser PIV measurements and high-speed video were used for the investigation of the water flow-field and the fiber concentration. Besides the drag acting on the particles, the turbulent dispersion force plays an important role in determining the momentum exchanged between the water and the fibrous phase and for the establishment of a certain vertical fiber concentration profile.

The deposition and re-suspension behavior of the fibers at low velocities was investigated by the same measuring techniques and in the same narrow racetrack channel. However, in this case obstacles were inserted into the channel to change the flow regime locally. CFD approaches consider the influence of the fiber material on the mixture viscosity and the dispersion coefficient on the transport of the solids.

A test rig was used to study the influence of the insulation material loading on the pressure difference observed in the region of the strainers. A CFD model was developed that uses the approach of a porous body. Correlations from the filter theory known in chemical engineering were adapted to the experiments and used to model the flow resistance depending on the particle load. This concept also allowed the simulation of a partially blocked strainer.

Finally, the interaction of the models was investigated in an integral test. By using high-speed video and laser (LDV and PIV) measurements, the progression of the momentum by the jet falling into the pool was investigated. Of special importance is the role that entrained gaseous bubbles play on disturbing the fluid and potentially influencing the fiber sedimentation and re-suspension.

1.1 Transport of Fibers within a Tank of a Test Facility

During the long-term core cooling operation following a LOCA, the water falls from the break several meters onto the sump water surface. On its way, the water will be mixed with air. Air bubbles and

released materials will be transported to the sump of a PWR. The jet-induced flow into the sump will influence the fiber transport to the strainer and therefore the head-loss across the strainer [E.1].

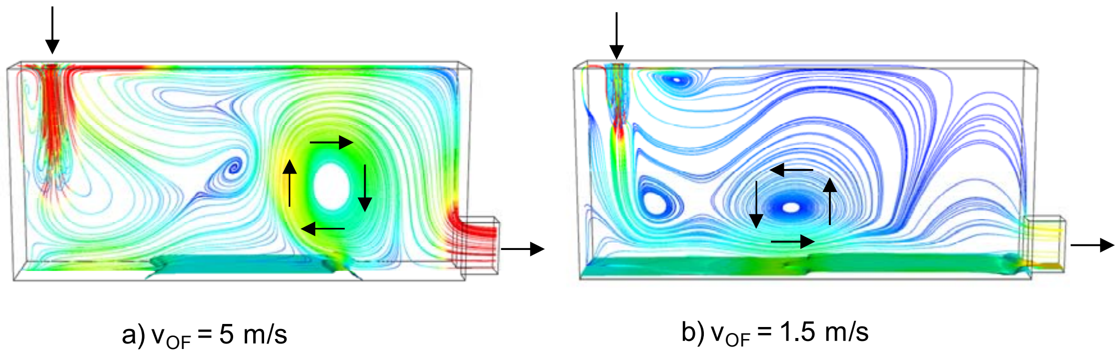


Figure E-1: Water Streamlines Projected on a Middle Plane for Different Jet Inlet Velocities V_{OF}. Deposited fibers at the bottom of the pool are shown as iso-surfaces of the fiber phase [E.1].

ANSYS-CFX calculations based on the models described in the previous chapter were performed to analyze the transport of fibrous material entrained by plunging water into a tank. Experiments were performed at the IPM Zittau. The numerical simulations applying an Euler/Eulerian three-field approach were performed at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The establishment of the large swirl caused by the entrained air dependent on the jet velocity V_{OF} was reproduced by the calculations (see Figure E-1). The deposition pattern of the fibrous material at the bottom of the pool was calculated with good qualitative agreement with the experiment.

1.2 Deposition of Insulation Material at the Spacers of Fuel Elements and Head-Loss across Clogged Spacers

CFD calculations of the head-loss across clogged spacers of fuel elements using the complete RPV geometry were performed at HZDR. Each fuel element was represented in a simplified manner. For the upper most spacer grid, the strainer model was applied. According to these investigations, in case of hot-leg injection at the beginning of sump cooling, the fibers accumulate at the spacers within down-flowing channels. Before the switch over of the ECC injection from flooding mode to sump mode, the coolant circulates in an inner convection loop in the core extending from the lower plenum to the upper plenum. The CFD simulations have shown that after starting the sump mode, the ECC water injected through the hot legs flows down into the core via so-called “break-through channels” located in the outer core region where the downward leg of the convection roll has established itself. The hotter, lighter coolant rises in the centre of the core. As a consequence, the insulation material is mostly deposited on the uppermost spacer grids positioned in the break-through zones. This means that the fibers are not uniformly deposited over the core cross section. Later, a redistribution of the fibrous material deposited on the spacers was calculated due to the reduced flow through clogged channels.

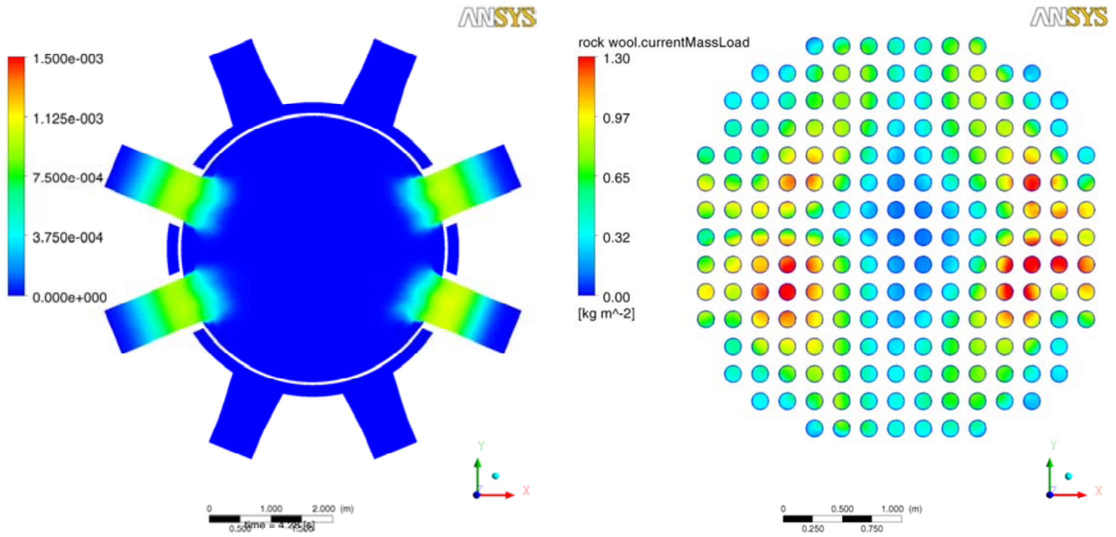


Figure E-2: Rock Wool Concentration [ppm] after Start-up of ECC Injection, Nozzle Plane (left) and Rock Wool Mass Load on the Upper Spacer Grid (right) [E.2].

TRANSPORT AND SEDIMENTATION WITHIN THE PRESSURE SUPPRESSION POOL OF A BWR

Calculations were performed to model the transport of fibrous material within the pressure suppression pool of a BWR type 69 and a BWR type 72. The 3D water flow distribution was calculated with the TISA software. TISA is a fast-running code based on the Navier-Stokes equations, using the shallow water wave approximation. The motion of fibrous debris particles was modeled by superposition of the particle sedimentation velocity relative to the water flow. The main result of the simulation was the fraction of the suspended particle mass which is deposited at the pool bottom, and the fraction which is transported to the strainers. Figure E-3 shows simulated pool regions from where debris particles are sucked in the direction of the strainers. Particles outside these regions were sedimented at the pool bottom.

The program was validated by experimental data of the Harburg test facility. Four experiments with different flow velocities were performed. The sedimentation rate was calculated for 5 sedimentation velocities. Good agreement of the calculated sedimentation rate was reached for a sedimentation velocity of 8 mm/s.

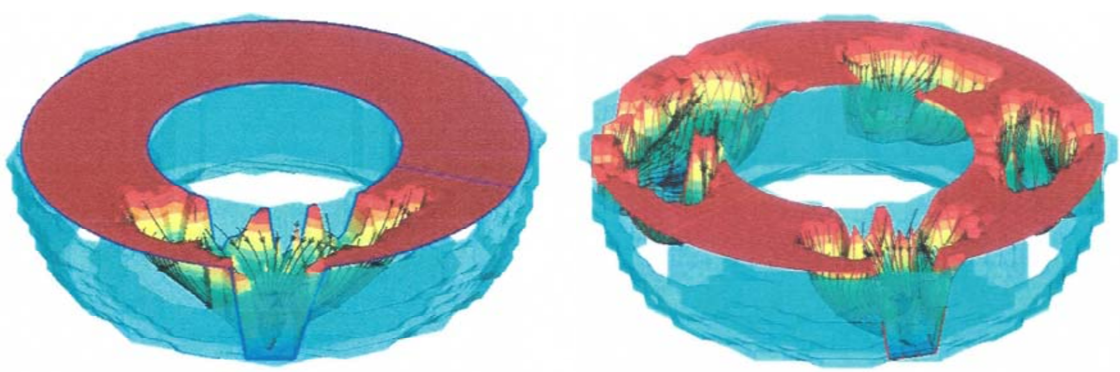


Figure E-3: Suction of Suspended Particles in the Direction of the Strainers in the Case of One ECCS Pump Resp. 5 ECCS Pumps, BWR Type 69 Wetwell Pool [E.3].

It has to be considered that the model of the pressure suppression pool is not very detailed (grid spacing about 1 m to allow for short computing times). In addition, a homogeneous initial distribution of fibers within the water and steady-state pumping operation was assumed.

CURRENT STATE OF CFD-MODELING

CFD is able to calculate the main flow characteristics for the investigated flow situations. To resolve the phenomena during a transient accident scenario a CFD simulation would be required of several thousand seconds of problem time. Also the complete sump geometry would have to be considered. This is beyond the currently available computational power. Therefore simplified assumptions/models have to be used. Any modeling approach should focus on either the essential parts of the geometry or a limited period of the accident scenario in which where the key phenomena arise.

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